Petroleum Res. J. Vol. 20 (2007); P. 1–20, 11 Figs.

Velocity Investigation and Depth Conversion Using Calibrated Seismic Velocity in Soluq Depression Area, NE-Libya

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تحقيق السرعة وتحويل العمق باستخدام معايرة السرعة الزلزالية في منطقة منخفض سلوق شمال شرق ليبيا

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يهدف هذا التحليل إلى تحديد الفرق بين السرعات ذات الاشتقاق السيزمي والسرعات المستمدة من المسوحات المبدئية والسرود الصوتية وإلى اختبار التأثير المحتمل لهذا الفرق على تحديد توزيع السرعة الحقيقية. وحيث من المفترض أن المنطقة تحت الدراسة تقع على خط التماس بين بيئتين فإن الرسوبيات قد تجمعت في بيئات مختلفة وبذلك فإنه من المتوقع وجود تغيير في المحتوى الصخري في كلا الاتجاهين الرأسي والأفقي. وفي هذه الحالة، فإن افتراض سرعة واحدة لن يكون صحيحا، حيث أن تغيرات سريعة قد تحدث في السرعة بين نقطة وأخرى ولذلك فإن تحديد دوال السرعة الحقيقية في المنطقة يعد عملا مهما ويتطلب أكبر قدر من الدقة.

تتألف بيانات السرعة المتوفرة لهذا التحليل من مسوحات السرعة في الآبار وقياسات السرود الصوتية في تسعة آبار. وتشتمل مجموعة البيانات قياسات السرعة الانعكاسية في 54 مقطعا سيزميا. ويحدد الجزء الأول من تحليل المقطع ومتوسط السرعات من مصادر هذه البيانات. وقد تم إنجاز مقارنة دقيقة لهذه السرعات المختلفة التي تم تحديدها مسبقا. وأخيرا تم تصحيح السرعات المقطعية لكي يتم التعويض على التأثير المفتعل تلقائيا الملاحظ خلال ربط الآبار. وتوضح رسومات مستويات السرعات السيزمية زيادة في السرعة مع العمق كما هو متوقع من عمليات التراص الطبيعية.

وعموما فإن رسومات السرعة تمثل مضاهاة مقبولة مع المتوقع جيولوجيا للتركيبات تحت السطحية وسوف تقود تفسيرات خرائط العمق والسرعة لكل تتابع سيزمي على حده مع ما يتوفر من بيانات جيولوجية وجيوفيزيائية، إلى تفسيرات نهائية أكثر دقة لمنطقة الدراسة.

Abstract: *Investigation of the difference between the seismic derived velocities and the check-shot and sonic log velocities, to examine what effect the difference might have on the determination of the true velocity distribution was conducted. Since the investigated area is assumed to be located on a hinge-line, sediments have been deposited in different environments and thus a change in lithology in both vertical and horizontal directions is expected. In such a situation, an assumption of constant velocity would not be valid, since rapid changes in velocity from one point to another may occur. Therefore, determination of the true velocity functions in the area is an important task, requiring as much accuracy as possible.*

The velocity data available for this analysis consists of borehole velocity survey and sonic log measurements from nine boreholes. The data set also includes seismic reflection velocity

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measurements from 54 seismic profiles. The first part of the analysis determines interval and average velocities from these data sources. A critical comparison of these different determined velocities has been done. The derived average and interval velocities are finally corrected using the mean average and interval velocity error, in order to compensate for a systematic biasing influence observed from the well ties. Contour plotting of the seismic velocities shows a general increasing velocity with depth, as expected with normal compaction. Generally, the velocity plots represent a reasonable correlation with the geological expectation of the subsurface structure. The interpretation of the depth and velocities maps for individual seismic sequences, together with all available geological and geophysical data, will lead to a more complete final interpretation in the study area.

