

Effect of Offset on Time to Depth Conversion

BY

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DEDICATION

This thesis goes to my beloved wife who supported me and patiently took care of our beautiful children during my studies.

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I am deeply grateful to my advisor and committee chair for his invaluable patience and feedback throughout my academic journey. I also express my appreciation to my committee members for their generous contribution of knowledge and expertise. Additionally, I cannot omit my family, particularly my parents, spouse, and children, who have been a constant source of belief, motivation, and support throughout this process. I cannot thank them enough for keeping my spirits high.

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LIST OF ABBREVIATIONS

V_{RMS} : Root-mean-square velocity

TWT: Two-way-time

AVO: Amplitude versus offset

CVS: Constant velocity stack

V_p : Compressional-wave velocity

θ_c : Critical angle

ABSTRACT

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The process of time-to-depth conversion is crucial for determining the depth of the next well to be drilled and for resource estimation. The most effective method to perform time-to-depth conversion is by using seismic velocity due to its dense spatial and temporal sampling. However, seismic velocity can lead to errors as it depends on the parameters used during velocity analysis in the processing stage. This study is aimed to investigate the relationship between offset and time-to-depth conversion.

A 2-D synthetic viscoelastic seismic data of the northern Ghawar field in Saudi Arabia was used to investigate the relationship between the offset range used during velocity analysis and time-to-depth conversion. Three formations (Shuaiba, Arab, and Qusaiba), at different depths were considered. Velocity analysis for each formation was carried out using three different offsets (equal to formation depth, double the formation depth, and all available offset). The results show that the amount of error in depth calculation decreases with offset. This agrees with the theoretically derived short-offset assumption, where limiting the offset increases the chance picking the correct velocity, leading to a depth closer to that calculated from the model. The estimated two-way travel time values usually had lower values than their corresponding values calculated from the model.

One reason for the decreasing depth accuracy with increasing offset might be phase change that occurs beyond the critical angle when very large offsets are used in velocity analysis. This phase (often polarity) change affects the semblance energy, making it weaker and leading to difficulties in picking the correct velocity. This eventually leads to large errors in

estimating the depth values. Therefore, it is recommended that we restrict the maximum offset during velocity analysis of a certain formation to the offset corresponding to the critical angle between that formation and its underlying formation.

ملخص الرسالة

الاسم الكامل: جمال عبد الناصر فلمبان

عنوان الرسالة: تأثير المسافة على التحويل من الزمن إلى العمق

التخصص: الماجستير في علوم الجيوفيزياء

تاريخ درجة الماجستير: أكتوبر 2024

تعد عملية تحويل الزمن إلى العمق من العمليات المهمة في تحديد عمق البئر وتقدير موارد الحقل. الطريقة الأمثل هي استخدام السرعة الموجية. الاعتماد على السرعة الموجية قد يؤدي إلى اتساع رقعة الخطأ لاعتمادها على طريقة اختيار السرعة في مرحلة معالجة البيانات الموجية. تهدف هذه الدراسة إلى بحث العلاقة بين المسافة والتحويل من الزمن إلى العمق.

طبقت هذه الدراسة على نموذج اصطناعي لحقل الغوار في المملكة العربية السعودية، لبحث العلاقة بين المسافة وتحويل الزمن إلى العمق. وقد تمت الدراسة على ثلاث طبقات رئيسية وهي: الشعيبة، العرب، والقصيية، بثلاث وضعيات أو مسافات مختلفة لكل طبقة. أظهرت النتائج أن نسبة الخطأ تقل كلما قلت المسافة، وذلك تباعاً لنظرية المسافة القصيرة في علم الموجات الصوتية. حيث أن تقليل المسافة يزيد من احتمالية اختيار السرعة الصحيحة وبالتالي يؤدي إلى تنبؤ صحيح لعمق الطبقة. قيمة الزمن على النقيض أقل من القيمة المحتسبة، ولا تمثل أي نزعة أو اتجاه معين.

تأثر عملية عكس الطور الموجي إلى ما بعد الزاوية الحرجة في اختيار سرعة التراص الصحيحة، حيث أن طاقة التشابه تضعف أو تقل وبالتالي إلى اتساع رقعة الخطأ في تحديد عمق الطبقة. استناداً لذلك، من الأمثل استخدام الزاوية الحرجة لتحديد المسافة القصوى المسموحة لاختيار سرعة التراص. زاوية السقوط الأولى يجب أن تكون صغيرة جداً للوصول إلى أقصى عمق تحت سطح الأرض.

CHAPTER 1

INTRODUCTION

1.1 Time to Depth Conversion

Time to depth (T2Z) conversion of the seismic data is an important task of the interpreter because seismic measurements are made in time, while well data is measured in depth. Prediction of depths and their associated errors is very critical, especially when these predictions influence new wells to be drilled in an economic way. Time to depth conversion can be carried out during processing, where the result is the depth volume, this is called depth migration. T2Z conversion of time seismic data is computationally simple and can be quickly repeated whenever new information is available.

The link between depth and time is the velocity model. A velocity model can be built depending on the purpose and availability of existing data. There are different ways to convert the two-way time map into a depth map. With the availability of well data, the average velocity at each well can be calculated using a simple formula, with the inputs being the time and depth at each well (Wildan, 2013).

Another method is to use the time–depth values from a check-shot survey; the interpreter often approximates the measured time–depth function with a mathematical function such as a straight line fitted to the time–depth points or nonlinear polynomial functions (Brown, 2005).

Analytical functions representing the variation of instantaneous velocity with depth have been used for depth conversion such as the following equation:

$$V_z = V_0 + K.z \quad (1)$$

This leads to a time–depth relationship as follows:

$$z = \frac{V_0}{k} (e^{kt} - 1) \quad (2)$$

where z is the depth, t is the one-way time and V_0 and k are functional parameters (Al-Chalabi, 1997).

Due to the complexity of the earth, a multilayer velocity model is used to account for the changes in rock properties from one formation to another. Each layer consists an interval velocity related to the lithology and pore-fluid of the layer. The following Dix formula is used to estimate the interval velocity:

$$V_{int} = \sqrt{\left(\frac{T_2 * V_2^2 - T_1 * V_1^2}{T_2 - T_1} \right)} \quad (3)$$

where V_1 and V_2 are the root-mean-squared (RMS) velocities and T_1 and T_2 are the zero-offset times from the surface to the top and bottom of the layer, respectively. The interval velocity is used to convert time thickness into depth thickness, and then the different thicknesses are added to find the target depth.

The seismic Root-mean-square (RMS) or stacking velocity is often used by interpreters in the process of constructing velocity models due to its extensive spatial sampling. These velocities are picked by the processor

during the velocity analysis stage in a panel called the velocity spectrum (Yilmaz, 2000). The average velocity can be extracted from the RMS or stacking velocity and can be used in T2Z conversion after calibration with well data (Singh et al., 2009).

1.2 Statement of the problem

Depth conversion plays a major role in predicting the next well to drill. The time-to-depth conversion using seismic RMS or stacking velocity is usually preferred by interpreters because it involves spatial and vertical information. However, there is an indirect relation between offset limitation and depth that might affect the accuracy of time-to-depth conversion.

1.3 Research Objectives

The objective of this research is to investigate the error in depth when the offset is limited. In particular:

1. At each reflector depth, three offsets are generated: (1) a maximum offset equal to the depth of the reflector, (2) a maximum offset equal to double the depth of the reflector, and (3) a maximum offset equal to the maximum available offset.
2. Test the method on synthetic data from a Saudi Arabian model using three different reflectors at three different depths.
3. The depth value obtained from the three different offsets for a particular reflector will be compared to the actual reflector depth value from the model at the analyzed common midpoint (CMP) location to estimate the amount of error.

1.4 Literature Review

A single time–depth curve, derived from a best fit to time–depth curves from wells and reservoir tops, can be used to generate a depth map. Oyedele (2013) used this method after fitting a polynomial to the time–depth curve, to convert the two-way time map into depth for the integration of seismic and well data for reservoir characterization in offshore Niger Delta oil province (Figure 1). This method is simple, quick, and assumes a constant velocity throughout the structure but lacks accuracy away from the well. It also ignores the structure, operates at known depth points, and uses only the seismic time at well points. The velocity information from the seismic data and all its spatial benefits cannot be used in this method. Therefore, in case of steeply dipping structures, the area of the reservoir might be overestimated (Singh et al., 2009).

Analytical functions representing the variation in the instantaneous velocity with depth have been used for depth conversion. Ogbamikhumi (2019) used this method during time-to-depth conversion in the Onshore Niger Delta, as it yielded a small residual among the other methods (Figure 2).

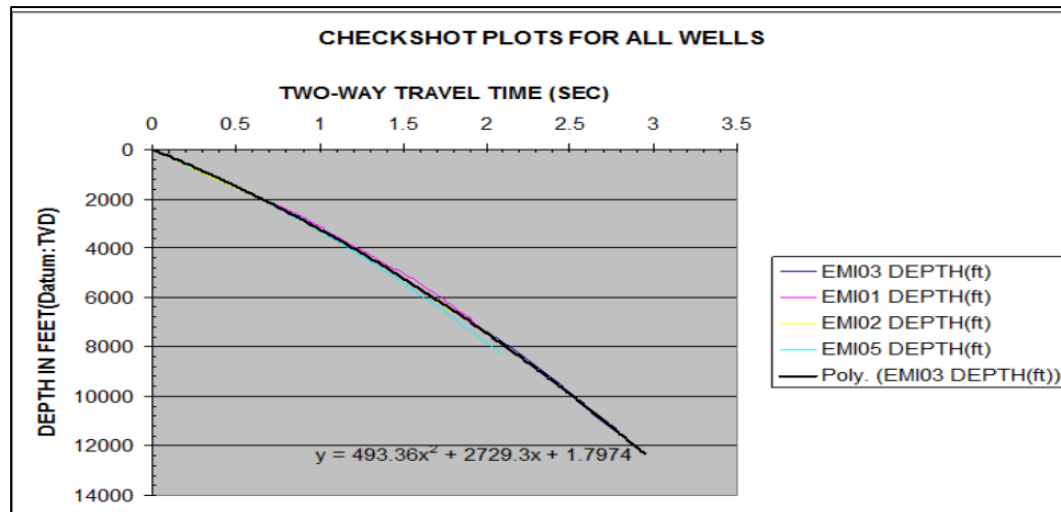


Figure 1. The time–depth curve function to the top of the reservoir (Oyedele, 2013).

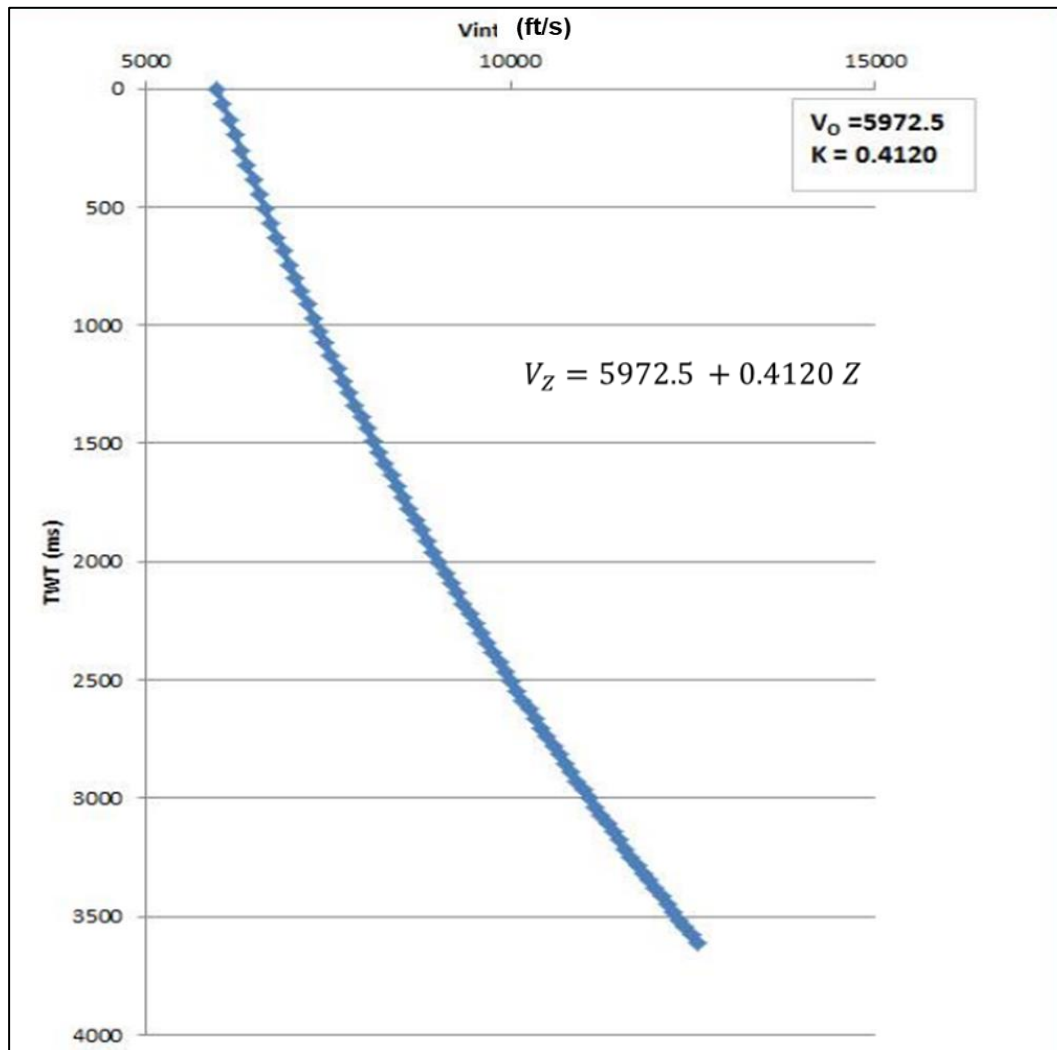


Figure 2. Two-way time against instantaneous velocity, where V_0 is the velocity at zero time and K is the gradient or change in velocity with depth (Ogbamikhumi, 2019).

