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3-D Land Seismic Acquisition in Saudi Arabia

Richard Hastings-James and Kamal M. Al-Yahya
Saudi Aramco

ABSTRACT

Between 1991 and 1996, Saudi Aramco has acquired more than 8,500 square kilometers of 3-D seismic data in Saudi Arabia. During this time, a universal approach to 3-D acquisition has been developed. The resulting acquisition schemes use a dense source point grid with a low sweep effort per source point, and a high number of recorded channels distributed over a large surface aperture. This sampling strategy results in high fold data. Cost-effectiveness is achieved by ensuring that the source and receiver effort are balanced. Comparisons have shown that increases in surface aperture and fold, cross-line fold in particular, improve the data quality significantly at a marginal increase in cost. The cost per unit of data is made significantly lower even if the cost per unit of time may increase.

INTRODUCTION

Saudi Aramco's goal is to increase its reserves base and to maximize hydrocarbon recovery through the use of the latest technology to achieve a full integration of geology, engineering and seismic data. It has been recognized that 3-D seismic data have the potential of providing highly detailed subsurface images that can substantially enhance the understanding of reservoir complexity, leading to improved reserves estimates, reduced drilling risks, and enhanced reservoir development strategies. However, it was not until the 1990s that the potential of the 3-D seismic has been fulfilled through the availability of improved technology.

Delay-free recording systems capable of handling well over 1,000 channels, multiple ground-force controlled vibrator sets, and fully automated relational databases for tracking detailed recording geometry are now commonly available. Source and receiver positions can be measured to sub-meter accuracy using the global satellite positioning system network. Concomitant advances have taken place in the computer speed and memory capacity required to handle the massive amount of data generated in a modern 3-D survey. Improved 3-D processing and inversion algorithms, together with the availability of visualization and interpretation workstations now make detailed subsurface imaging possible (Saudi Aramco, 1994).

Saudi Aramco conducted its first 3-D seismic survey in 1977 over an exploration prospect near the Abu Hadriyah field, followed by a marine 3-D survey over the Marjan field in 1978 (Al-Husseini and Chimblo, 1995). Since 1991, Saudi Aramco has acquired over 8,500 square kilometers (sq km) of onshore 3-D seismic data in Saudi Arabia in the areas shown in Figure 1. Data quality varies in these surveys from very good to very poor, allowing 3-D acquisition strategies to be evaluated under widely differing conditions. The cumulative coverage up to July 1996 is shown in Figure 2. Since the number of 3-D crews and the nature of the 3-D surveys conducted are variable over this period, conclusions about production rates can not be inferred from Figure 2. However, as shown in Table 1, a higher number of VPs (Vibroseis Points) are acquired per day in the later surveys. This is a result of using less sweep time per VP and dual vibrator sets operating in tandem.

The increase in source energy per sq km is attributable to the use of more and larger vibrators as the energy source. Later surveys generate much higher volumes of trace data per sq km than the early surveys. This is due to the use of larger surface apertures for wavefield sampling, leading to higher fold and to a concomitant improvement in image quality. Production rates, as measured in sq km/day, are also higher in later surveys than those in the early surveys.

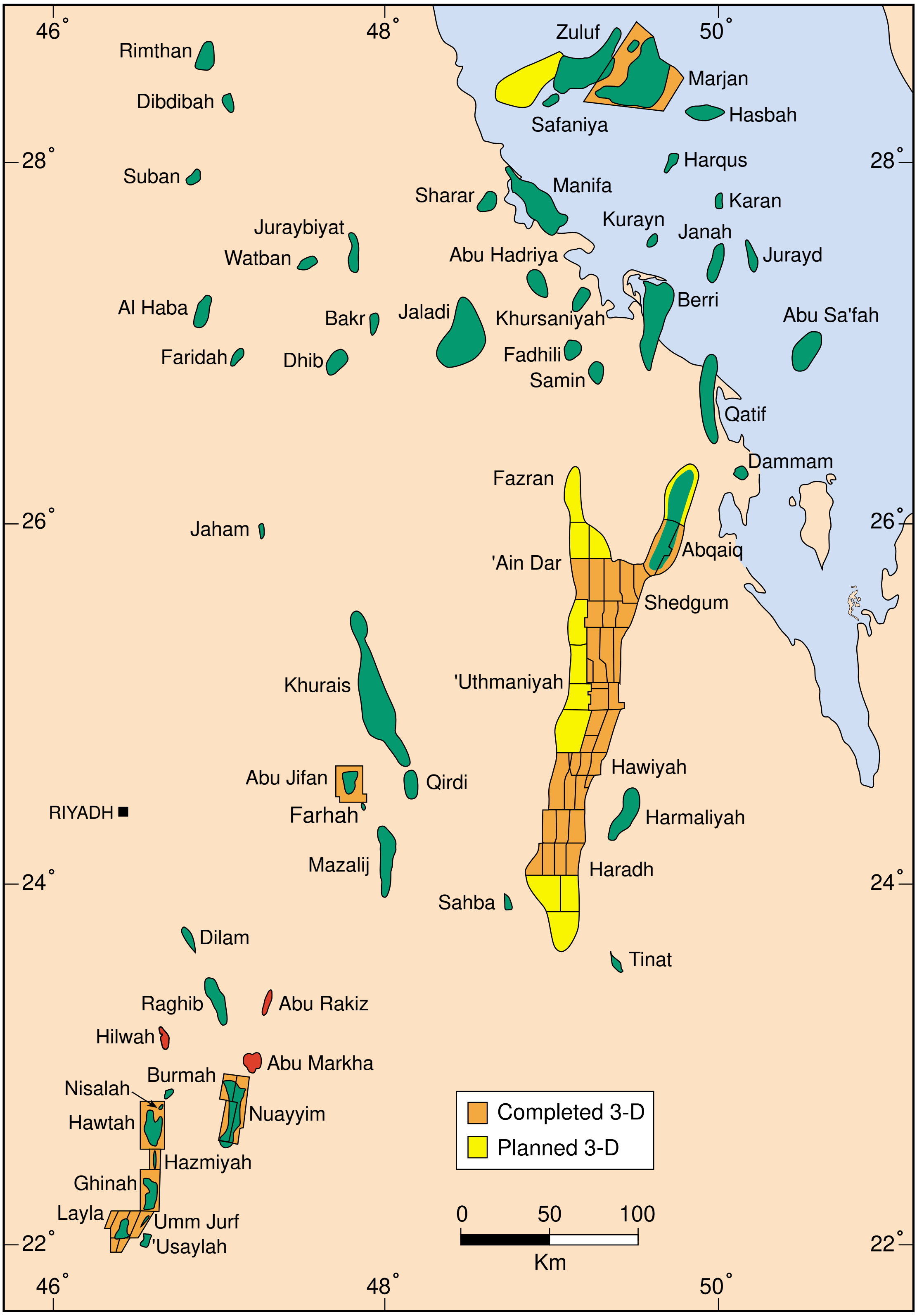


Figure 1: Saudi Aramco major 3-D seismic surveys. Data quality and survey objectives vary widely from area to area, permitting 3-D designs to be developed and tested under a variety of conditions.