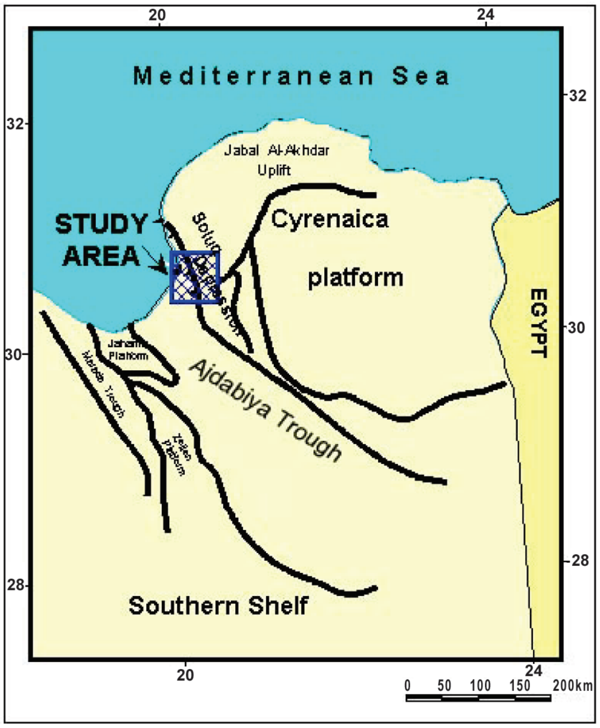


Fig. 1. Location map of the study area, and the major tectonic elements in NE- Libya.

INTRODUCTION

The area of the present study is located on concession NC129 of AGOCO (Fig. 1). Geologically, the area approximately lies on a hinge-line between the Mesozoic-Tertiary Sirt Basin to the west and the stable Cyrenaica Platform to the east. The Ajdabiya Trough forms the most eastern part of the Sirt Basin, while the Soluq Depression is the western part of the Cyrenaica Platform (Fig. 1).

Analyses of true velocity variation are very useful for local stratigraphic interpretation and lithologic evaluation, and for conversion of two way time to depth. Many technical papers have been published on the subject of velocity analysis. Among them are the following which focus on the concept of velocity and its application to structural-stratigraphic interpretation: Al-Chalabi (1974 and 1979), Lindseth (1982), Banik (1984), Peikert (1985), Dobrin and Savit (1988) and Sheriff and Geldart (1995).

The overall aim of this research is to compute and interpret the velocity distribution across the hinge-line between the Sirt Basin and Cyrenaica Platform. The velocity distribution fields for each depositional sequence in the area are calculated, and used to indicate lithologic and stratigraphic changes to help evaluate the geological and tectonic history of the area. Reliable depths to the top of each sequence, by converting travel times using calibrated average velocity information, is also produced.

During the last four decades, a number of regional and local geological studies, in the Sirt Basin and Cyrenaica Platform have been published (Barr (1972), Burke and Dewey (1974), Berggren (1969, 1974), Van Houten (1983) and Anketell and Ghellali (1991). Most of the geological studies done on NE Libya have concentrated on the surface outcrops in the Al Jabal al Akhdar region. Rohlich (1974) described the principle stratal features and evaluated the tectonic development of Al Jabal Al Akhdar exposures. El-Arnauti and Shelmani (1985) studied the stratigraphy and structural development of the Palaeozoic and Mesozoic in the subsurface of the Cyrenaica Platform. El-Shari (2004) studied the stratigraphic sequences and analysed the subsidence and sedimentation rates across the hinge-zone between Sirt Basin and Cyrenaica Platform.

GEOLOGICAL SETTING OF SOLUQ DEPRESSION

The most prominent surface morphologies in the Cyrenaica region are Al Jabal al Akhdar uplift in the north, the Soluq Depression in the southwest and the Cyrenaica Platform in the east and southeast (Fig. 1). In the southern part of the area, a partially marine Palaeozoic sequence has unconformably overlain the basement, while in the east and northeast, the basement is overlain by a wedge of marine Palaeozoic rocks which thickens towards the east (El-Arnauti and Shelmani, 1985). The Palaeozoic rocks are widespread in the Cyrenaica region and show variation of thickness, which can be attributed to the post-early Palaeozoic tectonic activity and subsequent erosion (Sola and Ozcick, 1990).