This special case of the vertical time–depth relationship is the most relevant for depth conversion processes, as it considers the change in velocity with increasing depth. However, this method is not directly applicable in multilayer depth conversion since it assumes a single layer from the reflector to the surface (Al-Chalabi, 1997).

Both methods above utilizing average velocity, interval velocity or instantaneous velocity (Figure 3), use the information from the well to calculate velocity values. They then interpolate or extrapolate by different gridding algorithms (Abrahamsen, 1996) to create velocity maps for converting the two-way time map without considering the spatial variation of velocity (Brown, 2005).

Neither the single time–depth curve nor the analytical function methods consider the change in rock properties for different layers. Therefore, the interval velocity for multilayer depth conversion using the Dix formula (equation (3)) is applied to account for different layer properties (Dix, 1955; Sheriff and Geldart, 1995).

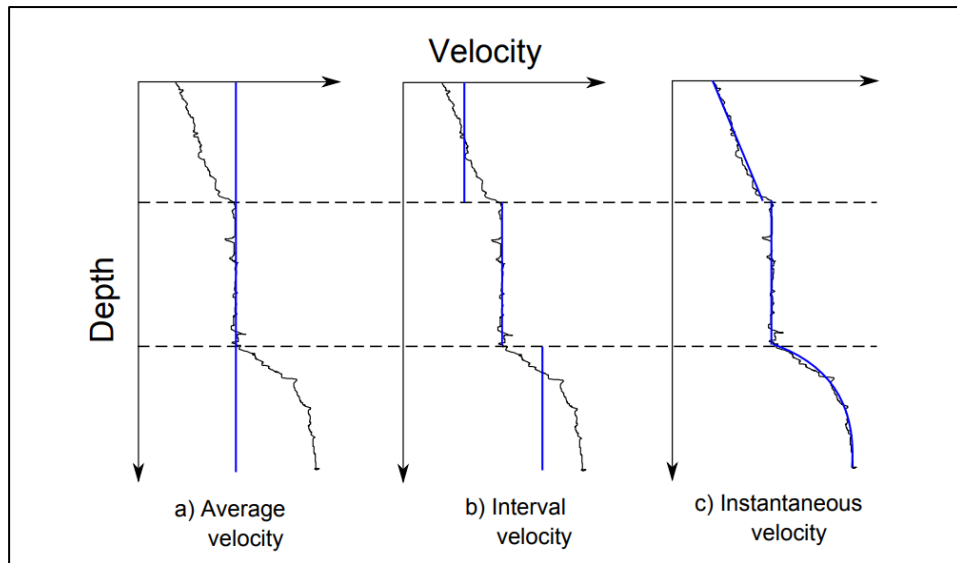


Figure 3. Three different velocity types of the velocity model are used to describe the velocity inside the layers (Viol, 2015).

Seismic velocity has spatial and vertical information since it provides measurements at every CMP interval depending on the acquisition parameters (Sheriff and Geldart, 1995). Interval and average velocities can be computed from Root-mean-square or stacking velocity after calibration with well data and then used to convert the two-way time map into a depth map. Singh et al. (2009) used average velocity extracted from stacking velocity to generate different depth maps for volumetric estimation. The uncertainty of the RMS or stacking velocity depends on the noise level of the seismic data, the picking velocity analysis during the processing stages and the method used to estimate the velocity (Yilmaz, 2000).

The stacking velocity can be estimated by the constant velocity stack (CVS) method. The CVS method uses stacking of a small section of the seismic line using a different constant velocity for each panel (Figure 4), with the best velocity yielding the best stack (Yilmaz, 2000).

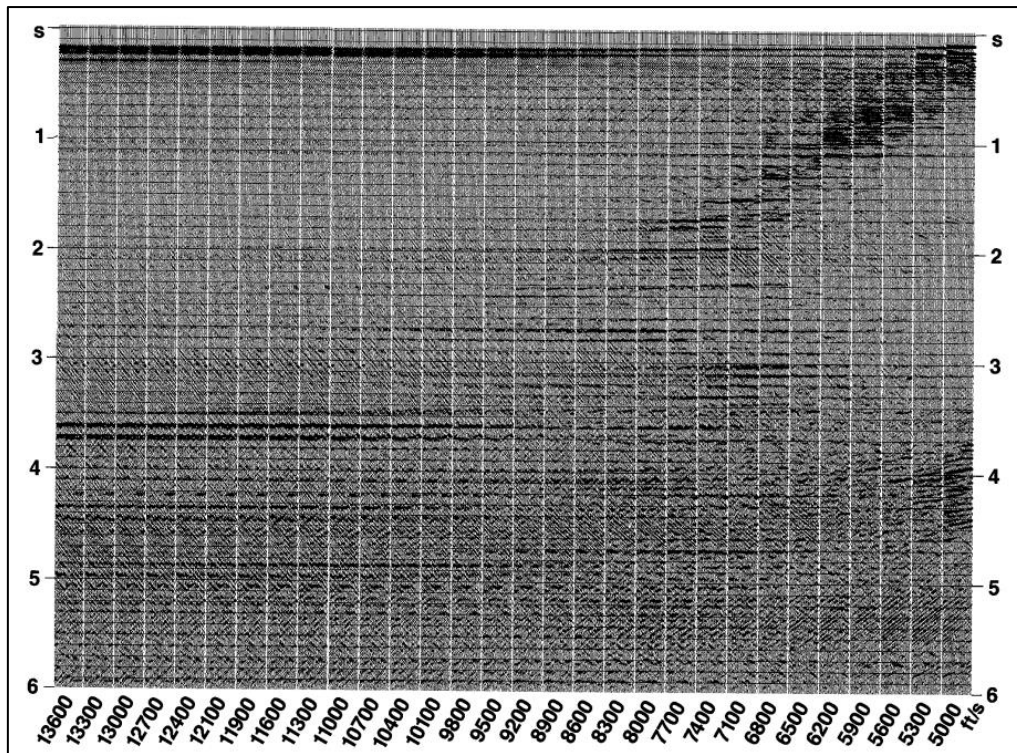


Figure 4. Constant velocity stacks of 24 CMP gathers using velocities of 5000-13,600 ft/s (Yilmaz, 2000).

Another technique for velocity analysis is the velocity spectra (Taner and Kohler, 1969). This method attempts to display signal coherency (semblance) over a fitted hyperbola in a determined time gate in the two-way time zero-offset versus velocity domain. The best-fit stacking velocity corresponds to the highest signal coherency (Carlino et al., 2016), as shown in the example in Figure 5.

There is a difference between NMO and stacking velocities that is often ignored in practice. The NMO velocity is based on a small spread hyperbolic time, while stacking velocity is based on a hyperbola that best fits the entire spread length (Taner and Kohler, 1969; Al-Chalabi, 1973).

Measuring the semblance has been an indispensable tool for velocity analysis of seismic records. Although effective in most practical situations, the semblance becomes troublesome in the case of strong variations in amplitudes of seismic events. Ratcliffe and Adler (2000) and Sarkar et al. (2001, 2002) developed algorithms for correcting the semblance measurement for amplitude variations.

Fomel (2009) derived an explicit expression for the AB semblance and analyzed it to quantify the observable loss of resolution, where A and B denote the amplitude versus offset (AVO) intercept and gradient. However, the AB semblance method uses the amplitude trend as opposed to the conventional semblance method, that uses a constant amplitude, suffers from issues of low resolution and high sensitivity to noise.

Celis (2002) introduced a selective correlation method between traces rather than all traces and discard the traces that exceed a chosen threshold

value to improve the velocity analysis resolution in the presence of closely interfering events.

Luo and Hale (2012) introduced another method in increasing semblance resolution using weighted semblance by an offset-dependent weighting function to minimize semblance, where semblance peaks equal to 1.0 are not affected by the weighting function and semblance less than 1.0 is minimized to boost the resolution of the existing peaks.

Liu et al. (2014) proposed a different weighted approach based on the local similarity between each trace and a reference trace. The reference trace can be a zero-offset or stacked trace. This method can be combined with the AB semblance method for handling AVO anomalies.

Abdulrahman (2017) investigated the effect of the short-offset assumption on velocity analysis to determine the correct velocity at a target formation. He concluded that there is no need to honor the short-offset assumption to pick velocity, as the error differences between short and long offsets are small in estimating the interval velocity.

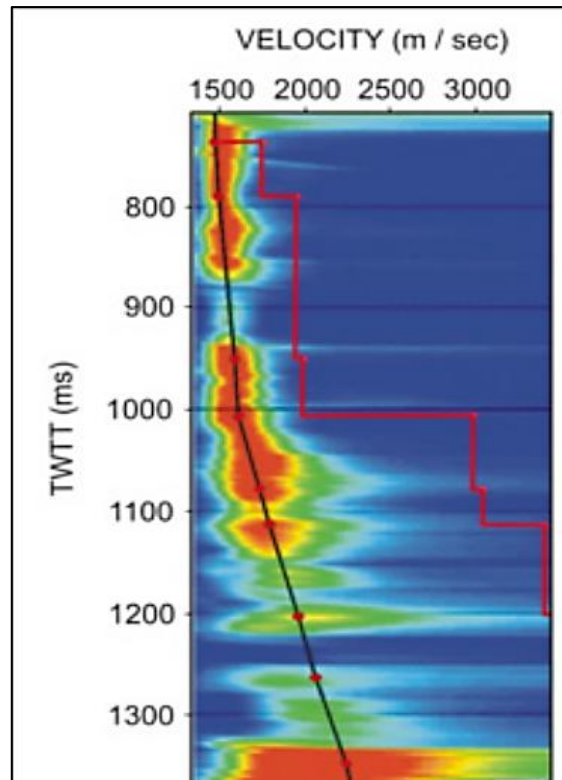


Figure 5. Velocity spectrum (Carlino et al., 2016).

CHAPTER 2

MODEL AND DATA GENERATION

2.1 Study area and geological setting

The study area is situated to the north of the Ghawar structure in the eastern region of Saudi Arabia. The Ghawar structure is considered the most extensive and productive onshore oil field globally, and the primary source of oil production comes from the Jurassic section, which covers more than 100 meters of oil column. The field's dimensions are 250 km in length and 30 km in width, and it trends from north to south (Figure 6).

The field is located within the Arabian platform, where Phanerozoic sedimentary rocks crop out on the west side and gently dip toward the east at approximately 1 degree (Powers, 1966; Lindsay et al., 2006). It sits on the En-Nala anticline structure trending north-northeast, formed by deep basement faults due to Precambrian compressional movement about 640-620 Ma (Ziegler, 2001). Different datasets, such as seismic and drilling evidence, show that the Ghawar structure extends from the Precambrian metasedimentary basement up to the Paleozoic sedimentary rocks and terminates in the Mesozoic succession (Ayres et al., 1982; Wender et al., 1998; Al-Husseini, 1997; Konert et al., 2001).

The basement was reactivated episodically during several geologic times, including (1) the late Devonian to early Carboniferous stage because of Hercynian Orogeny, (2) the early Triassic stage associated with the opening of the Neo-Tethys Sea, (3) the late Cretaceous because of compressional stress in response to the closing of the Neo-Tethys Ocean (Konert et al., 2001), and (4) middle to late Tertiary stages

2.2 Digital depth model

To generate 2D synthetic seismic data, viscoelastic parameters must be prepared to create a realistic model representing the subsurface. Different sources have been reviewed to collect data and information for various formations (Mooney et al., 1985; Alfaraj et al., 1998; Wender et al., 1998; Saner and Sahin, 1999; Dasgupta et al., 2000; Macrides and Kelamis, 2000; Meyer et al., 2000; Konert et al., 2001; Dasgupta et al., 2002; Afifi et al., 2005; Lindsay et al., 2006; Bridle et al., 2007; Mittet et al., 2007; Al Ahmadi et al., 2009; Ameen et al., 2009; Faqira et al., 2009; Liu et al., 2013).

There is no single reference in the literature with complete subsurface data covering the Precambrian to Cenozoic succession in the Ghawar field. Therefore, the data for the geological and geophysical models of the subsurface were compiled from different sources, collecting only references that showed complete information about their presented data, such as depths, formation tops, V_p , V_s , density logs with clear scales and units (Al-Shuhail et al., 2019). Twenty-three layers and five major faults were defined and digitized at different intervals. The 2D model has dimensions of 6000 m in depth and 38,400 m in length (Figure 7). P-wave velocities and densities of the model were mostly determined from well data available in Alfaraj et al., (1998), Macrides and Kelamis (2000), and Liu et al., (2013).