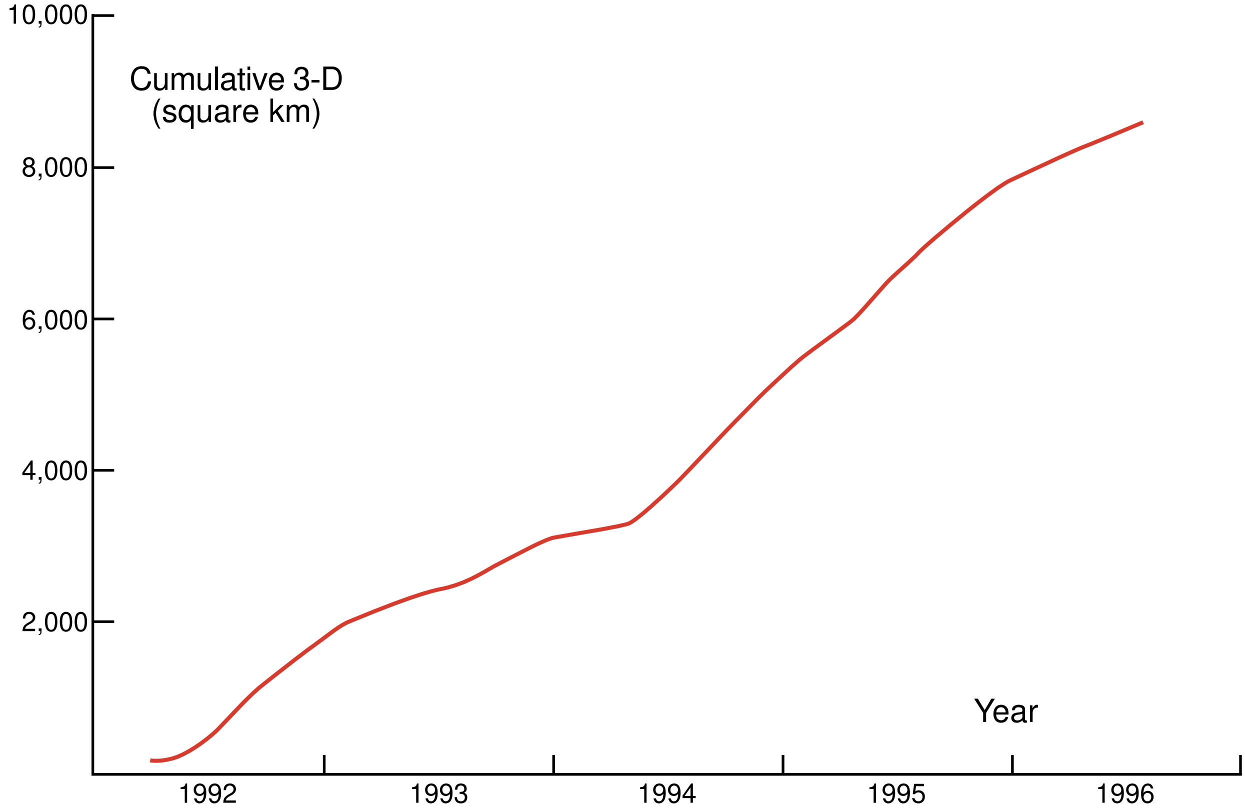


Figure 2: Cumulative 3-D sq km acquired in Saudi Arabia between 1992 and 1996.

Table 1
3-D Production and Acquisition Statistics between 1992 and 1996

Date	VP/day	Fold	Traces/sq km	sq km/day	Relative Source Energy
May 1992	138	45	71,796	1.38	100%
January 1993	394	96	153,600	1.97	82%
November 1993	403	96	153,600	2.02	82%
April 1994	451	144	228,148	2.25	117%
June 1994	480	144	230,400	2.40	117%
November 1994	641	144	230,400	3.21	117%
March 1995	752	170	272,000	3.76	117%
May 1995	1,052	288	460,800	2.63	117%

Note: Production rates (sq km/day), data density (traces/sq km), and fold have risen dramatically over this period of time, while the source energy injected per sq km has been maintained. As a result of the increase in acquired data density, 3-D image quality has improved dramatically, while acquisition costs have been reduced by using the techniques described in the text.

Acquisition of high fold 3-D data does not have to be a slow and expensive process. Current survey designs utilize a high areal source density, with a low source effort per VP, together with a large number of recording channels. They economically produce wide aperture 3-D data, with multiple coverage of up to 300 fold and far trace offsets to 6,000 meters (m).

In this paper we lay out the theoretical foundation of our acquisition scheme which leads to high fold seismic data. Cost factors of these acquisition schemes will be considered, along with their impact on crew configuration. These configurations will be discussed in terms of balanced operations that results in optimum block width and source and receiver layout.

UNIFORM ACQUISITION DESIGN FOR 3-D SURVEYS

The fundamental first step in acquisition design is to ensure that the seismic wavefield is sampled adequately. This requires that the spatial and temporal sampling intervals are small enough to prevent data or operator aliasing. It also requires that the apertures in time and space over which the sampling is performed are adequate to fully image the exploration objectives. In practice, although temporal sampling is not a problem, achieving adequate spatial sampling may be difficult with limited resources.

The 3-D design process should attempt to minimize the problems associated with the necessarily inadequate spatial wavefield sampling as a first priority. Other aspects of 3-D survey design, such as the source effort requirements, may be addressed as a separate issue once the basic acquisition geometry has been determined. Decimation in processing may be used to determine the effects on image quality of reducing the number of recorded channels and/or source point density. Experience in Saudi Arabia indicates that any reduction in sampling effort deteriorates image quality, even with 3-D recorded folds as high as 300.

The sampling aspects of 3-D survey design may be addressed in various ways. We choose to examine the common shot and common mid-point (CMP) domains, as these seem the most natural way to formulate the problem from an acquisition point of view. We note that the various other wavefield sampling domains are determined by the combined common source and mid-point domains (Vermeer, 1990).

The data are generated and recorded in the common shot domain. The spatial sampling in this domain is naturally defined by specifying how the recorded channels are deployed relative to the source point location. This is the usual method of specifying crew configuration and survey preplan. For example, the commonly used Shell Processing Support™ (SPS) database format contains the source and receiver survey data, and the source to receiver relational data in the S, R, and X files.

Commercially available 3-D acquisition design and quality control packages analyze the effects of recording geometry and source movement on wave-field sampling in the CMP domain. CMP bin offset and azimuth distributions may easily be determined throughout a survey area with these packages, using actual source and receiver locations. This enables a straightforward assessment of the adequacy of alternative recording schemes, once sampling requirements in the CMP domain are established.

The following fundamental 3-D acquisition design principle serves as a uniform basis for all of our 3-D surveys:

Consistent with available resources, generate and record the seismic wavefield over the maximum useable surface and time apertures, using the finest, most uniform, and most consistent sampling possible, in both the common source and common mid-point domains.

The uniform acquisition design principle can lead to non-traditional acquisition methods, particularly in the high fold data sets generated. It is extremely important to record 3-D data with an adequate sampling grid over a large two-dimensional surface aperture. Although the effects of surface recording aperture on imaging may be more pronounced in regions with difficult data, significant differences in imaging are noted even in good data areas. High fold 3-D acquisition is a natural outcome of meeting the shot and CMP domain wave-field sampling consistency requirements.

Uniform sampling in the CMP domain requires that CMP bins should be square, and that all bins within the full-fold survey boundaries must contain the same number of traces. The traces in the CMP bins must have a sufficient number of evenly distributed source to receiver offsets to adequately sample the wavefield over the required aperture. Trace offset and azimuth variations from bin to bin should be minimal. These CMP bins imply the existence of a corresponding ideal surface grid of source and receiver locations. Although 3-D data may be binned arbitrarily, there are restrictions on the placement of source and receiver locations such that the mid-points will fall at the center of the CMP bins. The dimensions of the ideal surface grids defining these locations will necessarily be twice the corresponding dimensions of the subsurface grid defined by the CMP bin centers.

Uniform sampling in the shot domain requires that the recorded channels are equally and symmetrically distributed relative to the source point location. They must be distributed at a suitable sample interval in both the in-line and cross-line directions over the maximum useful aperture. If receivers are deployed on all of the available points on the surface grid lying within the required aperture, then the use of suitable receiver arrays with effective dimensions equal to the fundamental receiver grid spacing will result in a continuous and uniform distribution of geophones over the entire surface aperture.

If the source point location grid is identical to the receiver location grid, but offset by half a grid interval from it in both the inline and crossline directions, then occupying all of the available source grid point locations would result in an approximate 3-D extension of the 2-D stack array requirement (Anstey, 1986; Onkiehong and Askin, 1988). This would bring the additional benefit of optimum surface wave suppression during processing.

At present, achieving optimal sampling in the source domain is impractical. It requires that receiver line spacing is equal to the in-line receiver group interval, and that there are as many receiver lines as there are in-line receiver groups. Current practice is to reduce both the crossline aperture and sample interval by using from four to twelve receiver lines separated by a distance equal to an integer multiple of the inline group interval. Decimating the ideal grid of source point locations results in other well-known acquisition schemes, including orthogonal, brick wall, zigzag, and double zigzag source patterns.

For example, a 3-D survey designed with 25 by 25 m subsurface bins and a 3,000 m far trace offset requirement would need a 50 by 50 m surface grid over an aperture of 6,000 by 6,000 m. Fully occupying the receiver grid requires an active spread of 14,400 channels. This could be laid out as 120 receiver lines with a separation of 50 m, and with each receiver line consisting of 120 channels at a 50 m group interval. Occupying every available source grid point would also be required to achieve maximal wavefield sampling consistency, resulting in 400 VPs per sq km, and a CMP bin fold of 3,600.