The Soluq Depression, which lies mainly on the Cyrenaica Platform, is connected with the Ajdabiya Trough of the Sirt Basin. Within this depression, the main structural trend is northwest-southeast. During Triassic, Jurassic and Early Cretaceous times, the Soluq Depression was high with NE dipping Palaeozoic strata, which was subjected to erosion (Yanilmaz *et al.*, 1989). The Lower Cretaceous is absent in this region, where the basin is probably underlain by Lower Palaeozoic age rocks.

During Late Cretaceous, the fluctuation in sea level resulted in the deposition of limestone interbedded with shale. At this time, a local depocentre developed, and over 2500m of Upper Cretaceous sediments were deposited. The axis of the basin, and its depocentre, shifted towards the east during Palaeocene and Eocene times. During the Oligocene and Miocene, periodic fluctuations in sea level resulted in cyclic shoaling-upward carbonate cycles. Figure 2 shows that the sedimentary succession is dominated by marine carbonates, but significant amounts of shale were also deposited in the area. During low stands of sea level, evaporites were deposited upon shallow parts of the platform.

DATA BASE AND METHODOLGY

The database for this analysis is comprised of 507 velocity analysis tabulations from 54 seismic reflection profiles, continuous velocity logs, and well velocity surveys from nine wells. The seismic lines form an approximate 2 km square grid over a rectangular area of around 60 x 60 km. The locations of the wells and the seismic lines used in this project are shown in Figure 3.

The seismic data quality over the studied area is generally good. The seismic data pointed to a basin-to-shelf depositional setting (Fig. 4). In such an area, lateral and vertical changes in geology are expected to reflect different depositional environments. In order to evaluate the lateral facies changes, and to control the distance between the expected major features of the area, a close seismic line spacing was chosen.

The analysis begins by determining the velocity from these three different sources of data. Then, results of the velocities derived from the seismic reflection data and those derived from the sonic logging and well velocity surveys in the boreholes are compared. The derived average and interval