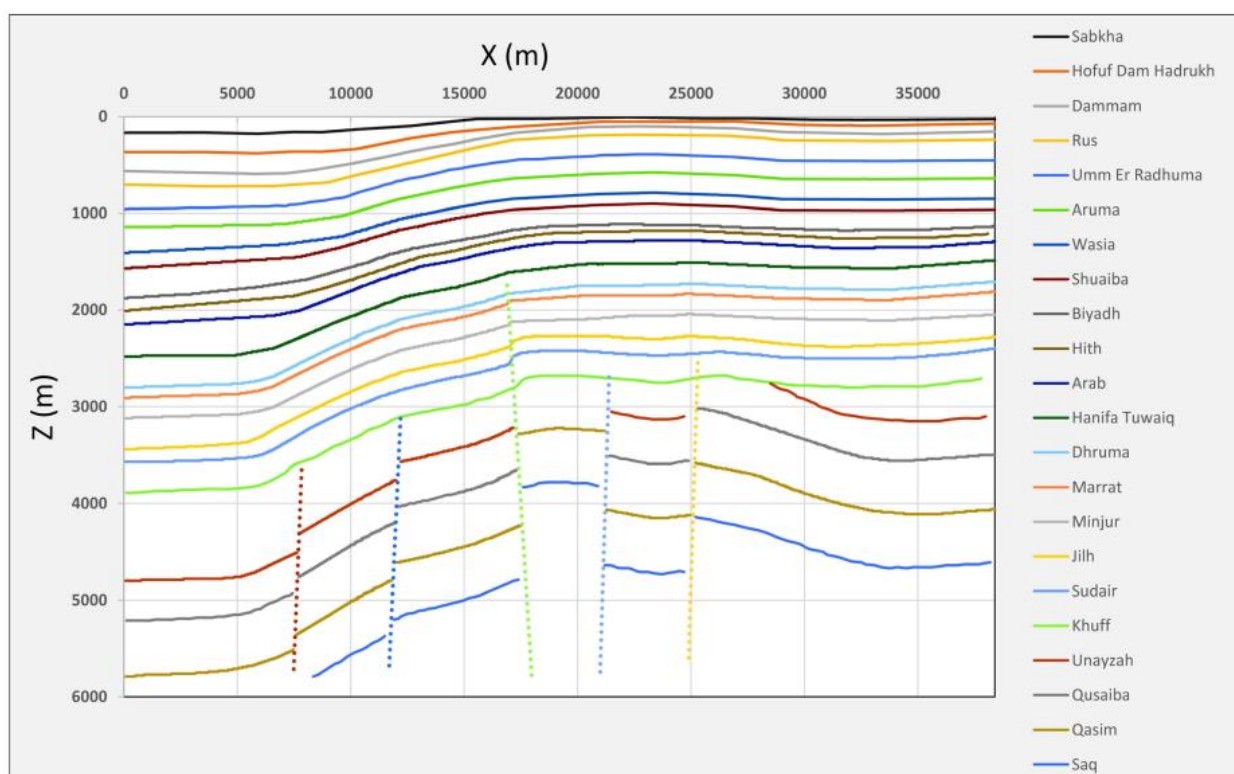


Figure 7. The 2D model of the Ghawar structure, solid lines represent horizons, and dotted lines represent faults (Al-Shuhail et al., 2019).

Table 1 summarizes the values and relations used to calculate the properties of the viscoelastic model. Only 2D model and 2D synthetic seismic data were generated to reduce the computational cost. Although the model honors the viscoelastic effects, it does not consider anisotropy. Figure 8 shows P-wave 2-D model.

Layer No.	Formation	Lithology	Vp (m/s)	Density (kg/m3)
L-1	Quaternary	Sand	850	1500
L-2	Houfuf and Hadrukh	Mixed limestone and siliciclastic	1835	1877
L-3	Dammam	Limestone	3110	2289
L-4	Rus	Anhydrite	4267	2282
L-5	Umm Er Radhuma	Limestone	3318	2028
L-6	Aruma	Limestone	2730	2091
L-7	Wasia	Sandstone	3233	2277
L-8	Shuaiba	Limestone	3010	2037
L-9	Biyadh	Sandstone	4045	2364
L-10	Hith	Anhydrite	4483	2960
L-11	Arab	Limestone	5398.5	2400
L-12	Hanifa and Tuwaiq Mountain	Limestone	5697.5	2550
L-13	Dhruma	Limestone	5033	2458
L-14	Marrat	Shale	3272	2410
L-15	Minjur	Sandstone	3930	2394
L-16	Jilh	Dolomite	4823	2400
L-17	Sudair	Shale	5182	2372
L-18	Khuff	Dolomite	4953	2706
L-19	Unayzah	Sandstone	3752	2405
L-20	Qusaiba	Shale	3898	2486
L-21	Qasim	Sandstone	3685	2380
L-22	Saq	Sandstone	3765	2350
L-23	Basement	Igneous and metamorphic	6380	2800

Table 1. Lithology, P-wave and densities for the Ghawar model (Al-Shuhail et al., 2019). Gray rows indicate the formations analyzed in this study.

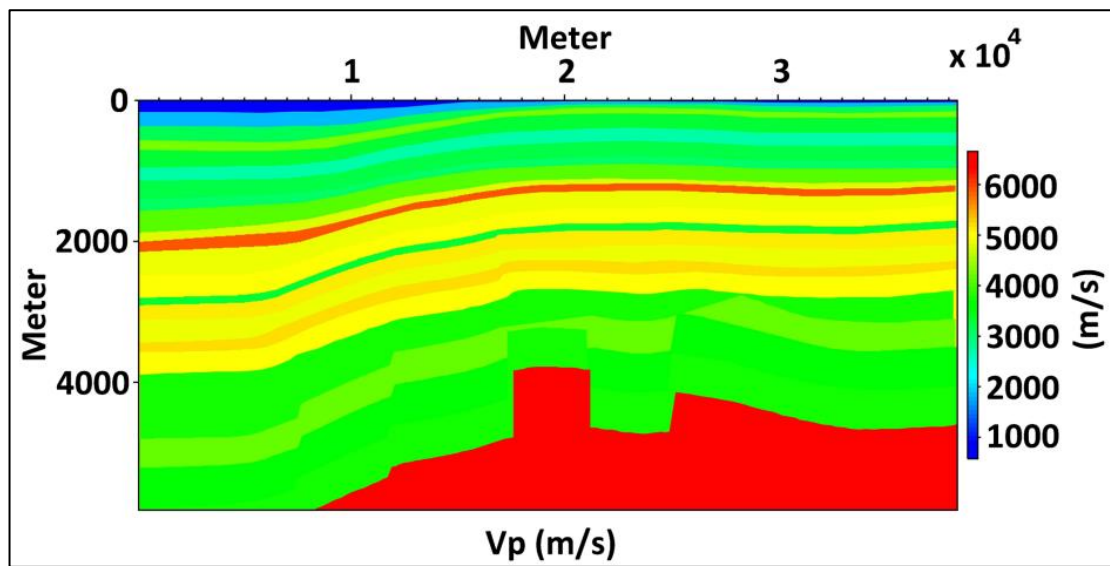


Figure 8. 2D P-wave velocity model of the Ghawar structure. The color scale of the model is indicated with units. The horizontal axis is distance while the vertical axis is depth in meters (Al-Shuhail et al., 2019).

2.3 Synthetic seismic data generation

After establishing the viscoelastic parameters, synthetic seismic data were generated using the finite-difference (FD) method. In this method, the wave equation for viscoelastic media is defined through a linearized equation of motion (Newton's second law) and equation of deformation (Hook's law) as described in Robertsson et al., (1994). Finite Difference parameters depend on the frequency content of the source wavelet.

It is important to select a grid spacing that minimize numerical dispersion. The general rule for negligible dispersion FD is to have five or more grid points per minimum wavelength:

$$\Delta x = \Delta z \leq \frac{V_{min}}{5f_{max}} \quad (4)$$

where Δx and Δz are the grid sizes along the x-axis and z-axis, respectively, which are assumed to be equal. The minimum velocity in the model is 501 m/s, and the maximum frequency of the wavelet is 60 Hz, which is the frequency at which the amplitude spectrum of the source wavelet drops below 1% of its peak at 20 Hz (Thorbecke, 2016). The resulting grid size is 1.5 m in the x and z directions. In addition, the time marching steps (Δt) in FD must satisfy the Courant-Freidrichs-Lewy (CFL) stability condition (Thorbecke, 2016):

$$\Delta t \leq \frac{0.606\Delta x}{V_{max}} \quad (5)$$

where V_{max} is the maximum P-wave velocity in the model. Using a basement rock velocity of 6380 m/s and $\Delta x = 1.5$ m; then, $\Delta t = 0.14$ msec.

The open-source code called 2D Finite-Difference Wavefield Modelling (Thorbecke, 2016) was utilized to generate the 2D viscoelastic seismic synthetic dataset. For the model boundaries, absorbing boundary conditions with a taper of 375 grid points for the bottom, left, and right boundaries of the model, and a free surface for the top boundary were used. The taper length was calculated:

$$Taper\ length = \frac{4V_{max}}{\Delta x * f_{max}} \quad (6)$$

For the data acquisition, a conventional 2D land seismic survey geometry was used. Sources span from $x = 50$ m up to $x = 38,400$ m with a source every 50 m. Additionally, receivers span from $x = 50$ m up to $x = 38,400$ m with a receiver every 25 m. Both sources and receivers were buried 15 m below the subsurface to minimize the effects of ghost reflection from the free surface (Thorbecke, 2016). The offset ranges from a minimum of 0 m up to a maximum of 38,350 m, which is suitable for common objectives of seismic data processing, imaging, and velocity analysis. Table 2 summarizes the modelling and acquisition parameters used to generate the synthetic seismic data.

Parameter	Value
Source wavelet	20-Hz zero phase Ricker
Time sampling interval for FDM calculation	0.14 msec
Square-grid size for FDM calculation	1.5 m
Receiver spacing	25 m
Shot spacing	50 m
Recording time sampling interval	4.0 msec
Total recording time	6.0 s
Total number of receivers	1535
Receivers x-axis	50 to 38,400 m
Receivers z-axis	− 15.625 m
Shots x-axis	50 to 38,400 m
Shots z-axis	− 15.625 m
Offset range	0 to 38,350 m
Total number of shots	768 shots

Table 2. Summary of the modeling and acquisition parameters used to generate the synthetic seismic data (Al-Shuhail et al., 2019).

Gaussian random noise with zero mean and 10% standard deviation was added to the data to simulate ambient noise effects. Figure 9 shows shot records for the vertical and horizontal components respectively. No amplitude gain was applied to the data.

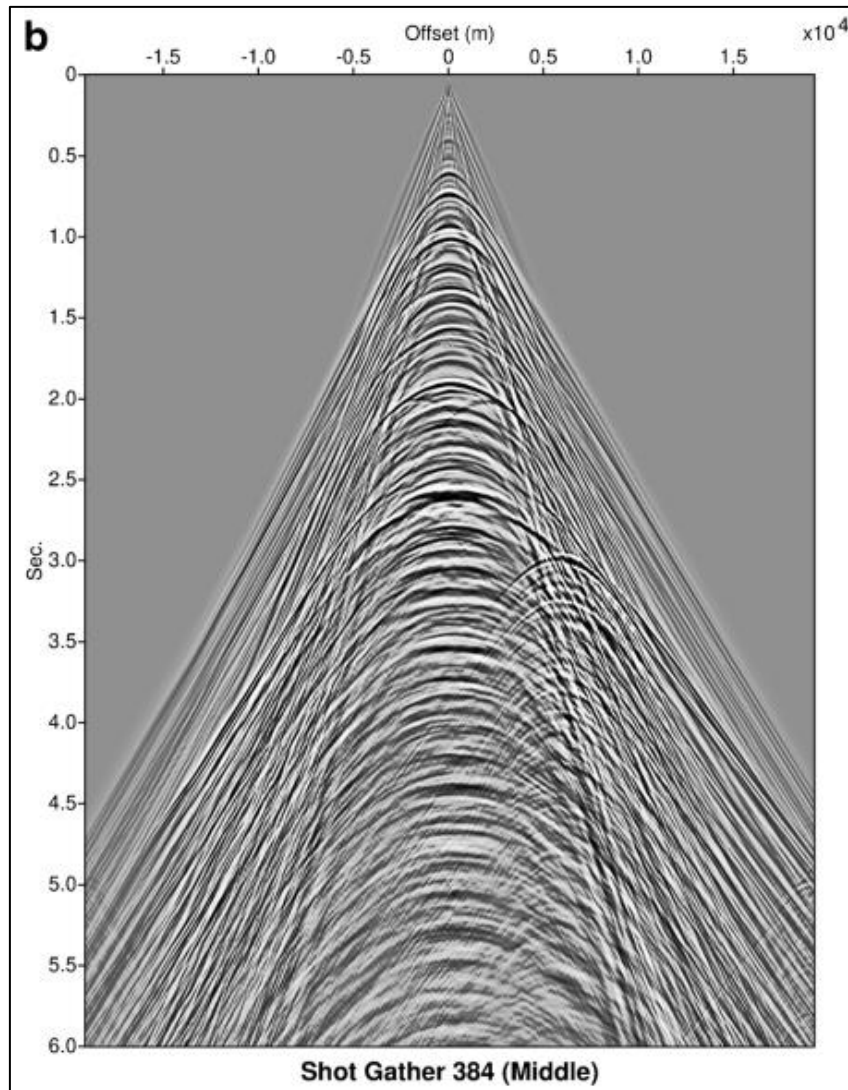


Figure 9. Sample raw shot gather at $x = 19,150$ m (Al-Shuhail et al., 2019).