The constraints imposed by available resources forces decimation of the above realization. The method that we currently use is to design the in-line receiver lines in a symmetrical split spread configuration with an appropriate group interval (normally 50 m, but this is survey dependent). The far trace offset (aperture) is chosen appropriately for the survey objectives (for the example above, a 60/60 split spread using a 50 m group interval). Thus the inline sampling and aperture are not compromised. The number of available receiver lines should now be maximized according to the acquisition block width considerations below, and is solely dependent on equipment availability. Using 12 lines in the above example would require recording 12 times 120 = 1,440 channels.

Receiver line separation is chosen as a compromise between achieving a receiver line spacing equal to the in-line group interval (50 m) and a symmetric (6,000 m) source aperture at the surface (that is, equal far trace offsets in the in-line and cross-line directions). Current practice for a 50 m in-line group interval is to use a 200 m receiver line separation, which is a four-to-one ratio between in-line and cross-line sample intervals. Source points are located on a 50 by 50 m grid, offset from the receiver grid by 25 m. Source points are constrained to lie between the two central receiver lines in order to minimize source to receiver offset and azimuthal variations from VP to VP.

Unlike the receiver case considered above, it is practical to occupy all of the available source point locations (400 VPs per sq km). That has been done on several surveys in very poor data areas by using a compressed double zig-zag vibrator pattern. Normally, only half of the available locations are occupied (200 VPs per sq km) through the use of a conventional double zig-zag vibrator pattern.

Clearly, the larger the separation between the receiver lines, the larger the variations in trace attributes will become as the VPs traverse the area between the two central receiver lines. This can result in an undesirable acquisition footprint on the data. In the ideal case the receiver line separation is equal to the surface sampling grid interval. That is equal to twice the subsurface bin dimension, or in our case, since the bin is square, equal to the inline receiver group interval. In this case, there is only one crossline VP location for each receiver spread location, resulting in an identical source to receiver trace geometry at each VP.

With a line separation of 200 m, for example, there are four crossline VP locations for each surface receiver spread location, each with a slightly different source to receiver offset and azimuth distribution. Locating VPs beyond the area defined by the two central receiver lines, which is sometimes done to increase production rates, results in unnecessary irregularities in the wavefield sampling. Restricting

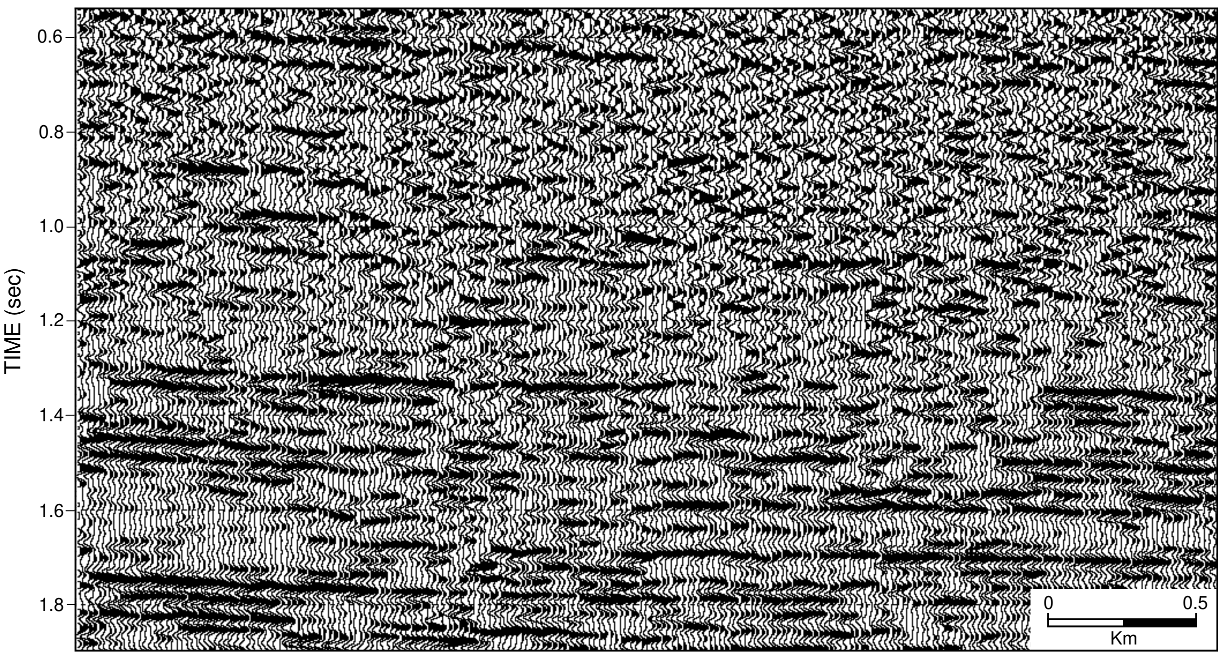


Figure 3a: Early 96 fold 3-D data set acquired using a surface aperture of 800 by 4,800 m.

the VPs to lie between the two central receiver lines requires that all but one of the receiver lines are common between two adjacent swaths in order to maintain uniform coverage. The implications are dealt with below in 3-D acquisition block design.

In the above example, 12 receiver lines at a 200 m separation would result in an effective surface source aperture of 6,000 m in-line direction and 2,400 m in the crossline direction. This will result in a fold of 360, rather than 3,600 that would result from the ideal sampling scheme outlined above. Thus sampling is severely biased in favor of the receiver line direction, both in terms of aperture and sample density. It is noted that as receiver line separation is increased, the variations in trace attributes between CMP bins will increase, which violates the uniform sampling requirement in the CMP domain.

Decimation of various data volumes acquired with ten or twelve receiver lines has shown that 3-D image quality is strongly dependent on cross-line sampling, and that at least ten or twelve receiver lines are desirable. We expect that imaging would continue to improve with more receiver lines, but have been unable to verify this hypothesis due to equipment constraints.

Comparison data sets showing the benefits of improved wavefield sampling were recently obtained in an overlap region between two 3-D surveys, as shown in Figure 3. The earlier survey (Figure 3a) was acquired at 96 fold using a restricted surface aperture of 8 receiver lines of 96 channels each spaced at 100 m and at a source density of 200 VP/sq km. The later survey (Figure 3b) at 288 fold using 12 receiver lines of 96 channels each spaced at 200 m using a source density of 400 VP/sq km.

Although the improvement in image quality for the later high fold survey is obvious, the source effort measured in sweep seconds per sq km is less. However, the source energy input per sq km of the later survey is actually higher than that of the early survey because of the larger vibrators used. The production rate, measured in sq km/day, of the later survey is about 30% higher than that of the earlier survey.

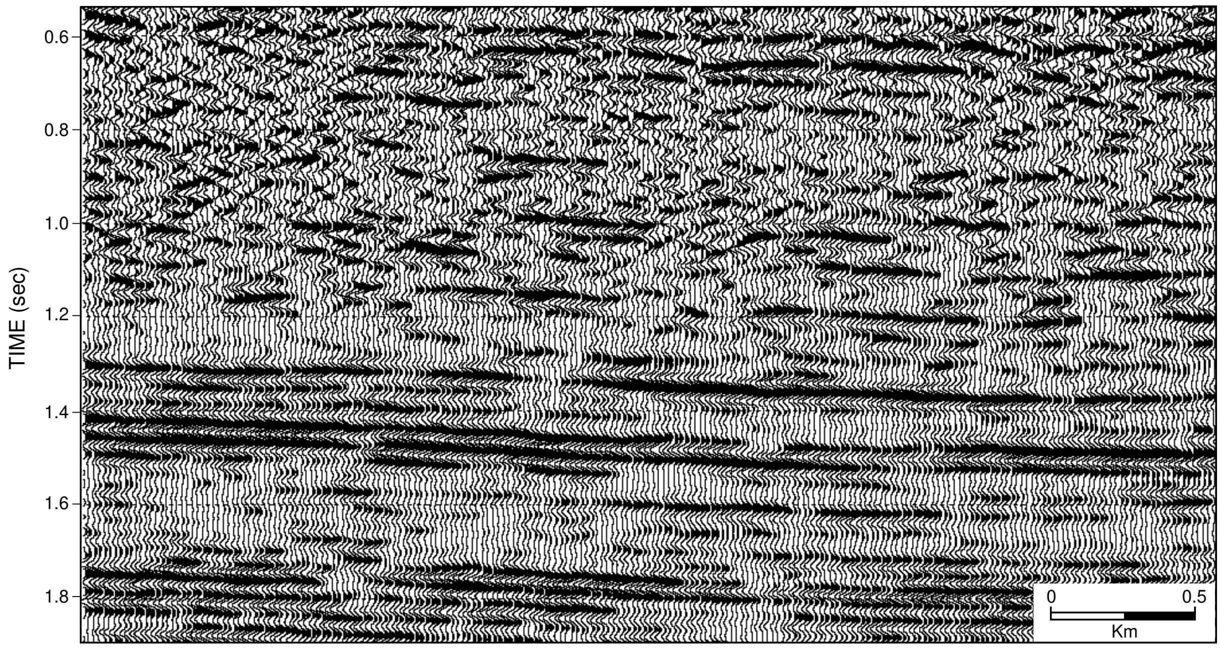


Figure 3b: Improvement in imaging of a later 288 fold 3-D data set acquired over the same subsurface line as in Figure 3a using a surface aperture of 2,400 by 4,800 m.