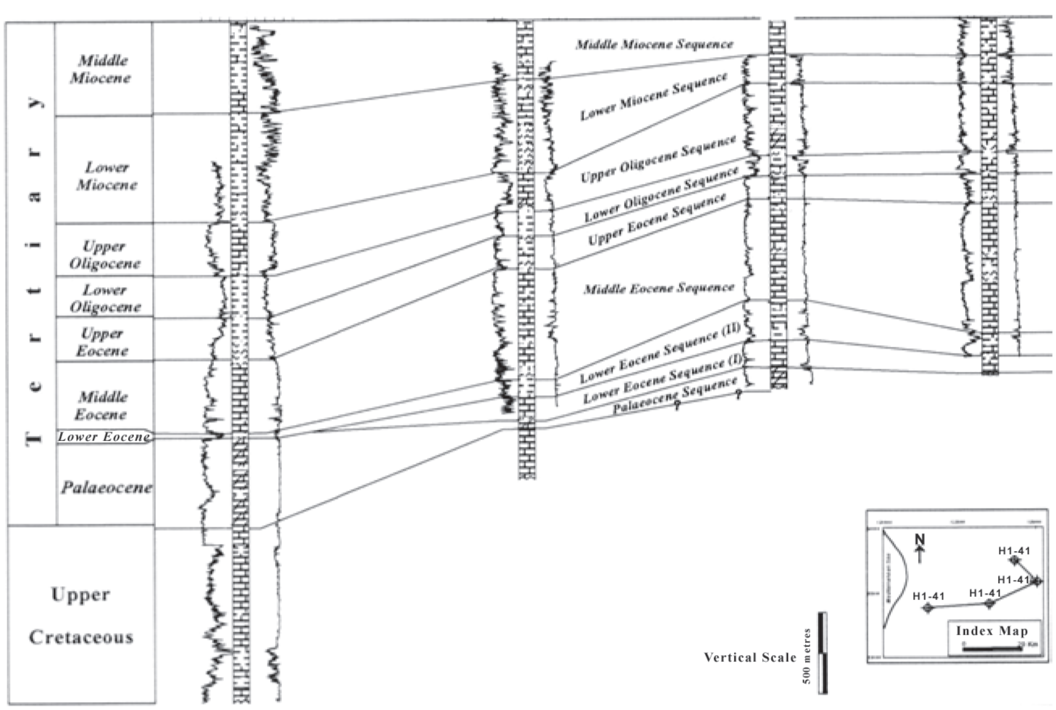


Fig. 2. Chronostratigraphic correlation with lithostratigraphy of the penetrated sedimentary sequences of four wells located on the hinge-zone of the Cyrenaica Platform with Sirt Basin, the correlation of the wells is based on the final lithological composite log and on the interpretation of gamma-ray and sonic logs. Log curves have been plotted with a sampling interval of 3 meters, and the datum is mean sea level.

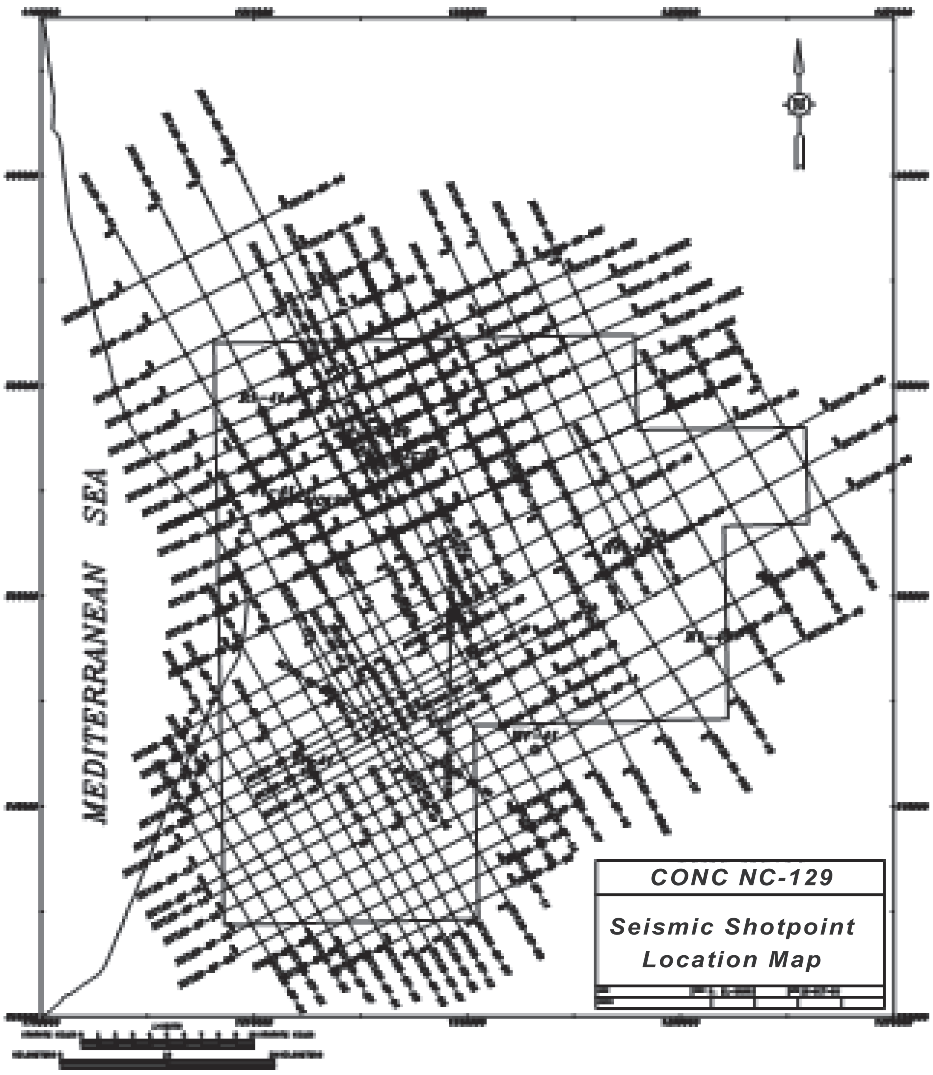


Fig. 3. Seismic reflection profiles and wells location in Concession NC-129.