CHAPTER 3

METHODOLOGY

3.1 Data Preparation

The velocity analysis using the velocity spectrum method has been carried out on three formations: Shuaiba, Arab, and Qusaiba formations. These formations are particularly important in Saudi Arabia as they are the primary sources of hydrocarbons.

The 2D viscoelastic model used has a record length of 4 seconds, 768 shot records, 1535 receivers, and 1,178,880 traces. Before applying velocity analysis, the data needs to be processed. Seismic Unix software has been employed to process the data.

To account for the loss of amplitude due to spherical divergence and absorption, gain has been applied to the data using t^2 method with a clipping quantile value of 0.95 because the data has less than 5% noisy points. The data are currently in the shot domain and need to be sorted to the common depth point (CDP) domain to perform velocity analysis. Once sorted, the data will be limited to the required CDP or offset to test the method, as shown in Figure 10.

The next step is to generate versions of the selected CDP after limiting the offset as follows:

1. Equal to the depth of the formation.
2. Equal to double the depth of the formation.
3. Equal to the maximum available offset.

In total, there will be nine different CDP versions at different offsets for the three different formations. Therefore, the velocity analysis will be performed three times for each formation, as illustrated in Figures 11 and 12.

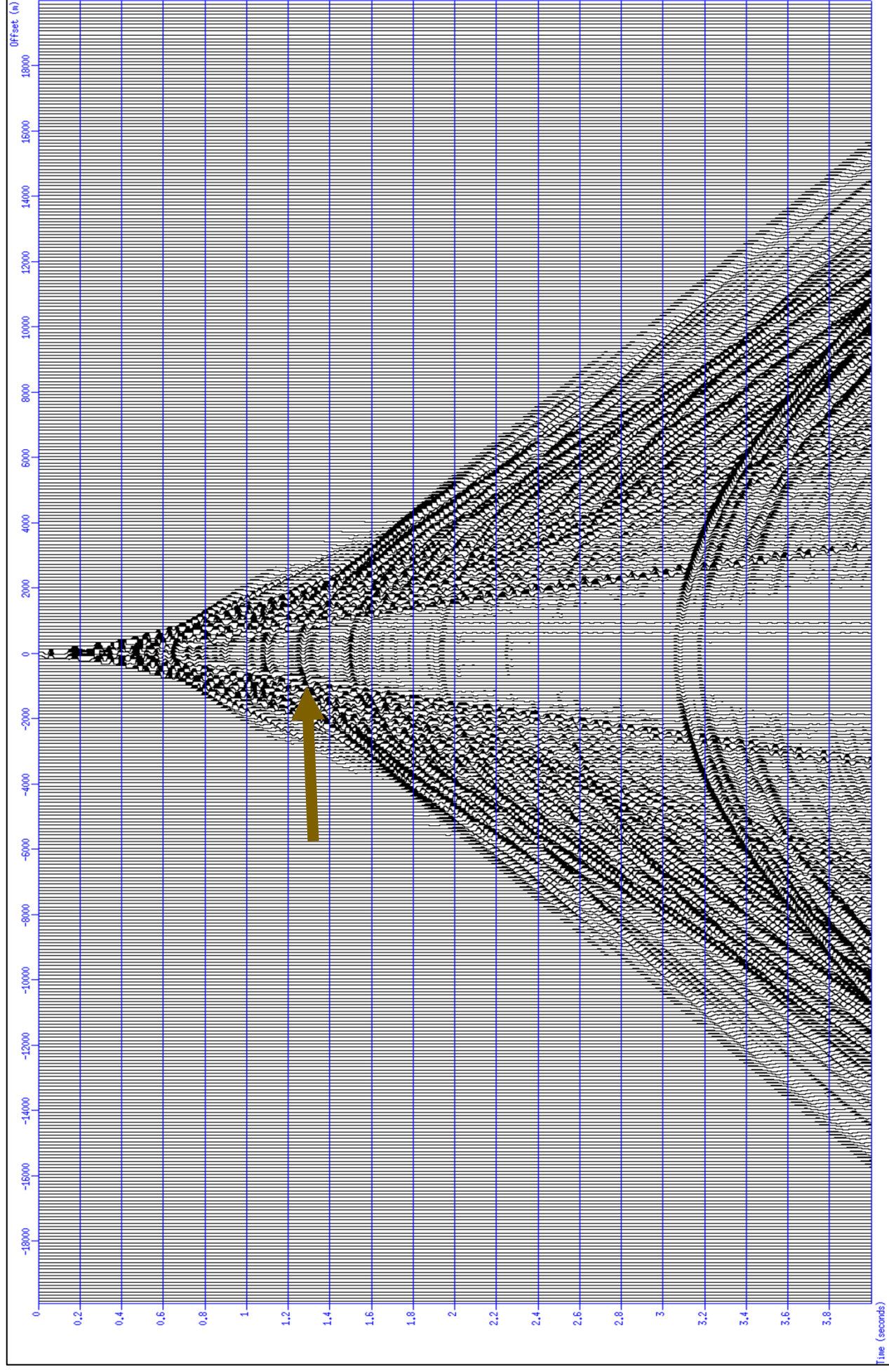


Figure 10. Example CDP 800 (at 10,000 m) including all offsets. Arrow indicates Arab reflector.

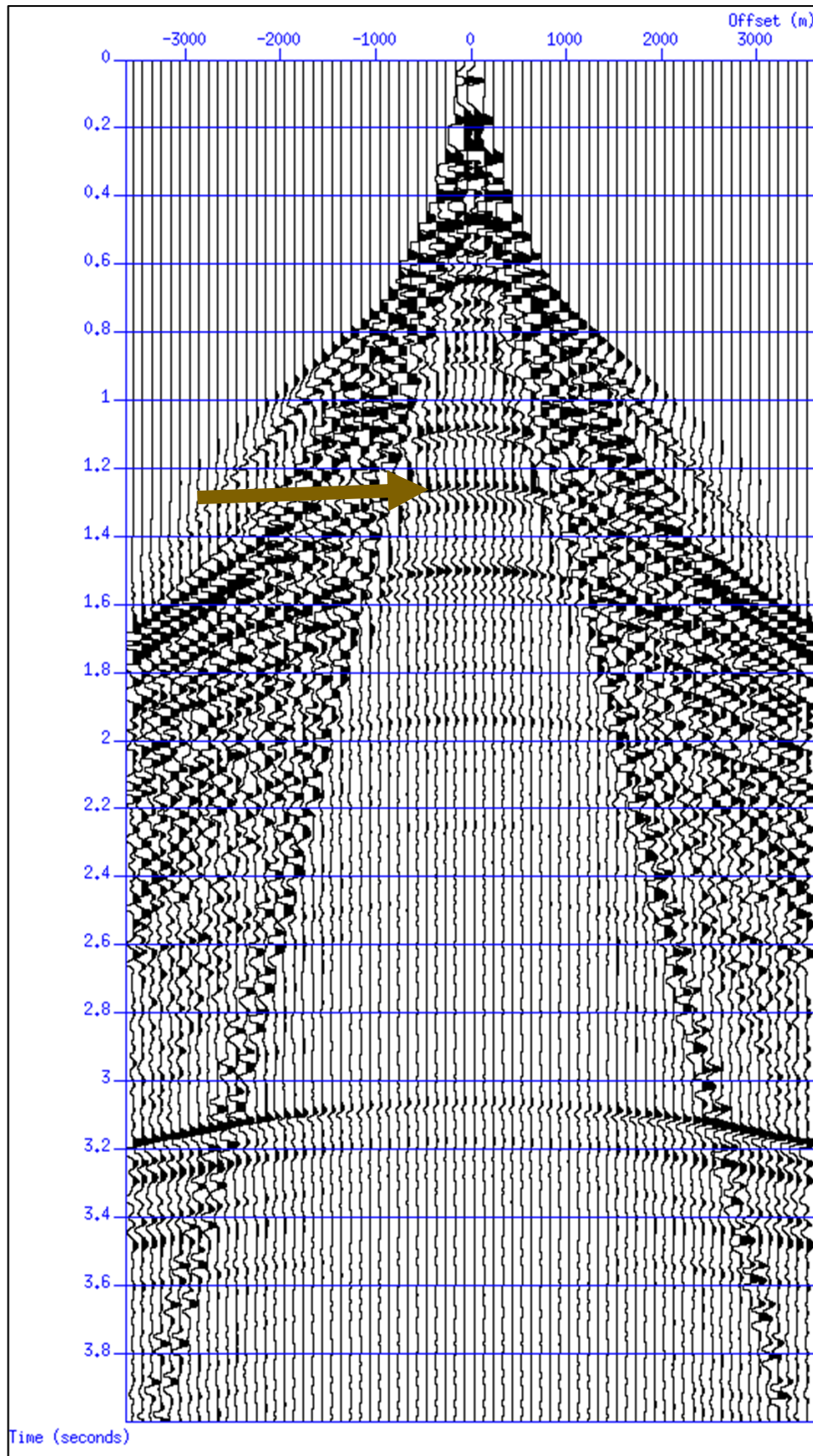


Figure 11. CDP 800 after limiting offsets to double the depth of Arab formation (3600 m). Arrow indicates Arab reflector.

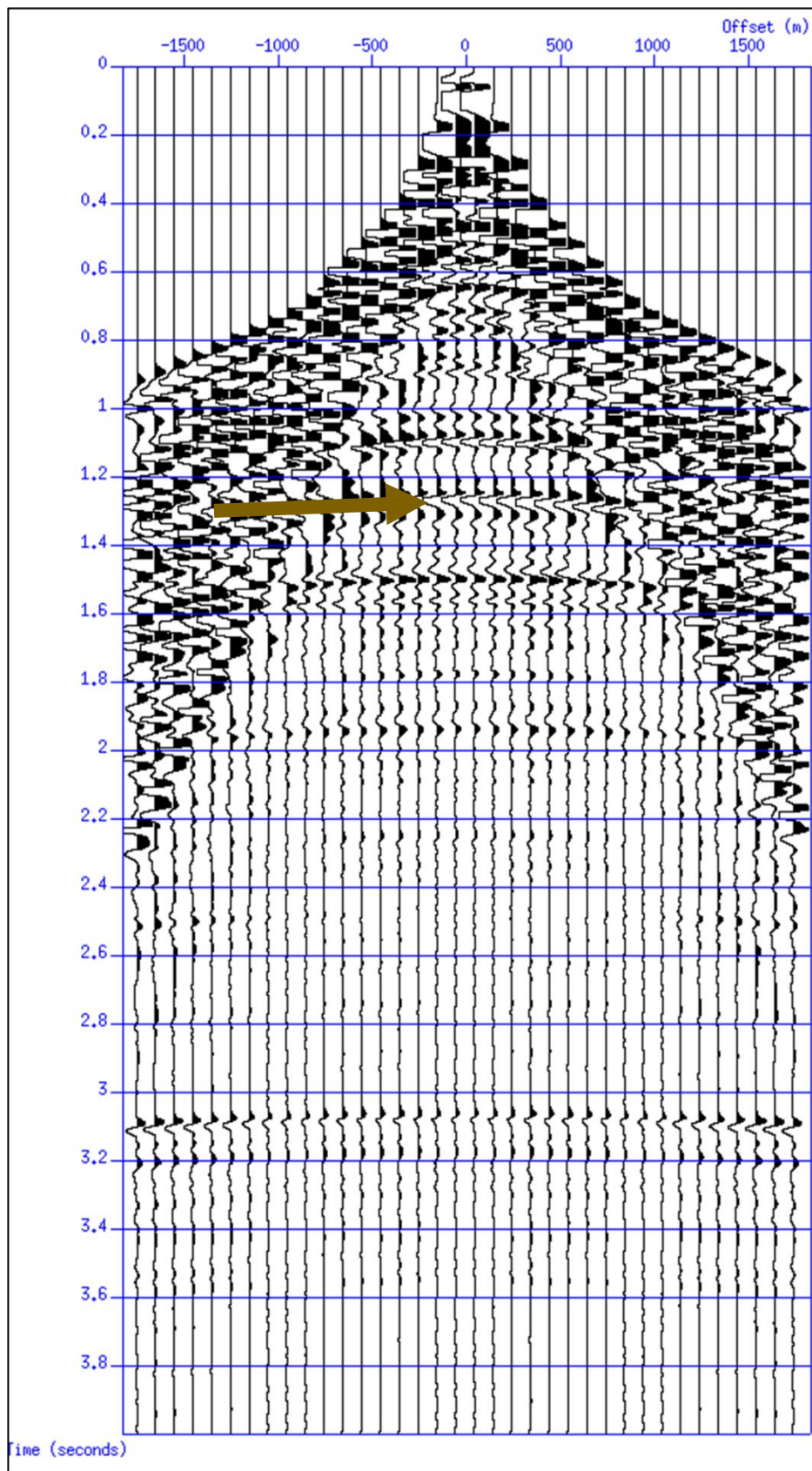


Figure 12. CDP 800 after limiting offsets to the depth of Arab formation (1800 m). Arrow indicates Arab reflector.