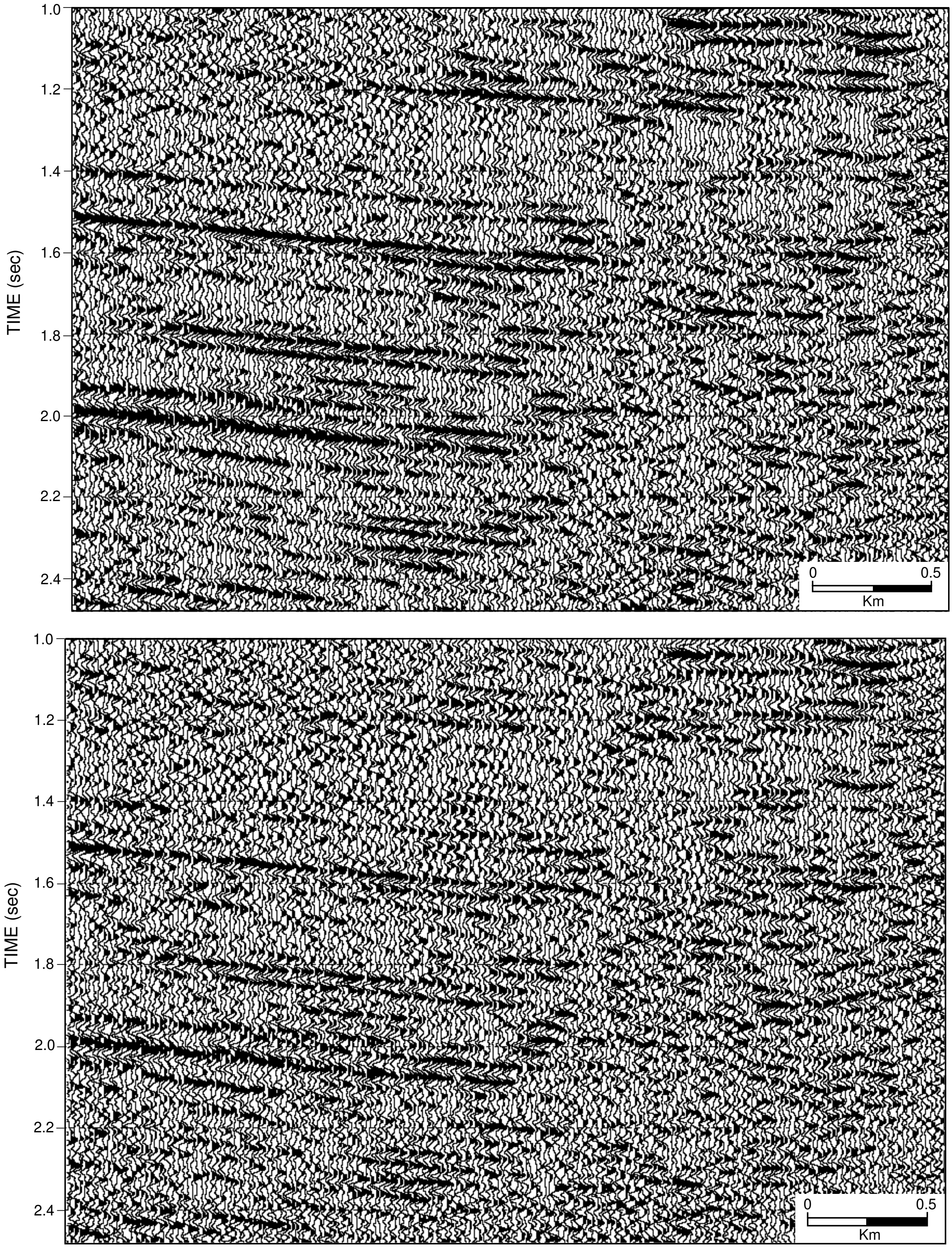


Figure 4: The effects of data decimation on image quality. The top image shows the imaging of the data set as acquired. The bottom image shows the reduction in signal to noise ratio that results from dropping every other source point, and the image to the right the effect of dropping every other receiver line. In the image to the right, the effective crossline aperture is maintained, while the crossline sample spacing is increased by a factor of two, thereby halving the fold. The effects on data quality are less evident in this case. However, note for example the degradation in the events just below 1.4 seconds on the left hand side of the section, and the events above 1.2 seconds on the right hand side of the section.

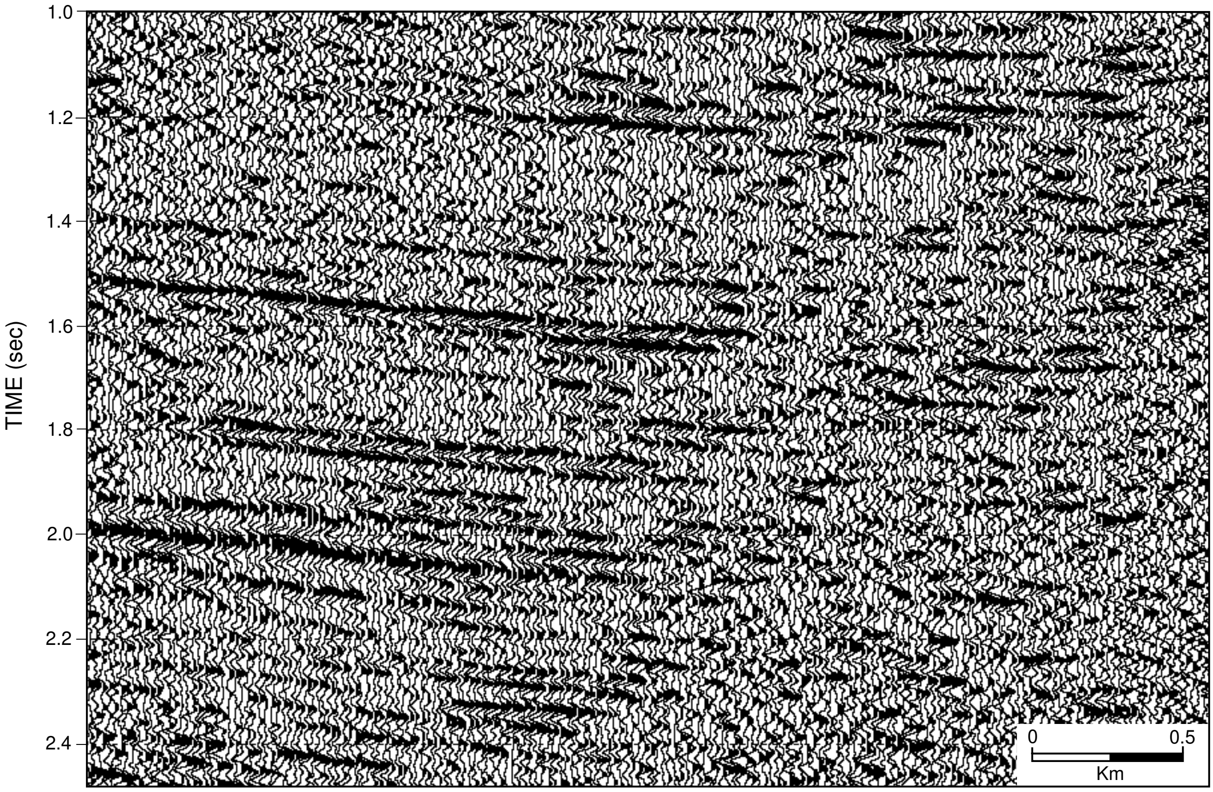


Figure 4: continued

Figure 4 illustrates the detrimental effect on imaging, for one particular data set (Figure 4a), of reducing the fold to approximately one half. Figure 4b shows the effect of dropping half of the shots, and Figure 4c shows the effects of dropping every other receiver line during processing. Note that the effect of dropping every other receiver line is to increase the crossline sampling interval while maintaining the effective crossline aperture unchanged. In this particular case, increasing the crossline sample interval has a relatively marginal effect on overall image quality, although the difference was judged to be significant from an interpretation viewpoint.