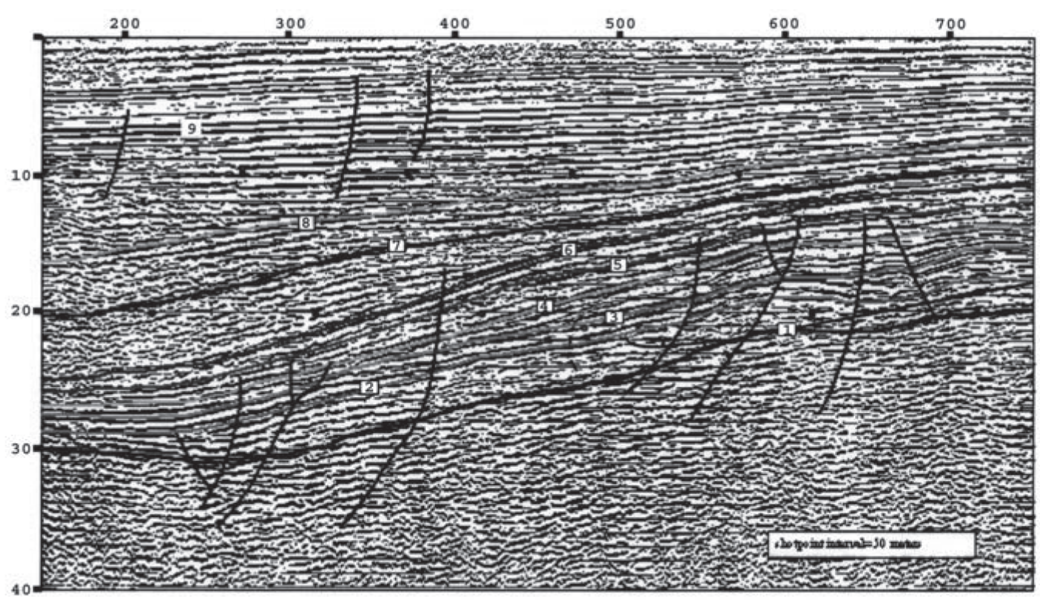


Fig. 4. Seismic interpretation along line NC129-87-08. The boundaries between the sequences shown as following; (1) base Palaeocene sequence, (2) top Palaeocene sequence, (3) top Lower Eocene sequence I, (4) top Lower Eocene sequence II, (5) top Middle Eocene sequence, (6) top Upper Eocene sequence, (7) top Lower Oligocene sequence, (8) top Upper Oligocene sequence, (9) top Lower Miocene sequence. Note that all faults are of extensional type and mostly downthrown in the direction of the basin (after El-Shari, 2004).

seismic velocities have been edited to exclude unrealistic values, and adjusted to tie with well information.

After the final calibration of both average and interval seismic reflection velocities, velocity maps have been constructed. The interval velocity and its changes, related to stratigraphy and lithology of the particular section, are of great value in the geological interpretation. Using the calibrated average velocity, a depth map for each depositional sequence has been constructed for the area of study.

VELOCITY DETERMINATION

Observation of lithologic well logs in the study area indicates that the subsurface geology, and hence, velocity distribution, of most sedimentary sections, is likely to be complex. Rapid variations of physical properties with depth characterise the sedimentary succession. In addition to heterogeneity within layers of similar material, the interfaces separating the layers are frequently discontinuous, due to faulting and unconformity.

Generally, there are only two sources of subsurface velocity information: wells and seismic data. Borehole check shots and sonic log provide reliable measurements of the vertical velocity-depth function local to the well bore, and also precise details of the velocity variation within any chosen interval. However, the spatial distribution of wells is usually insufficient to constrain the lateral variations of velocity that must be defined over a prospect. In contrast, the seismic reflection data generally provide coverage across both high and low areas. The seismic reflection data give reliable estimates of subsurface velocities if the velocity layering, and hence the geological structure, is exactly horizontal.