3.2 Data Calculation

Table 3 summarizes the geological column of the Ghawar field, which consists of twenty-three layers with different average thicknesses, V_p and lithologies for each formation.

Layer Number	Formation	V_p (m/s)	Thickness (m)
L-1	Quaternary	850	6.75
L-2	Hofuf Dam Hadrukh	1835	45.05
L-3	Dammam	3110	50.2
L-4	Rus	4267	87
L-5	Umm Er Radhuma	3318	206
L-6	Aruma	2730	190
L-7	Wasia	3233	211
L-8	Shuaiba	3010	113
L-9	Biyadh	4045	201
L-10	Hith	4483	80
L-11	Arab	5398.5	100
L-12	Hanifa and Tuwaiq	5697.5	230
L-13	Mountain Dhurma	5033	230
L-14	Marrat	3272	100
L-15	Minjur	3930	220
L-16	Jilh	4823	220
L-17	Sudair	5182	160
L-18	Khuff	4953	265
L-19	Unayzah	3752	365
L-20	Qusaiba	3898	460
L-21	Qasim	3685	560
L-22	Saq	3765	570
L-23	Basement	6380	

Table 3. Thickness, lithology and V_p for the formations in the Ghawar field (Al-Shuhail et al., 2019).

Gray rows indicate the formations analyzed in this study.

To calculate the depth to the top of a formation, the thicknesses of formations overlying the selected formation are added:

$$\text{Formation depth} = \sum_{n=1}^N \Delta d_n \quad (7)$$

where Δd_n is the thickness of the n^{th} formation and N represents the formation of interest.

Since the thickness and velocity are provided in Table 3, ΔT can be calculated by dividing the thickness of each formation by the P-wave velocity and then multiplying the value by 2000 to obtain the thickness in time with milli-second unit (ms).

$$\Delta T = \frac{\text{Thickness}}{\text{P-wave velocity}} \times 2000 \quad (8)$$

For calculating the TWT to a formation, I add the interval TWT from the surface to the formation top:

$$TWT \text{ to } N^{th} \text{ formation} = \sum_{n=1}^N \Delta T_n \quad (9)$$

The next step is to calculate the (RMS) velocity using the interval velocity (Table 3) and TWT of each layer:

$$V_{RMS \ N} = \sqrt{\frac{\sum_{i=1}^N V_i^2 \times \Delta T_i}{\sum_{i=1}^N \Delta T_i}} \quad (10)$$

Table 4 summarizes the interval TWT in each formation as well as the depth, total TWT, and RMS velocity from surface to each formation.

Layer Number	Formation	Depth (m)	Interval TWT (ms)	Total TWT (ms)	RMS Velocity (m/s)
L-1	Quaternary	6.75	15.9	15.9	850
L-2	Hofuf Dam Hadruk	51.8	49.1	65.0	1649
L-3	Dammam	102	32.3	97.3	2242
L-4	Rus	189	40.8	138.0	2987
L-5	Umm Er Radhuma	395	124.2	262.2	3148
L-6	Aruma	585	139.2	401.4	3010
L-7	Wasia	796	130.5	531.9	3066
L-8	Shuaiba	909	75.1	607.0	3059
L-9	Biyadh	1110	99.4	706.4	3216
L-10	Hith	1190	35.7	742.1	3288
L-11	Arab	1290	37.0	779.1	3418
L-12	Hanifa and Tuwaiq	1520	80.7	859.9	3693
L-13	Mountain Dhurma	1750	91.4	951.3	3842
L-14	Marrat	1850	61.1	1012.4	3810
L-15	Minjur	2070	112.0	1124.4	3822
L-16	Jilh	2290	91.2	1215.6	3906
L-17	Sudair	2450	61.8	1277.3	3977
L-18	Khuff	2715	107.0	1384.3	4061
L-19	Unayzah	3080	194.6	1578.9	4024
L-20	Qusaiba	3540	236.0	1814.9	4008
L-21	Qasim	4100	303.9	2118.9	3963
L-22	Saq	4670	302.8	2421.7	3939

Table 4. Interval TWT in each formation. Also shown are the depth, total TWT and RMS velocity from surface to each formation calculated at CDP 1760. Gray rows indicate the formations analyzed in this study.

Figure 13 shows the plotted RMS velocity on the X-axis with m/s unit against the TWT with millisecond unit on the Y-axis. This figure should resemble the velocity trend from the surface to the basement in the velocity analysis panel. Figure 14 shows the location of CDP 22,000 m.

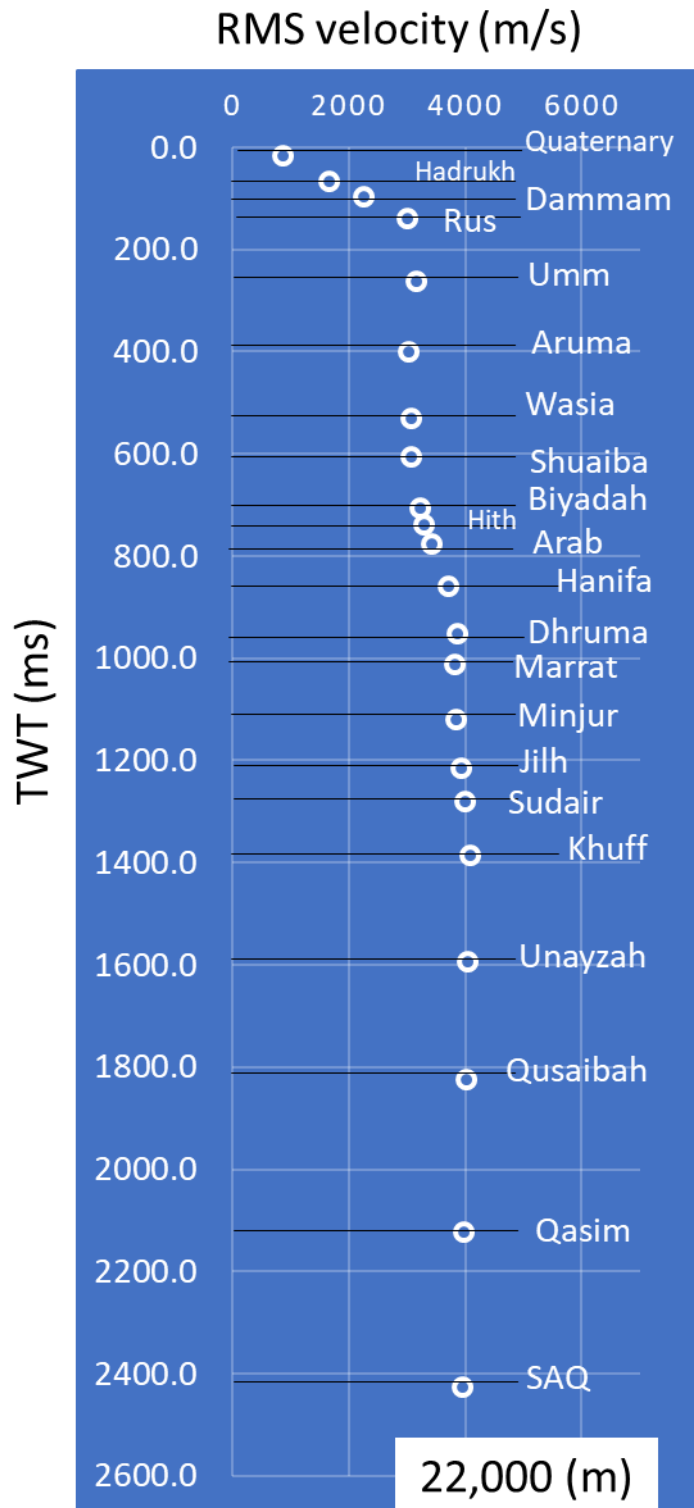


Figure 13. RMS velocity plotted against the total TWTs with the corresponding formation at CDP 1760.

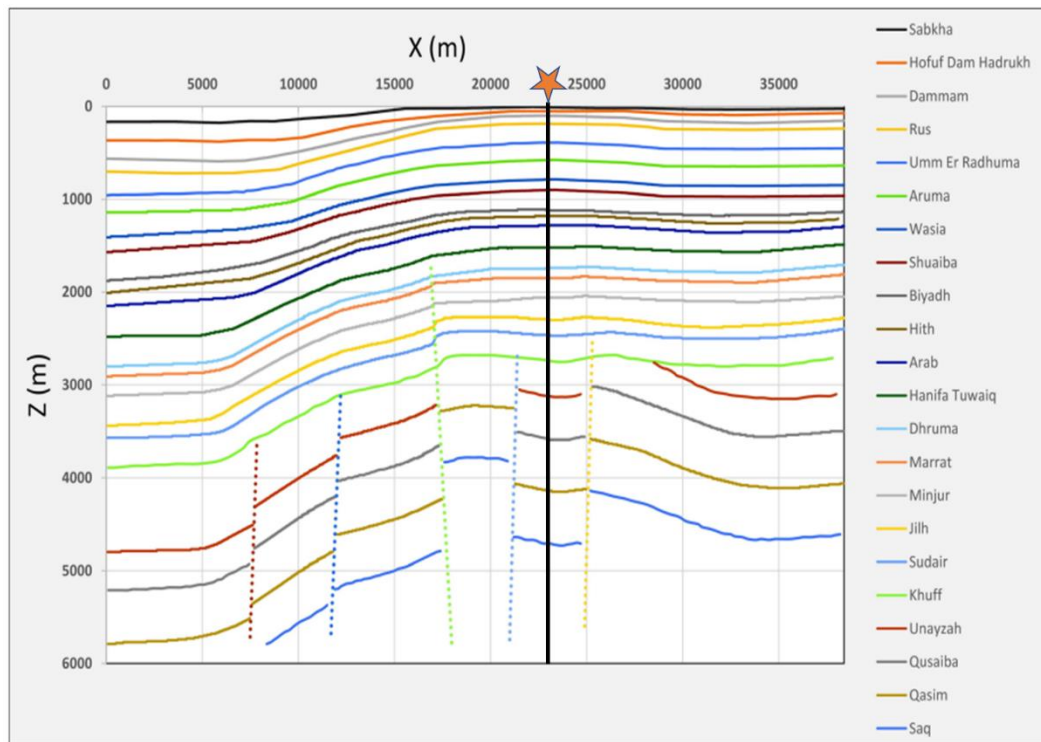


Figure 14. Ghawar model with the location of CDP 1760 (Al-Shuhail et al., 2019).

3.3 Velocity Analysis

Velocity analysis was carried out after preparing the data for different formations at different offsets to pick the velocity at the strongest semblance, which measures coherency, related to the time corresponding to each formation using the Velan function in SeismicUnix.

The velocity analysis in Seismic Unix involves the use of parameters such as f_v , which is the first velocity value. According to the model, the lowest velocity belongs to the Quaternary and is equal to 850 m/s. The maximum RMS velocity value derived from the model doesn't exceed 4500 m/s.

The velocity increment (dv) is dependent on the velocity difference between two formations. It has been observed that the velocity difference between the Wasia and Shuaiba formations must be at least 7 m/s to distinguish between the two reflectors. To make the picking process easier, the velocity increment should be less than 7 m/s. Figures 15-18 show four different panels of the velocity spectrum with different velocity increments at 100 m/s, 50 m/s, 25 m/s, and 5 m/s. As the velocity increment is decreased, the semblance becomes sharper, making the picking process easier. However, dv below 50 m/s does not significantly improve signal sharpness. Therefore, using 50 m/s will produce the same results as using 25 m/s or 5 m/s.

After picking several points or similarities related to different formations, a summary report was generated showing the velocity values and their corresponding two-way times, as shown in Figure 19, for CDP 2080 and Shuaiba formation with offset limited to double the depth of the formation.

These values were used to calculate the estimated depth at each formation for different offsets. The calculated depth from the software utilizing equation 11, will be

compared to the real depth value from the model to estimate the error between real and calculated values.

$$\textit{Depth to formation} = \textit{RMS Velocity} \times \textit{TWT}/2000 \quad (11)$$

where RMS velocity is the velocity from the surface to the top of the formation and TWT is the corresponding two-way time for that reflector.