Figure 5 illustrates how the use of an inadequate surface recording aperture for the given target horizon can detrimentally affect the 3-D image quality. In this case limiting the inline far trace offset to 2,570 m (Figure 5a) resulted in severe multiple leakage. Figure 5b shows the improvement in fault definition obtained by extending the surface aperture to 5,300 m in the receiver line direction.

Figure 6 illustrates the potentially highly detrimental effect of an inadequate crossline surface aperture on image quality. The same recorded data set is used to produce both Figures 6a and 6b. The 44 fold stack in Figure 6a uses only a single near receiver line in processing, resulting in a surface aperture with zero crossline dimension. The 288 fold stack in Figure 6b utilizes all of the twelve recorded receiver lines at 200 m spacing, with an effective crossline aperture of 2,400 m.

The remarkable difference in imaging capability of the inline aperture (low fold) data set and the wide crossline surface aperture (high fold) data set is a very general phenomenon, which has been observed throughout Saudi Arabia. Further examples containing comparison data sets from a number of these areas may be found in Hastings-James and Al-Yahya (1996).

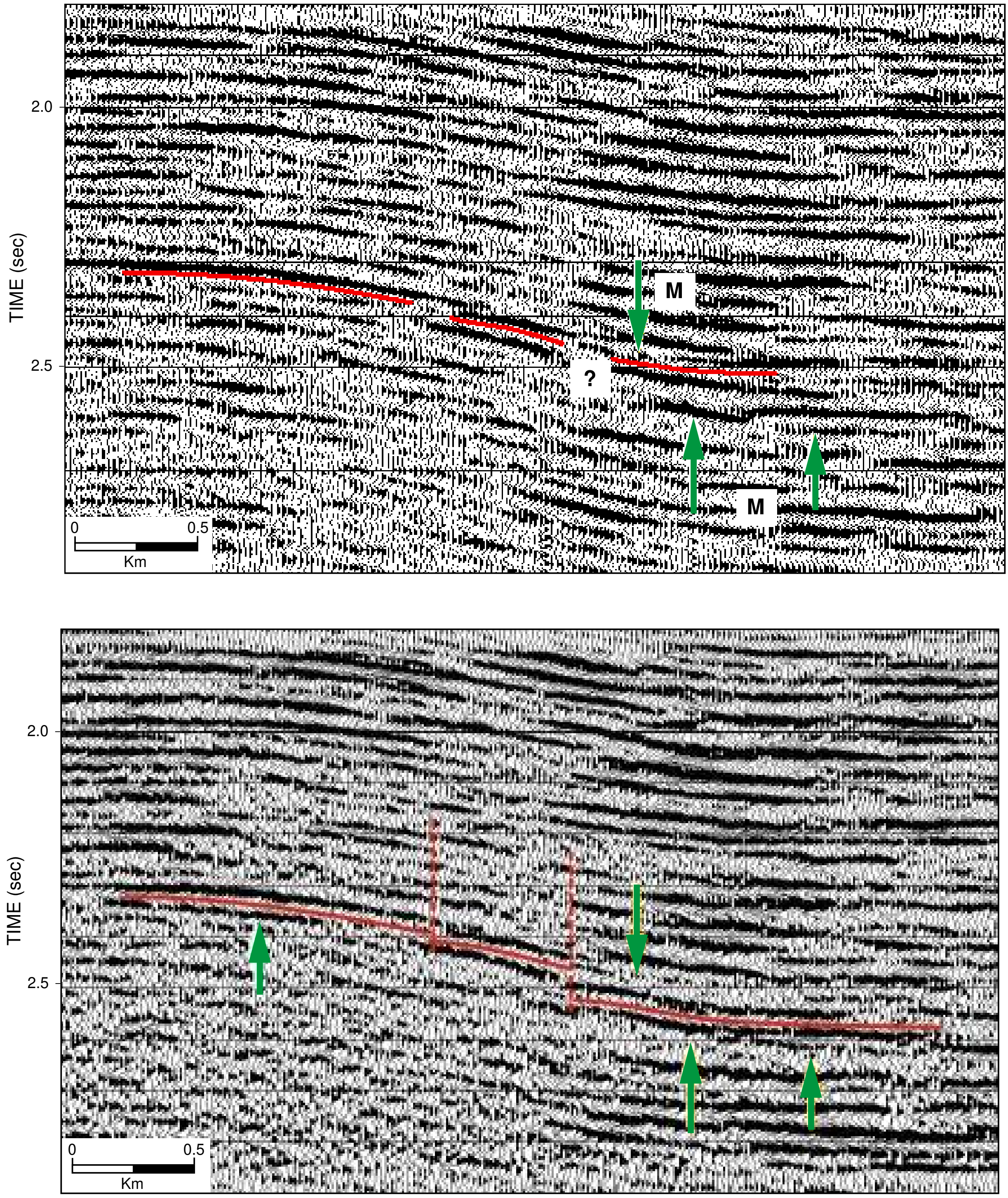
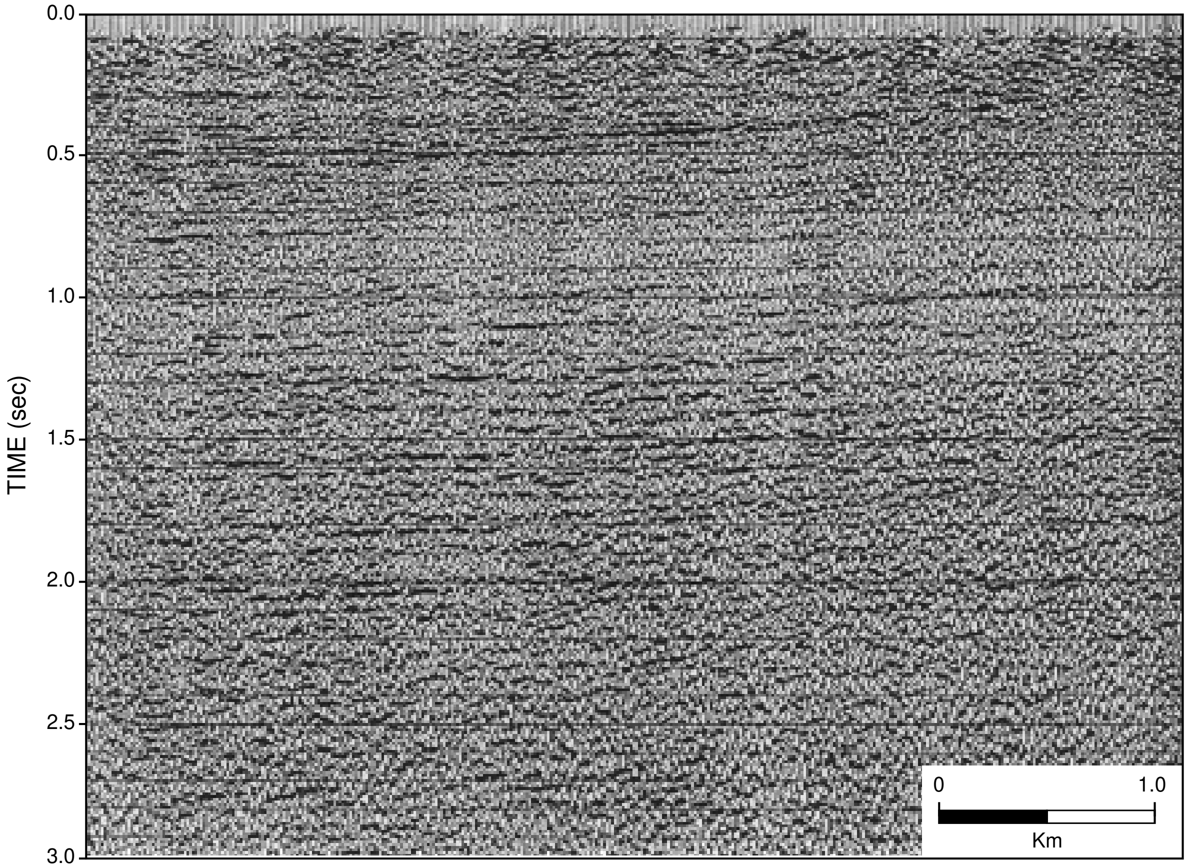


Figure 5: Comparison of 3-D image quality for two different surface apertures. Note that the multiple interference on the data set acquired with the smaller inline aperture shown in the top image makes the fault interpretation difficult when compared with the bottom image.