However, for this research, an accurate method of velocity-determination that will improve the interpretation of the seismic reflection data is desired. The velocity is also used for the conversion of seismic travel times to depths and for computation and mapping of interval velocities, which are important indicators of subsurface lithology. Since the investigated area is assumed to be located on a hinge-line, sediments have been deposited in different environments and thus a change in lithology in both vertical and horizontal directions is expected. In such a situation, an assumption of constant velocity would not be valid, since rapid changes in velocity from one point to another may occur. Therefore, determination of the true velocity functions in the area is an important task.

COMPARISON OF VELOCITIES FROM THREE DATA SOURCES

The comparison of the velocities derived from the seismic reflection data and those derived from sonic logging and well velocity surveys in the boreholes is carried out in this section. Many authors have noted the differences between travel times (and associated velocities) derived from the sonic log and well velocity surveys, either using the check-shot technique or the vertical seismic profile (VSP) (*e.g.* O'Brien and Lucas, 1971; Stewart *et al.,* 1984; De *et al*., 1994).

The sonic logs provide comprehensive velocity information of the subsurface, measuring the transit time over very small intervals of the geological column. It is common, however, to have errors in travel times (and thus errors in the derived velocities) because of the instrument problems, borehole conditions and. In addition, the determination of sonic velocity in carbonates commonly shows less accuracy due to the development of vuggy porosity, caused by irregular dissolution of grains and rocks in limestones and dolomites.

However, the well velocity survey is characterised by the measurement of the direct travel time of seismic signal from source to receiver through the ground, which enables the tool to measure travel time accurately. The well velocity survey, therefore, is considered the most reliable source of vertical velocities measured within the borehole. In this study, the well velocity survey was used to improve the accuracy of the initial velocity functions.

Every tool has some degree of reliability for travel time measurements and, of course, their associated derived velocities. The main reason for the observed differences between the sonic log and the well velocity survey, is that the sonic logging tool uses an ultra-sonic source of high frequency of 15-20 khz, propagating very short distances (several feet) along a path adjacent to the borehole. In contrast, the well velocity survey uses a seismic source of low frequency of 50-100 hz, which may be offset several hundred feet from the wellhead. O'Brien and Lucas (1971), Stewart *et al*. (1984) and De *et al*. (1994), conclude that frequency dependent dispersion is the main contributing factor to observed discrepancies between the sonic logs and well velocity surveys. In addition, the propagation path of the well velocity survey samples the ground many tens of feet from the borehole, whereas, the sonic log samples the material close to the borehole wall only. However, the amount of the velocity data obtained from the surface seismic survey is relatively large compared with other *in situ* velocity measurements. It has a lower cost than well velocity surveys and sonic logging, and provides data coverage over large areas, but it has been shown that the seismic velocities derived by normal move out velocity methods do not always measure the same physical parameters as well as survey velocities (*e.g.* Al-Chalabi, 1979; Levin, 1978; Lindseth, 1982).

The comparison curves of the two-way times, calculated from each source versus depth, are displayed in Figure 5. The depth values in the seismic reflection data are estimated using average velocity, which is calculated from the stacking velocity at each well. Constant stacking velocity was assumed in the