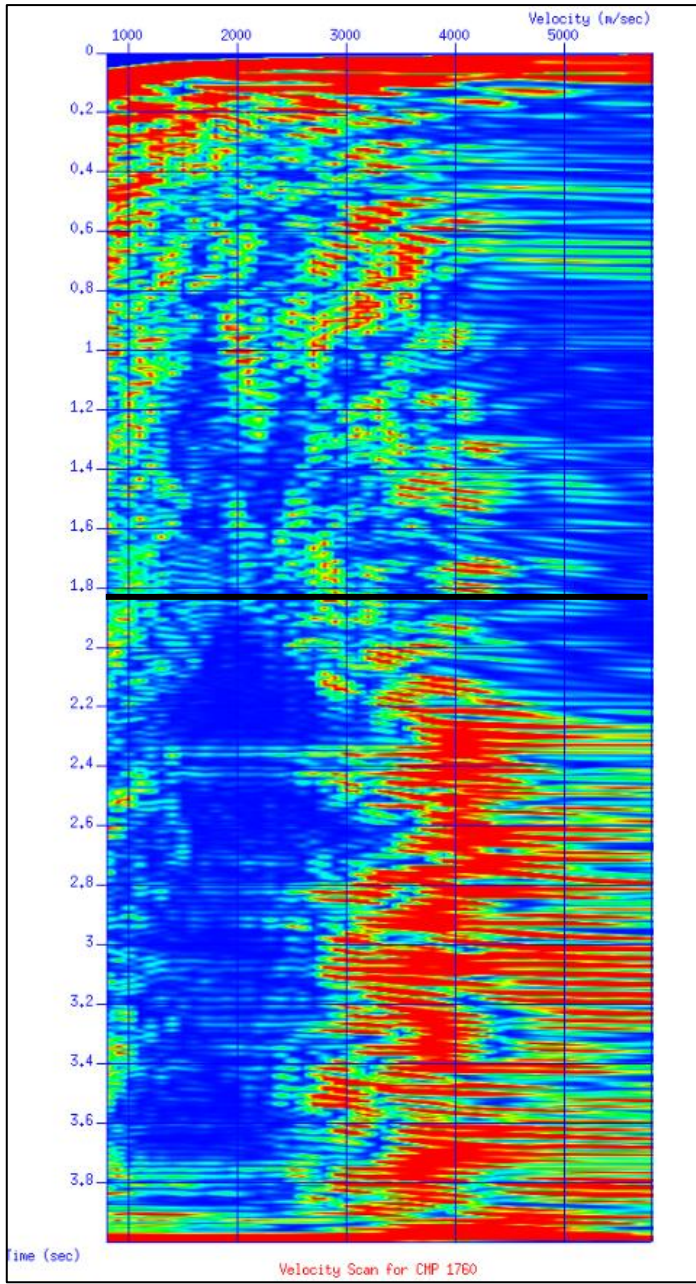


Figure 16. Velocity spectrum using 100 m/s velocity increment, at CDP 1760 with limited offset equal to Qusaiba depth (-3540 m). Black line indicates Qusaiba reflector.

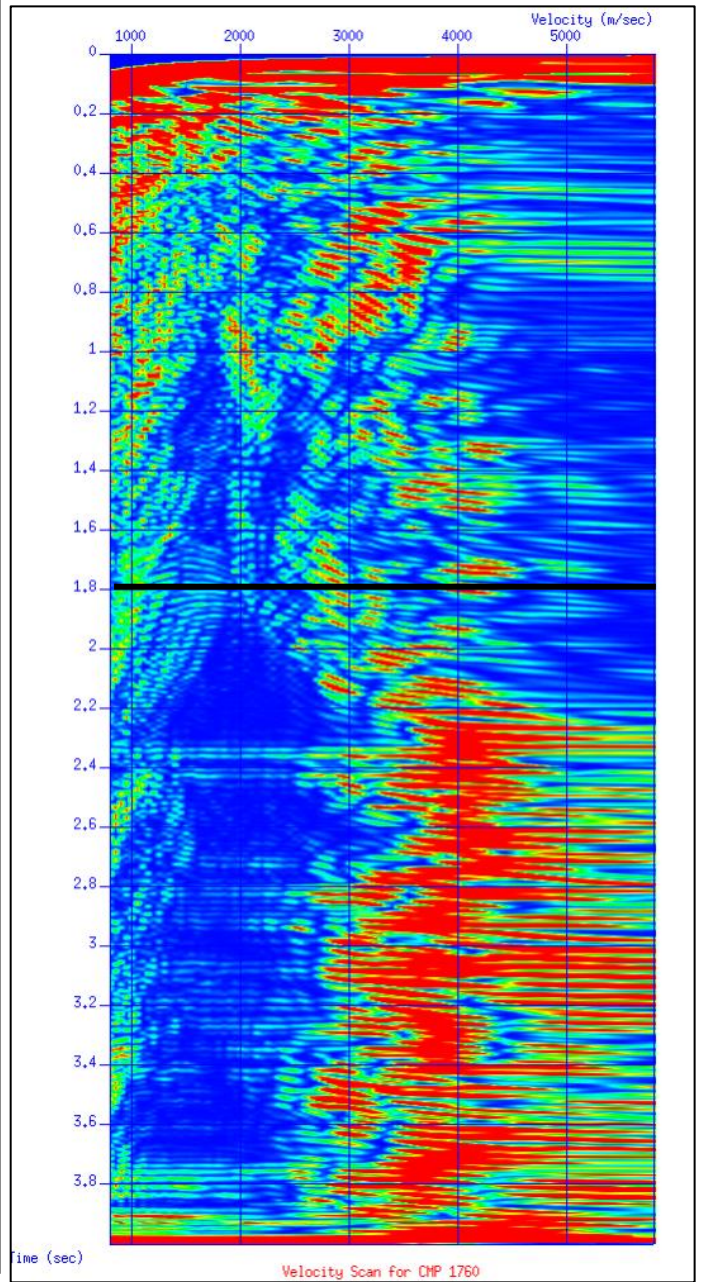


Figure 15. Velocity spectrum using 50 m/s velocity increment, at CDP 1760 with limited offset equal to Qusaiba depth (-3540 m). Black line indicates Qusaiba reflector.

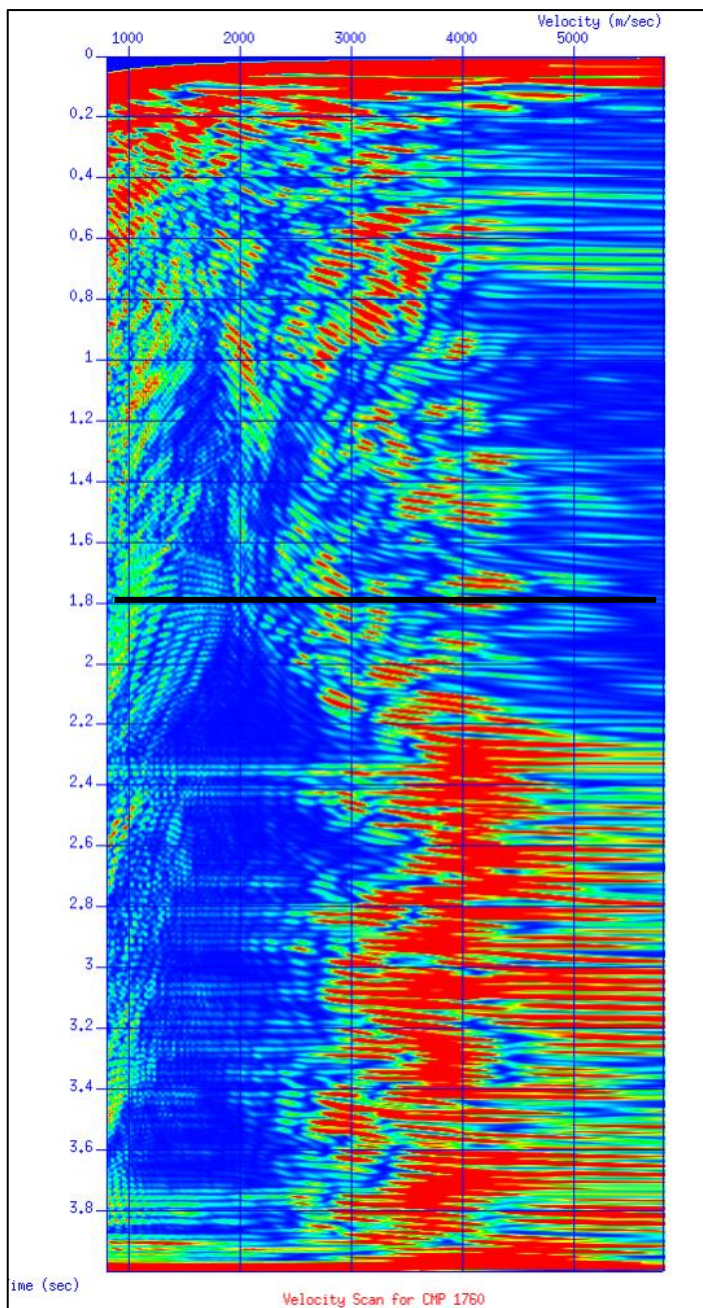


Figure 18. Velocity spectrum using 25 m/s velocity increment, at CDP 1760 with limited offset equal to Qusaiba depth (-3540 m). Black line indicates Qusaiba reflector.

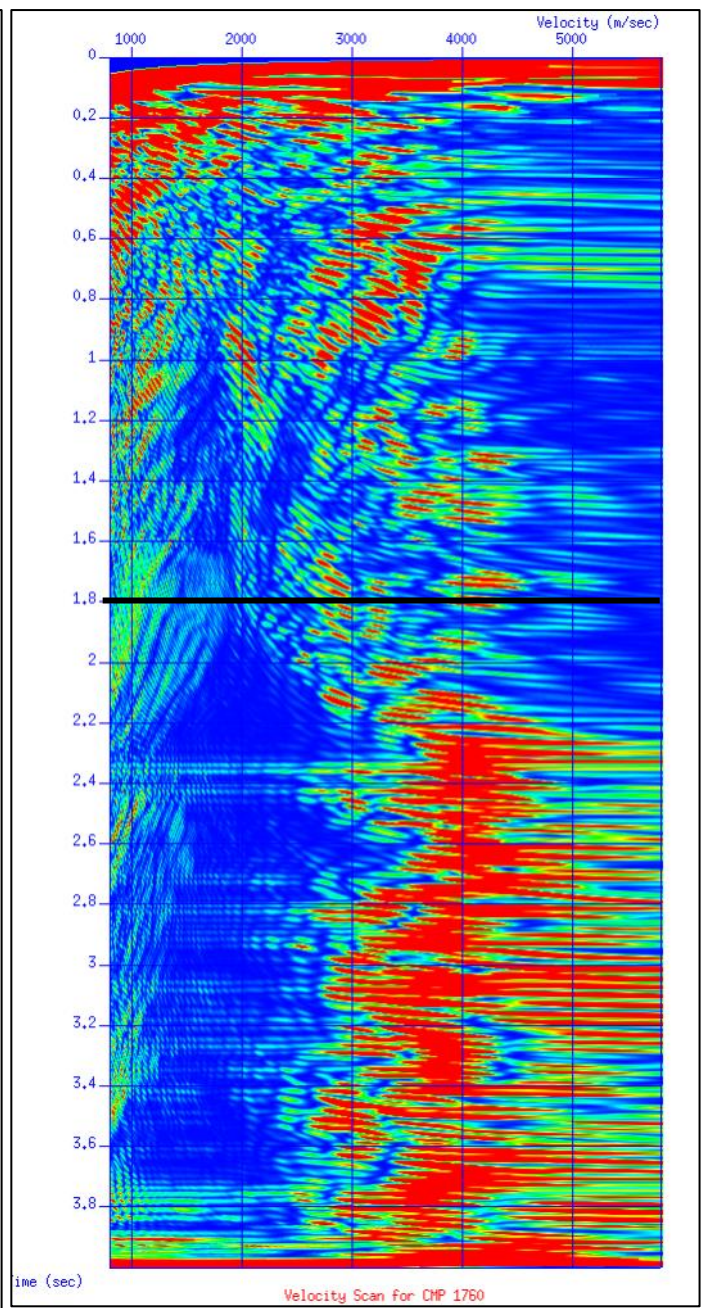


Figure 17. Velocity spectrum using 5 m/s velocity increment, at CDP 1760 with limited offset equal to Qusaiba depth (-3540 m). Black line indicates Qusaiba reflector.

```
1 cdp=2080
2 tnmo=0.602333,0.733828,1.00954,2.66384,3.72004
3 vnmo=3137.21,3583.72,4030.23,4858.14,5193.02
```

Figure 19. Seismic Unix report generated after velocity analysis at CDP 2080, with limited offset limited to double the depth of Shuaiba formation, showing velocity values with corresponding TWT values.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Depth Error

Velocities were generated for three formations in CDP gathers: CDP 800, CDP 1120, and CDP 1760, which are located at x-coordinates: 10,000 m, 14,000 m, and 22,000 m, respectively. Figure 20 shows the location of the three CDPs. The estimated depths were calculated using the total TWT and RMS velocity picks from the velocity analysis. The difference between the actual depths and estimated depths was recorded. The percentage errors were then calculated by dividing the difference between the model and estimated depths by the actual depth and multiplying by 100. The results of these calculations are shown in Table 5. Figure 21 shows the percentage errors for different offsets with different formations at different CDPs locations.

There is a clear trend in which the depth error increases as the offset increases, with the exception of CDP 1760 in the Arab formation. To obtain more precise depth estimates, it is advisable to reduce the offset and follow the short-offset assumption. This assumption states that if we decrease the offset to a maximum of double the depth of the reflector, we have a better chance of selecting the correct velocity, and the estimated depth values become closer to the actual values. Additionally, the velocity generally increases as the offset increases, but there are some exceptions, such as CDP 1120 in the Shuaiba and Qusaiba Formations, where similar velocity values are displayed for different offsets. On the contrary, the TWT values show unpredictable fluctuations in the various offset scenarios. Furthermore, the TWT

values obtained from the velocity analysis are lower than those computed from the model.