Figure 6 (facing page): The effects of surface crossline recording aperture on image quality. The top image shows the image obtained using an in-line surface aperture with zero crossline dimension, obtained during processing by removing the data from all but one of the near receiver lines. The bottom image illustrates the image quality using all twelve recorded receiver lines with the same inline aperture as that in the top image, but with an effective crossline aperture of 2,400 m. Note that there is no visible loss of frequency content in the wide aperture data when compared to the narrow aperture data, and that improved imaging extends throughout the section.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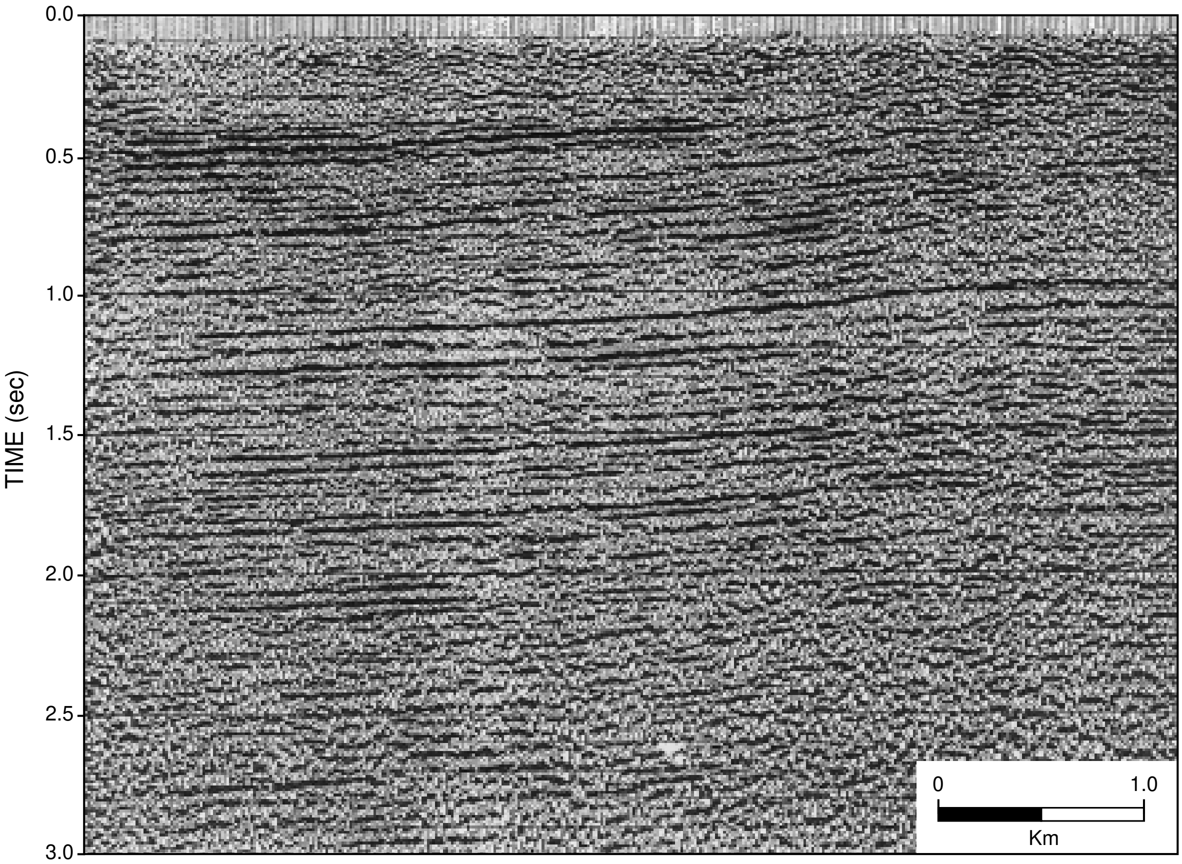
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THE COST OF HIGH FOLD SEISMIC DATA

High fold acquisition immediately invites cost benefit analysis. The general problem of optimizing data attributes, while minimizing the cost and acquisition time per unit of data acquired is not tractable. However, we may consider the costs associated with various crew configurations that produce 'equivalent' results in the sense that they provide alternative data sets with approximately equivalent seismic data attributes that meet the survey objectives. In this simplified problem, crew configuration decisions generally involve simple cost-to-benefit analyses of adding recording and/or source capabilities with the associated personnel and support equipment. The incremental cost associated with mobilizing and using the additional equipment and personnel over the remaining life of the project is then compared with the potential cost savings accruing from the estimated increase in production rates.

We choose to use 'cost per unit of data' rather than 'cost per unit of time' as the objective function to minimize. Optimizing acquisition costs may require the mobilization of a large crew resulting in a higher cost over a shorter period of time. The cost per unit of seismic data is calculated by dividing the total cost of deploying the crew during the time that the acquisition is taking place by the total data produced. This cost should include any pro-rated overheads such as mobilization and demobilization. Clearly, in order to minimize the net cost of acquisition per unit of data, it is necessary to maximize production while minimizing total crew operating costs.

The primary factors affecting seismic crew direct costs, which are basically time dependent are:

(1) Crew equipment (amount, type, mobilization, demobilization, fuel, support),
(2) Crew personnel (number, type, support costs),
(3) Terrain difficulty and remoteness (support equipment, transportation, supplies), and
(4) Re-allocated internal expenses and overheads.

The controllable factors which place limits on production rate include:

(1) Source effort (source time per unit area, making allowances for intra and inter VP source movement, and for any repeated VPs required in overlap region between acquisition blocks),
(2) Line effort (time taken to roll the receiver stations laid out per unit area), and
(3) Overheads (testing, terrain, equipment limitations, etc.).

We address optimizing the controllable factors in detail below. The level of testing or other non-productive time expenditure required on a given crew is an individual choice, and not addressable in any generalized sense. Equipment limitations should not be a major issue if modern technology is employed, since equipment speed and reliability are now very high.

Configuring 3-D Sources for Production Efficiency

Experience has shown that data quality is often only weakly dependent on increases in source energy per VP, once a threshold level is reached. In many areas, this threshold level appears to be quite low. Data quality can, however, respond remarkably to improvements in the spatial distribution of source energy, due to the concomitant improvement in wavefield sampling. This improved sampling can be achieved by distributing a given amount of source effort, as measured in sweep seconds, over a greater number of VPs per sq km. Clearly a given level of source effort, measured as sweep seconds per sq km, may be distributed in a number of different ways. The same total source energy per sq km may be achieved through the use of a high source point density (high number of VPs per sq km) with a low source effort per VP (sweep seconds per VP), shown conceptually in Figure 7a, compared with a lower source point density (low number of VPs per sq km) and a higher effort per VP (large number of sweep seconds per VP) shown in Figure 7b.

0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5

2.0	0	2.0	0
0	0	0	0
2.0	0	2.0	0
0	0	0	0

Figure 7: A conceptual illustration of how a given amount of source energy may be distributed in a number of different ways over a unit area. To the left, every available source point location is occupied, and a relative source effort of 0.5 is injected at each source point location. On the right, only every fourth source point location is occupied but a relative source effort of 2.0 is injected, thereby achieving the same energy input per unit area. Increasing the source effort, as measured in sweep seconds, at a given VP location may have marginal effect in improving data quality once a threshold is reached. However, increasing the number of occupied source point locations may result in significant improvements to data quality due to improved wavefield sampling in the CMP domain.

The amount of time required to inject the required level of source energy into the ground is a critical determining factor in the production capability of any seismic crew. Upgrading the ground force capacity of the vibrators on a crew is a particularly effective way of increasing crew efficiency by decreasing the sweep time requirements at each VP. Relative source energy level is directly proportional to the number of vibrators and the ground force capability of each vibrator. However, it is only proportional to the square root of the sweep time. Therefore, doubling the ground force capability of the vibrators reduces the sweep time requirement for a given energy level by a factor of four. For example, replacing a vibrator set consisting of four 37,500 pound (lb) vibrators (total ground force 150,000 lb) with a set of five 60,000 lb vibrators (total ground force 300,000 lb) would allow the effort per VP to be reduced from six 12 second sweeps to a single 18 second sweep, while maintaining the same source energy level. These theoretical relationships have been demonstrated to hold in practice through production data comparisons. Special tests include the acquisition of a 2-D multifold experimental line directly comparing the performance of sets of 35,000 lb and 60,000 lb vibrators.