There is no relation of formation depth at certain or specific CDP location and the percentage error. CDP 1120 at 14,000 m shows that Shuaiba formation the shallower formation has larger errors compared to Qusaiba the deeper formation. On the other hand, CDP 1760 at 22,000 m shows that Qusaiba has the larger errors compared to the other shallower formations Shuaiba and Arab.

Comparing CDP's depths at the three different locations show that CDP 800 at 10,000 m, which is the deeper CDP, has the larger error values compared to the other two shallower CDPs. Therefore, it can be said that as the CDP's depth increases the amount of error increases as it is illustrated in Figure 21.

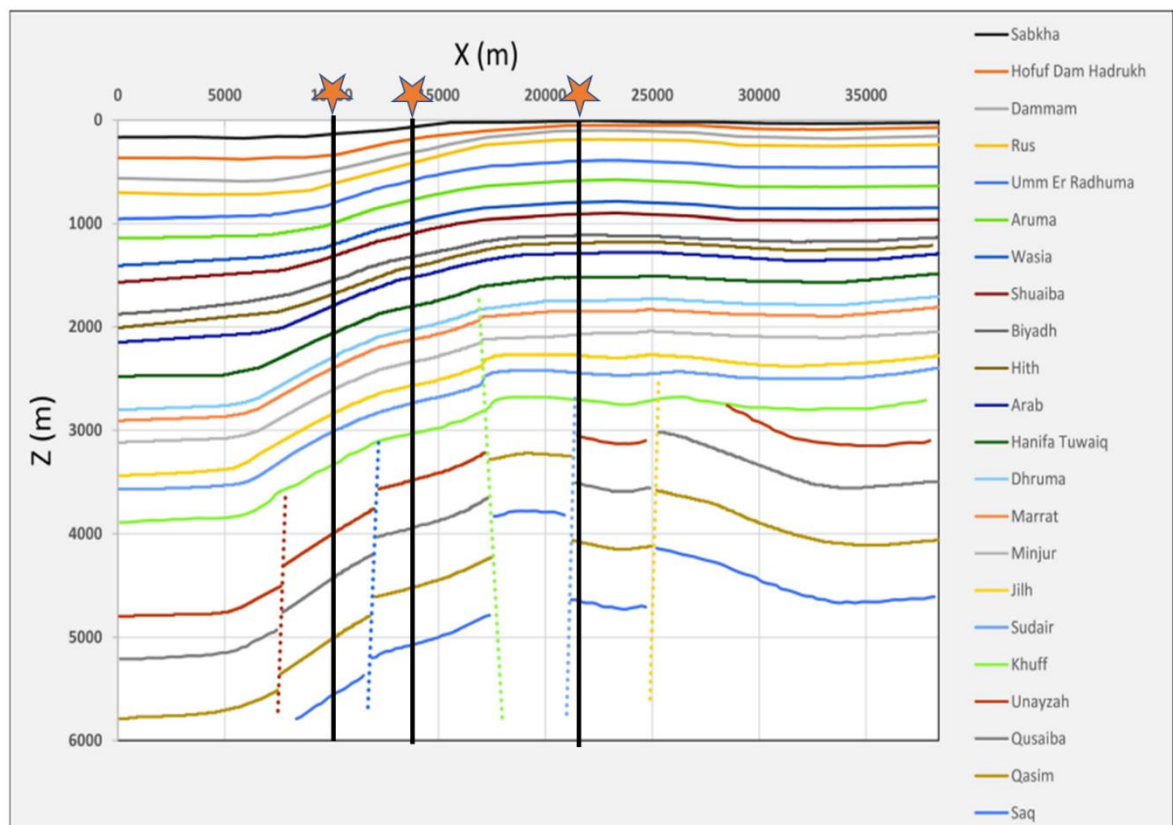


Figure 20. Locations of CDPs at 10,000 m, 14,000 m and 22,000 m.

Formation	CDP no.	Offset (m)	RMS (m/s)	Model RMS Velocity (m/s)	Model TWT (s)	Picked TWT (s)	Estimated Depth (m)	Model Depth (m)	Difference (m)	Depth Percentage Error
SHUB	800	1320	2517	2697	1.158	1.083	1460.6	1320	140.6	10.7%
SHUB	800	2640	2517	2732	1.158	1.090	1489.1	1320	169.1	12.8%
SHUB	800	22000	2517	2837	1.158	1.067	1513.5	1320	193.5	14.7%
SHUB	1120	1080	2743	3000	0.841	0.802	1202.5	1080	122.5	11.3%
SHUB	1120	2160	2743	2895	0.841	0.803	1161.7	1080	81.7	7.6%
SHUB	1120	28000	2743	2906	0.841	0.802	1164.9	1080	84.9	7.9%
SHUB	1760	909	3059	3000	0.607	0.610	915.7	909	6.7	0.7%
SHUB	1760	1818	3059	3011	0.607	0.618	929.9	909	20.9	2.3%
SHUB	1760	32700	3059	3034	0.607	0.611	927.1	909	18.1	2.0%
ARAB	800	1800	2908	2965	1.376	1.308	1938.9	1800	138.9	7.7%
ARAB	800	3600	2908	3174	1.376	1.281	2032.7	1800	232.7	12.9%
ARAB	800	22000	2908	3290	1.376	1.299	2137.1	1800	337.1	18.7%
ARAB	1120	1510	3132	3174	1.037	1.006	1597.1	1510	87.1	5.8%
ARAB	1120	3020	3132	3058	1.037	1.055	1613.6	1510	103.6	6.9%
ARAB	1120	28000	3132	3081	1.037	1.047	1612.3	1510	102.3	6.8%
ARAB	1760	1290	3418	3197	0.779	0.782	1250.3	1290	39.7	3.1%
ARAB	1760	2580	3418	3244	0.779	0.783	1270.0	1290	20.0	1.6%
ARAB	1760	32700	3418	3267	0.779	0.779	1271.9	1290	18.1	1.4%
QUSB	800	4440	3666	4069	2.601	2.470	5024.6	4440	584.6	13.2%
QUSB	800	8880	3666	4104	2.601	2.479	5087.4	4440	647.4	14.6%
QUSB	800	22000	3666	4104	2.601	2.482	5092.8	4440	652.8	14.7%
QUSB	1120	3980	3843	3930	2.150	2.034	3996.6	3980	16.6	0.4%
QUSB	1120	7960	3843	3930	2.150	2.062	4051.4	3980	71.4	1.8%
QUSB	1120	28000	3843	3930	2.150	2.053	4034.4	3980	54.4	1.4%
QUSB	1760	3540	4008	4151	1.814	1.748	3627.2	3540	87.2	2.5%
QUSB	1760	7080	4008	4186	1.814	1.736	3632.6	3540	92.6	2.6%
QUSB	1760	32700	4008	4197	1.814	1.756	3685.2	3540	145.2	4.1%

Table 5. Summary of offset used for velocity analysis, model RMS velocity, picked RMS velocity, model TWT, picked TWT, estimated depth, model depth, difference between model and estimated depths, and depth percentage error.

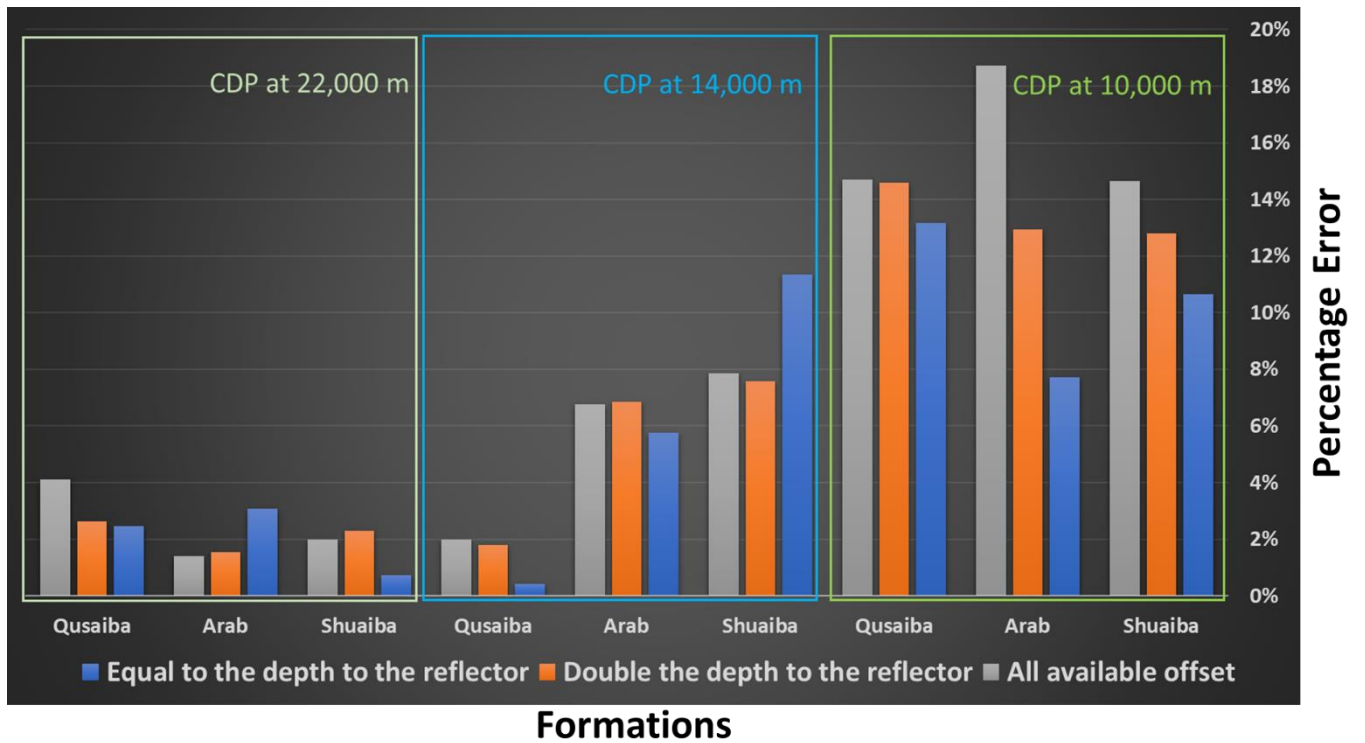


Figure 21. Percentage errors for different offsets and different formations at different locations.

It is noticed also that the offset has a significant impact on the semblance energy, which becomes weaker as the offset increases as demonstrated in Figure 22. This could be a possible explanation for the challenge in picking the correct velocity, which ultimately results in an increase in the estimation error at the given depth.

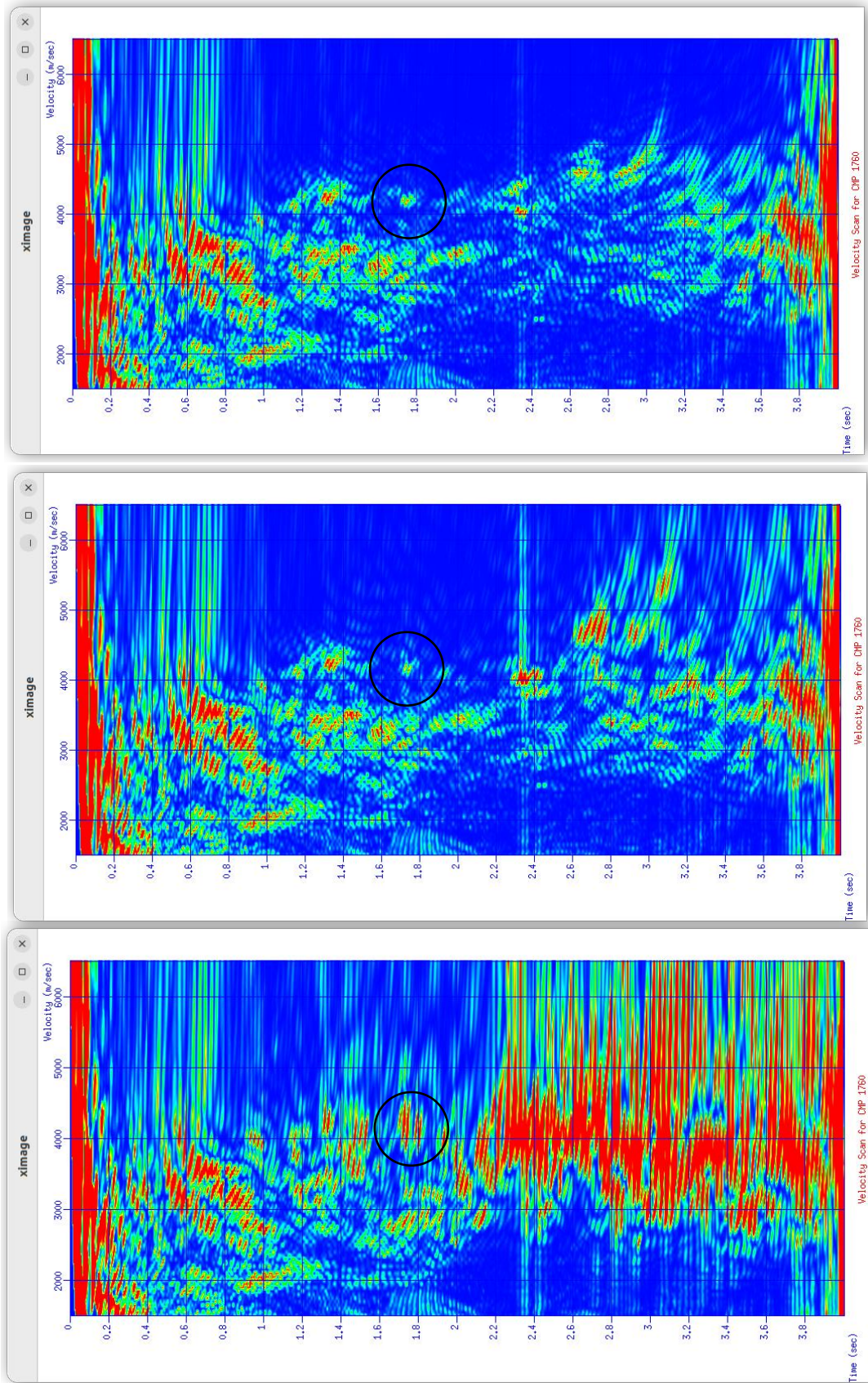


Figure 22. Panels of velocity analysis at CDP 1760 for Qusaiba formation. (left) offset equal to depth of Qusaiba. (middle) offset equal to double the depth of Qusaiba. (right) offset equal to 32,700 m (Full offset). Notice semblance of Qusaiba at 1.8 seconds highlighted in black circles is strongest on the left panel when offset is limited to the depth of Qusaiba equal to the depth of Qusaiba reflector offset.

4.2 Phase change

When the offset increases, the semblance energy decreases due to possible phase change that occurs beyond the critical angle (Aki and Richards, 2002). This means that adding up different amplitude values with different phases weakens the signal or semblance, making it difficult to accurately determine the correct velocity which results in increasing the error in depth estimation.

The critical angle can be determined by using the following equation:

$$\text{Critical Angle } (\theta_c) = \sin^{-1}\left(\frac{V_1}{V_2}\right) \quad (12)$$

where V_1 and V_2 are the velocities of the upper and lower formations.

To prevent phase change, it is recommended to stay below the critical angle. The critical angle can be calculated using Equation 12, and the maximum offset that can be allowed before the phase reversal affects the amplitude can be determined through ray tracing. Tables 6, 7, and 8 provide examples of this for various formations at CDP 1760 at $X = 22,000$ m.

According to Snell's law, the angle of incidence can be determined using the formula below:

$$\frac{\sin \theta_1}{V_1} = \frac{\sin \theta_2}{V_2} \quad (13)$$

To calculate the offset within a layer the following equation is used:

$$\Delta X = 2 * \tan \theta * \text{Thickness} \quad (14)$$

The ΔX value is shown in the offset column in the tables below. Then, the offsets are added from the surface to the target reflector to calculate the complete distance between the shot and receiver as the ray travels back from the target formation. This complete distance is displayed in the partial offset column.

If the velocity of the upper formation is higher than that of the lower formation, the critical angle will not exist. In such cases, Tables 6, 7, and 8 show #Num! indicating that there is no critical angle value for that specific formation.

To determine the angle of incidence in the topmost formation, the following back-propagation method is used:

1. The critical angle (θ_c) in the target formation (e.g., Arab) is calculated by equation (12).
2. The maximum allowable angle (θ_{max}) to avoid phase changes is set at 90% of the critical angle in the target formation (i.e., $\theta_{max} = 0.9 * \theta_c$).
3. The incidence angle in the formation overlying the target formation is calculated using equation (13).
4. Step 3 is repeated going upward until the incidence angle in the topmost formation (i.e., Quaternary) is calculated.

According to this study, if the angle of incidence in the first formation is greater than approximately 11.1 degrees, the traces with offsets corresponding to more than this angle should be avoided when doing velocity analysis for Shuaiba formation. Similar arguments can be used for the Arab (8.1 degrees) and Qusaiba (8.6 degrees) formations.

Formation	Vp (m/s)	Critical angle θ_c	θ (degrees)	90% θ_c	Tan θ	Depth (m)	Thickness (m)	X (m)	ΔX offset (m)	Partial offset (m)
Quaternary	850	27.59	11.10	24.84	0.20	-6.75	6.75	1.32	2.65	2.65
Hofuf Dam Hadruk	1835	36.16	24.57	32.54	0.46	-51.80	45.05	20.59	41.19	43.84
Dammam	3110	46.79	44.80	42.11	0.99	-102.00	50.20	49.85	99.71	143.55
Rus	4267	#NUM!	75.20	#NUM!	3.78	-189.00	87.00	329.21	658.42	801.97
Umm Er Radhuma	3318	#NUM!	48.75	#NUM!	1.14	-395.00	206.00	234.86	469.72	1271.69
Aruma	2730	57.61	38.21	51.85	0.79	-585.00	190.00	149.57	299.15	1570.84
Wasia	3233	#NUM!	47.10	#NUM!	1.08	-796.00	211.00	227.05	454.11	2024.94
Shuaiba	3010	48.08	43.00	43.28	0.93	-909.00	113.00	105.37	210.75	2235.69
Biyadh	4045	-	66.42	-	2.29	-1110.00	201.00	460.53	921.06	3156.76

Table 6. Summary of the calculated maximum offset that can be used for the Shuaiba formation to avoid phase change.

Formation	Vp (m/s)	Critical angle θ_c	θ (degrees)	90% θ_c	Tan θ	Depth (m)	Thickness (m)	X (m)	ΔX offset (m)	Partial offset (m)
Quaternary	850	27.59	8.14	24.84	0.14	-6.75	6.75	0.96	1.93	1.93
Hofuf Dam Hadruk	1835	36.16	17.79	32.54	0.32	-51.80	45.05	14.45	28.91	30.84
Dammam	3110	46.79	31.18	42.11	0.61	-102.00	50.20	30.38	60.77	91.60
Rus	4267	#NUM!	45.27	#NUM!	1.01	-189.00	87.00	87.82	175.64	267.24
Umm Er Radhuma	3318	#NUM!	33.53	#NUM!	0.66	-395.00	206.00	136.52	273.03	540.28
Aruma	2730	57.61	27.03	51.85	0.51	-585.00	190.00	96.95	193.90	734.18
Wasia	3233	#NUM!	32.57	#NUM!	0.64	-796.00	211.00	134.76	269.52	1003.70
Shuaiba	3010	48.08	30.08	43.28	0.58	-909.00	113.00	65.44	130.88	1134.58
Biyadh	4045	64.46	42.33	58.02	0.91	-1110.00	201.00	183.11	366.23	1500.80
Hith	4483	56.14	48.28	50.53	1.12	-1190.00	80.00	89.72	179.44	1680.24
Arab	5398.5	71.36	64.00	64.22	2.05	-1290.00	100.00	205.03	410.06	2090.30
Hanifa and Tuwaiq Mountain	5697.5	-	71.55	-	3.00	-1520.00	230.00	689.21	1378.42	3468.72

Table 7. Summary of the calculated maximum offset that can be used for the Arab formation to avoid phase changes.

Formation	Vp (m/s)	Critical angle θ_c	θ (degrees)	90% θ_c	Tan θ	Depth (m)	Thickness (m)	X (m)	ΔX offset (m)	Partial offset (m)
Quaternary	850	27.59	8.58	24.84	0.15	-6.75	6.75	1.02	2.04	2.04
Hofuf Dam Hadruk	1835	36.16	18.79	32.54	0.34	-51.80	45.05	15.32	30.65	32.68
Dammam	3110	46.79	33.08	42.11	0.65	-102.00	50.20	32.70	65.39	98.07
Rus	4267	#NUM!	48.49	#NUM!	1.13	-189.00	87.00	98.29	196.58	294.65
Umm Er Radhuma	3318	#NUM!	35.61	#NUM!	0.72	-395.00	206.00	147.54	295.07	589.73
Aruma	2730	57.61	28.63	51.85	0.55	-585.00	190.00	103.70	207.40	797.13
Wasia	3233	#NUM!	34.57	#NUM!	0.69	-796.00	211.00	145.37	290.74	1087.87
Shuaiba	3010	48.08	31.88	43.28	0.62	-909.00	113.00	70.30	140.59	1228.46
Biyadh	4045	64.46	45.22	58.02	1.01	-1110.00	201.00	202.56	405.13	1633.59
Hith	4483	56.14	51.88	50.53	1.27	-1190.00	80.00	101.95	203.90	1837.49
Arab	5398.5	71.36	71.33	64.22	2.96	-1290.00	100.00	295.91	591.81	2429.30
Hanifa and Tuwaiq Mountain	5697.5	#NUM!	88.96	#NUM!	55.03	-1520.00	230.00	12656.63	25313.27	27742.57
Dhruma	5033	#NUM!	62.03	#NUM!	1.88	-1750.00	230.00	433.18	866.37	28608.93
Marrat	3272	56.36	35.04	50.73	0.70	-1850.00	100.00	70.13	140.27	28749.20
Minjur	3930	54.57	43.60	49.11	0.95	-2070.00	220.00	209.53	419.06	29168.26
Jilh	4823	68.55	57.82	61.69	1.59	-2290.00	220.00	349.61	699.23	29867.48
Sudair	5182	#NUM!	65.42	#NUM!	2.19	-2450.00	160.00	349.77	699.54	30567.03
Khuff	4953	#NUM!	60.36	#NUM!	1.76	-2715.00	265.00	465.80	931.61	31498.63
Unayzah	3752	74.27	41.18	66.84	0.87	-3080.00	365.00	319.31	638.61	32137.25
Qusaiba	3898	#NUM!	43.16	90.00	0.94	-3540.00	460.00	431.38	862.75	33000.00
Qasim	3685	-	40.29	-	0.85	-4100.00	560.00	474.76	949.52	33949.52

Table 8. Summary of the calculated maximum offset that can be used for the Qusaiba formation to avoid phase change.

Tables 6, 7 and 8 show the calculated critical angle for each of the studied formations highlighted in yellow color. The offset calculated before reaching the critical angle for Shuaiba is 2,235 m, which is more than double the depth to Shuaiba reflector. Therefore, the maximum offset recommended in this case must not exceed double the depth to Shuaiba reflector (1,818 m). On the other hand, the offset calculated before reaching critical angle for Arab is 2,090 m. This offset is less than double the depth of Arab reflector (2,580 m). As a result, this offset is the maximum allowable offset without semblance weakening, due to phase change, leading to an increase of depth error. In the case of Qusaiba, there is no critical angle calculated because the ratio of velocities is more than 1. Consequently, it is recommended to stop at double the depth to Qusaiba (7,080 m) in velocity analysis.

To sum up the results, using the critical angle approach is important to pick correct velocity leading to small depth error. If the offset calculated using critical angle is less than double the depth of the formation, it is recommended to stop before the critical angle offset to avoid phase change that leads to weak semblance. On the other hand, if the critical angle offset is larger than double the depth to the reflector or there is no critical angle between the two formations, it is recommended to the maximum offset equal to double the depth to the reflector.

CHAPTER 5

CONCLUSION

The time-to-depth conversion is important when trying to determine the depth for the next well to be drilled and for resource calculation. The best approach is to utilize the RMS or stacking velocity due to spatial sampling, to perform time-to-depth conversion. However, RMS or stacking velocity depends on the velocity analysis in the processing stage and can lead to greater errors. This study was conducted to investigate the relationship between offset and time-to-depth conversion.

A synthetic viscoelastic model of the Ghawar field in Saudi Arabia was used for three different formations: Shuaiba, Arab, and Qusaiba, with three different offsets for each formation: equal to the depth of the formation, double the depth of the formation and maximum available offset, to investigate the offset-depth relation. The results showed that as the offset decreased, the amount of error decreased. This agrees with the short-offset assumption that states that when the offset is limited, there is a good chance of picking the correct velocity, which will lead to a depth closer to reality. On the other hand, the TWT values did not show any trend and usually had lower values than the calculated values.

Phase change near or beyond the critical angle weakens the semblance energy, leading to difficulties in picking the correct velocity, which eventually leads to errors in estimating the depth values. Therefore, when the near critical angle offset is less than double the depth of the reflector, it is recommended to stop at the near critical offset to avoid phase change. If the near critical angle offset is larger than double the depth of the reflector, the offset can be relaxed to this offset in velocity analysis. Furthermore, when there is no critical angle between two formations, it is

recommended to use short offset assumption. The first angle of incidence in the first formation was calculated using a back-propagation ray-tracing method.

Due to the difficulty in obtaining real data with accurate depth values, the study was not conducted on real data. Therefore, for future studies, I recommend repeating the same analysis on real data.

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Abstracts and Workshops:

1. Felemban, J. A., Al shalawi, F., Mohanna, M. R., (2024). Regional silurian seal thickness evaluation and lateral extent within a sequence stratigraphic framework: 4th EAGE/AAPG Hydrocarbon Seals Workshop, Khobar, Saudi Arabia.
2. Felemban, J. A. (2024). Machine learning application for reservoir characterization using well logs and seismic attributes: Deep Reservoir Imaging and Characterization, Khobar, Saudi Arabia.