It should be noted that there are some severe production overheads if the sweep time per VP becomes low. Factors affecting the time needed to complete the acquisition of a VP include not only the sweep time, but also the listen time, the vibrator move-up time, and other less quantifiable parameters. These include terrain type, the vibrator driving pattern (for example orthogonal, brick-wall, zig-zag, double zig-zag, or other), and the vibrator array configuration.

The manner in which the acquisition time per VP is affected by a change in one or more of these source parameters can either be estimated theoretically, or measured statistically in the field with a stop-watch once production has started. If, for a particular set of circumstances, reducing the sweep effort per VP would increase the production (VPs per day), then consider the use of a higher source point density at a lower sweep effort. The use of dual vibrator sets in a double zigzag pattern, a technique pioneered by PDO in Oman (Wams and Rozemond, 1996; Onderwaater et al., 1996) can significantly increase 3-D data production rates (by 30% to 70%) at these lower source efforts per VP. This is accomplished by eliminating much or all of the time lost due to vibrator move-up from one VP to the next.

The combined effects of the deployment of large ground-force capacity dual vibrator sets in an efficient source pattern using short sweep times per VP is very effective. It can lead to crew production capacity well in excess of 1,200 VPs per day, even in areas with demanding source energy requirements.

Efficient 3-D Acquisition Block Design

Surveys over large areas are sub-divided into acquisition blocks for reasons of operational efficiency. At the joins between these blocks, it is necessary to have source and/or receiver overlaps in order to merge the data in a seamless way such that the joins become transparent during processing. Because of the necessity for repeat coverage by sources and/or receivers at the block boundaries, it is critical, from an efficiency view-point, to minimize the number of inter-block joins. This requires that a seismic crew must be initially configured with a sufficient amount of line equipment to lay out wide enough acquisition blocks.

If a swath is acquired with a roll-on and a roll-off, narrow block widths result in a high percentage of repeated shots in the overlap zones between adjacent acquisition blocks. Total fold will reach 200% (representing wasted crew effort) in this block overlap zone in order to maintain consistent CMP trace offset distributions throughout the entire survey data volume.

If swaths terminate on a full receiver spread in order to avoid the need for repeated shots, then small block widths result in an excessive line equipment move rate. This is because a large number of the receiver stations laid out will not be vibrated on each swath. Once the swath is finished, all of the receiver groups in a receiver line must be rolled regardless of whether or not they were vibrated. Achieving reasonable equipment move rates will require the laying out of wide acquisition blocks to avoid an unreasonably high percentage of stations per swath that are not vibrated. Clearly, this approach places severe demands on crew equipment levels. It is probably best suited for crews recording a small number of receiver lines, when it can lead to very efficient operations.

The relationships between acquisition block width and the number of available channels on a crew may be chosen as follows to permit reasonable line operations.

Let N = the total number of available channels
L = the number of recorded receiver lines per shot record
GI = the receiver group interval
BW = acquisition block width

If L-1 is the number of receiver lines in common between adjacent swaths then the maximum acquisition block width that may be laid out is given by:

$$BW = (N \times GI)/(L + M)$$

The constant M varies from 0.5 to 1.0 depending on the particular type of line movement. If acquisition blocks start and end with a roll-on and roll-off, then M=0.5 is usually sufficient, since equipment roll rate is quite even. If blocks start and end on a full spread, then a value of M close to 1 is appropriate due to the irregular availability of equipment for pickup during acquisition. In this case, the full recording spread on one receiver line may not be picked up until after the last shot on the current swath, and the next swath may not be started until a full spread is available on the new receiver line.

Note that N is not the number of recorded channels, but the total available channels on the crew. N is often equal to the number of recorded channels plus 50% to 100% to allow extra equipment for line movement. As noted previously, the source points are constrained to lie between two central receiver lines to minimize variations in the recorded data attributes. In this case, L-1 receiver lines must be common between adjacent swaths in order to maintain uniform subsurface sampling in the CMP domain. Thus only one receiver line is rolled during the acquisition of each swath, regardless of the number of receiver lines being recorded. This effectively decouples the number of recorded channels from the amount of line effort required to move equipment.

Configuring Receivers for 3-D Production Efficiency

The number of recorded channels on a crew has little, if any, effect on crew production rates. The limitation on crew production rate imposed by equipment movement on the line depends primarily on the number of geophones that have to be picked up and planted after the completion of each VP. The number of geophones required to be moved per VP can be easily calculated from the basic acquisition geometry. Line equipment movement rates may then be estimated based on the required sweep seconds per VP, the terrain difficulty, and the vibrator movement time between VPs.

There can be secondary effects on production associated with high channel crews, due to the need to handle large amounts of line equipment. These include possible loss of time due to troubleshooting. Under normal circumstances this should be minimal with the level of systems reliability currently available in the field, provided that good geophones are available and environmental conditions do not require frequent replanting. With older systems, there may also be delays associated with handling the large amount of data acquired at the completion of each sweep, as well as with internal system checks associated with line roll. However, with the current 24 bit recording systems, these overheads are no longer a serious consideration.

Adding geophones to a crew is relatively expensive. It is, however, extremely important to use effective receiver arrays in order to minimize aliasing. We commonly use 72 geophones per receiver group because test results have indicated a degradation in data quality judged to be significant by interpreters at lower levels of effort, such as 48 geophones per group. In better data areas 48 and 60 geophones per group have, nevertheless, been used when the data continue to meet survey objectives, and when there are operational advantages to doing so.

As shown in Table 2, which is based on a detailed analysis of crew costs, the additional expense of adding recording channels is relatively low when compared to overall crew costs. This is due to the minimal impact of the additional channels on crew production rates, as noted above. The increase in cost is mainly associated with additional equipment maintenance, handling, and capital depreciation expenses. The ability to adequately sample the seismic wavefield over an improved aperture increases markedly with the addition of recording channels, making it a bargain in terms of improved data quality. Table 2 uses relative fold as an indicator of wavefield sampling capability versus relative crew cost.

Table 2
The Relative Costs and Benefits of Adding Receivers

Number of Channels	Number of Receiver Lines	Relative Cost	Relative Fold
240	2	1.00	1
480	4	1.04	2
720	6	1.08	3
960	8	1.13	4
1,200	10	1.17	5
1,440	12	1.21	6

Note: Adding recording channels to a crew is relatively inexpensive when viewed in terms of total crew operating costs. However, the potential benefits of using a large number of recorded channels are significant, as discussed in the text.

Balanced Operations

As source effort is lowered, the rate of vibrator progress increases to a point where it is no longer feasible to move line equipment fast enough to keep up with the vibrators. At this point, production becomes 'line limited'. Good survey design requires that production is balanced. In particular, it should never be line limited, since this means that the vibrators are idle for a significant portion of the

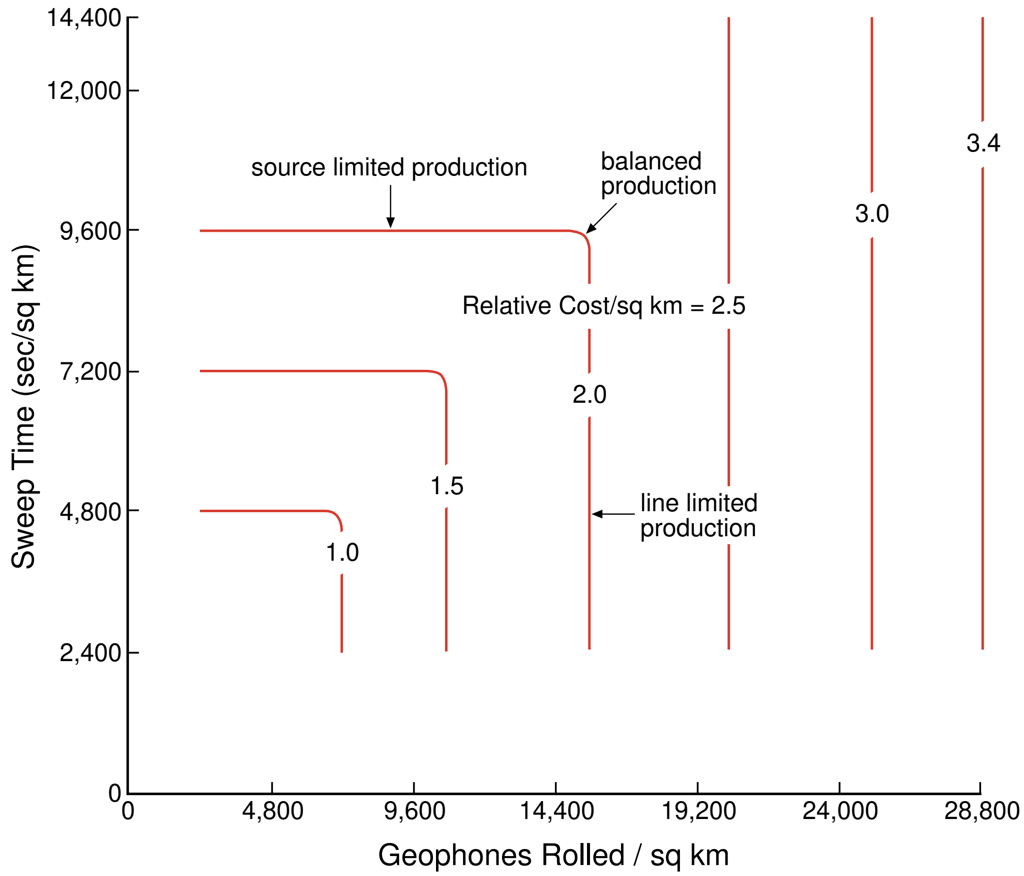

Figure 8: Cost as a function of source and line effort. The axes on this figure represent source effort as measured by sweep seconds per sq km, and line effort as measured by geophones rolled per sq km. The contours indicate the relative cost of acquisition of a sq km of data for various combinations of source and line effort. It can be seen from the graph that for a line effort of about 14,400 geophones rolled per sq km, the relative cost of acquisition does not decrease from 2.0 as the source effort is reduced below 9,600 sweep seconds per sq km. In this region of operations the crew would be operating in a 'line limited' mode. With a source effort of 9,600 sweep seconds per sq km, lowering line effort below about 14,400 geophones rolled per sq km results in no corresponding reduction in relative cost below 2.0. In this region of operations the crew would be in the 'source limited' mode. The intersection points between the horizontal portion of the constant cost contours, which indicate source limited production, and the vertical portion of the contours, which indicate line limited production, represent the ideal 'balanced' mode of crew operation. When a crew is operating in a balanced mode, an increase in either source or line effort will affect production rates, and hence cost.

time. They could use this idle time to in an attempt to improve the signal to noise ratio, or to extend the recoverable seismic bandwidth, for example. If no other solution is available, then the source effort must simply be increased to take up this idle time. When the correct balance between source and line effort is achieved, the vibrators do not have to wait for line layout, nor do the line labor have to wait for vibrator deployment.

Figure 8 illustrates the relationships between cost of acquisition, source effort, and line effort. It is evident from this diagram that in certain regions a reduction in the number of geophones rolled per VP does not result in a lowering of cost; this represents source limited production. In other regions of the graph, lowering the source effort does not produce a decrease in cost; this represents line limited production. The trajectory along which the two regions meet represents balanced crew operations. Here an increase in source or line effort will produce a change in production rates and hence cost, and the crew is operating at maximum efficiency.

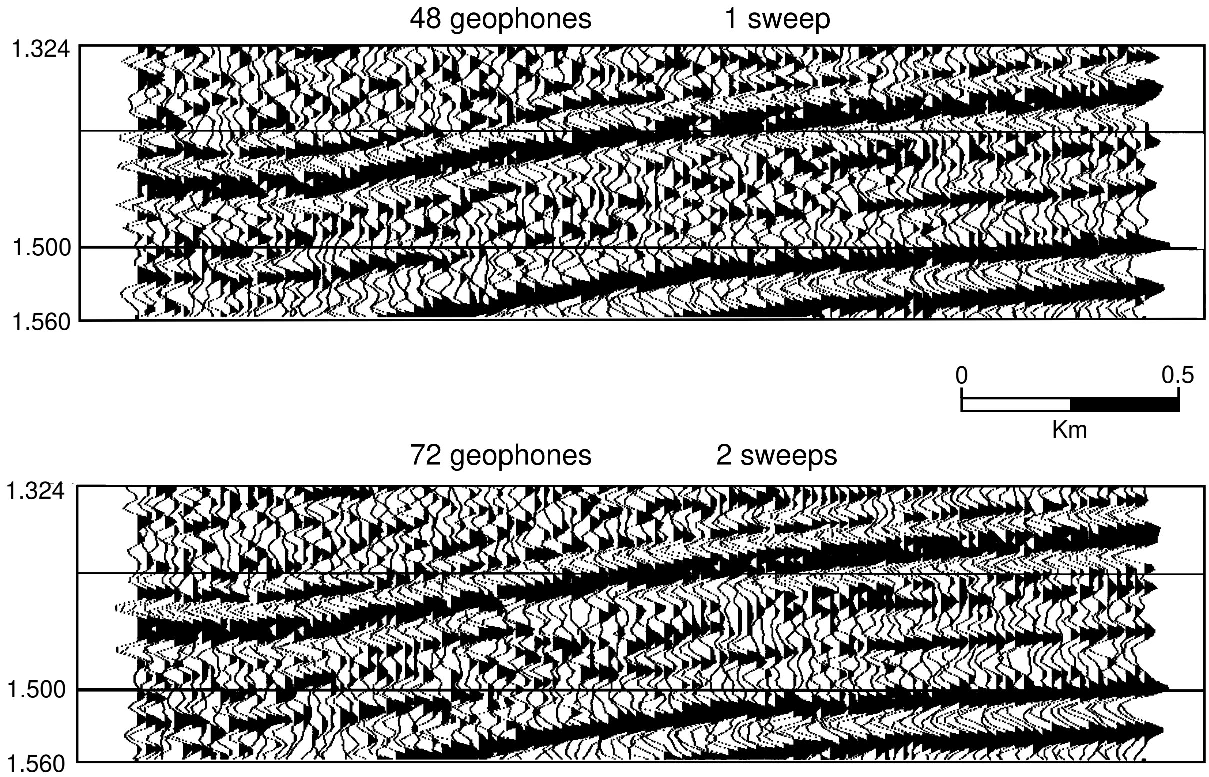

Figure 9: A design choice for balanced crew operations. The top image was obtained using one 12 second sweep per VP and 48 geophones per receiver group. The bottom image was obtained using two 12 second sweeps per VP and 72 geophones per group. Note the improvement in the continuity of the reflector package just above 1.5 seconds at the higher level of effort. Although using one 12 second sweep and 72 geophones per group also produced acceptable data quality, this was not a viable combination for 'balanced' crew operation. Considering this test data, the 3-D survey was acquired using two 12 second sweeps per VP and 72 geophones per group.

An example of achieving balanced crew operation is shown in Figure 9. Here the choice is between using 72 geophones per group with two 12 second sweeps per VP and 48 geophones per group with one 12 second sweep per VP. The higher effort data was preferred by all interpreters. The use of one 12 second sweep with 72 geophones per VP was also considered. In this case, the imaging was slightly deteriorated but also acceptable to the interpreters. However, the combination of one 12 second sweep and 72 geophones per group was not a viable option for balanced crew operation. The crew was not able to move 72 geophones per group at a fast enough rate to keep up with this lower sweep effort. The only meaningful choices are therefore the two cases illustrated.

CONCLUSIONS

Recent surveys have been acquired in areas of poor data quality with 3-D folds as high as 288 into 25 by 25 m bins. Using a uniform approach to 3-D acquisition design, surveys were acquired with a large surface aperture using a high number of channels, high areal shot density, and low energy per VP. This leads to high fold 3-D data volumes. Careful balancing of the line and source efforts required by these surveys has resulted in excellent crew efficiency and high recording production rates, while significantly increasing the quality of the data acquired.

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ABOUT THE AUTHORS

Richard Hastings-James *is currently Geophysical Consultant with Saudi Aramco. He has 16 years of exploration industry experience, 12 of which were with Amoco Production Company in Canada, Houston and various locations throughout Africa and the Middle East. Prior to that, he was an Associate Professor at the Technical University of Nova Scotia, Canada. He has been with the Geophysical Operations Division of Saudi Aramco since 1992. Richard has a BEng degree in Electrical Engineering from the Technical University of Nova Scotia and a PhD from Trinity College, Cambridge. He is a member of the SEG and Dhahran Geological Society.*

Kamal M. Al-Yahya *has a BSc in Physics (1980) from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, a MSc in Engineering Geosciences (1983) from the University of California, Berkeley, and a PhD in Geophysics (1987) from Stanford University. Currently he is serving as Acting Manager, Exploration Applications Services Department, Saudi Aramco. His areas of interest include signal processing, integrated reservoir studies and data acquisition. He is a member of the SEG, EAEG and Dhahran Geological Society.*

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