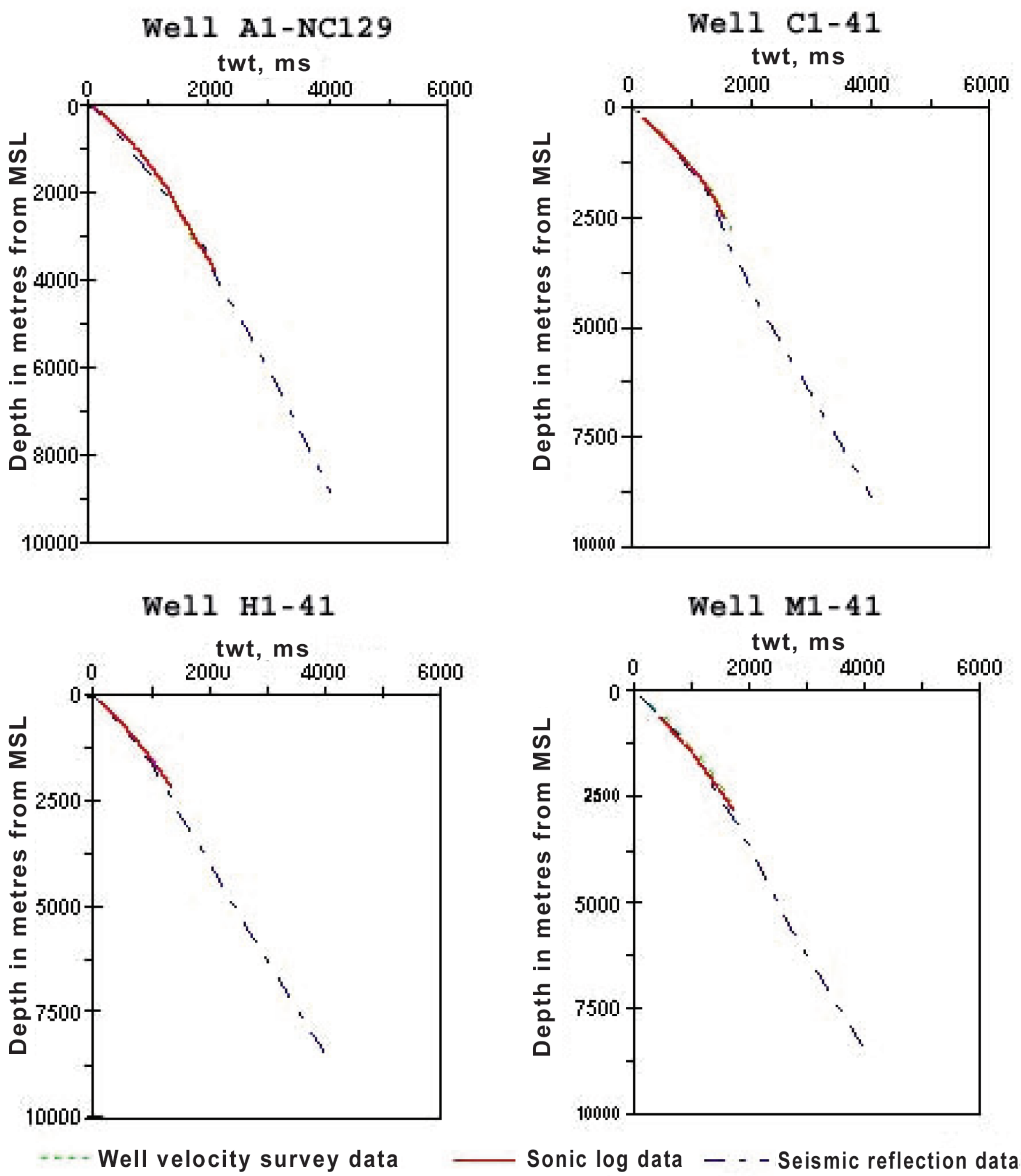


Fig. 5. Comparison of two-way travel times derived from three sources data; seismic reflection profiles, sonic logs and well velocity surveys.

deeper parts of all seismic profiles. The plots show a systematic difference between the two-way travel times obtained from seismic reflection data and those obtained from the sonic logs and well velocity surveys. In all wells, the two-way travel times measured from the seismic reflected data are slightly but systematically shorter than those measured from the other two sources. Most wells display good agreement of the measured two-way travel times from the well velocity surveys and sonic logs. A diversion between the three curves is noticed at depths of about 2000 meters, and clearly increases with depth. However, the resolution of the seismic reflection data decreases as depth increases, making the seismic reflection data less reliable.

Figure 6 shows comparison plots between velocity data derived from the three data sets. The resulting comparison indicates the well survey velocities are systematically lower than the sonic log velocities at most depths. The difference between the sonic log average velocities and well survey velocities range between +16 and -7 percent, with an average of +2.3

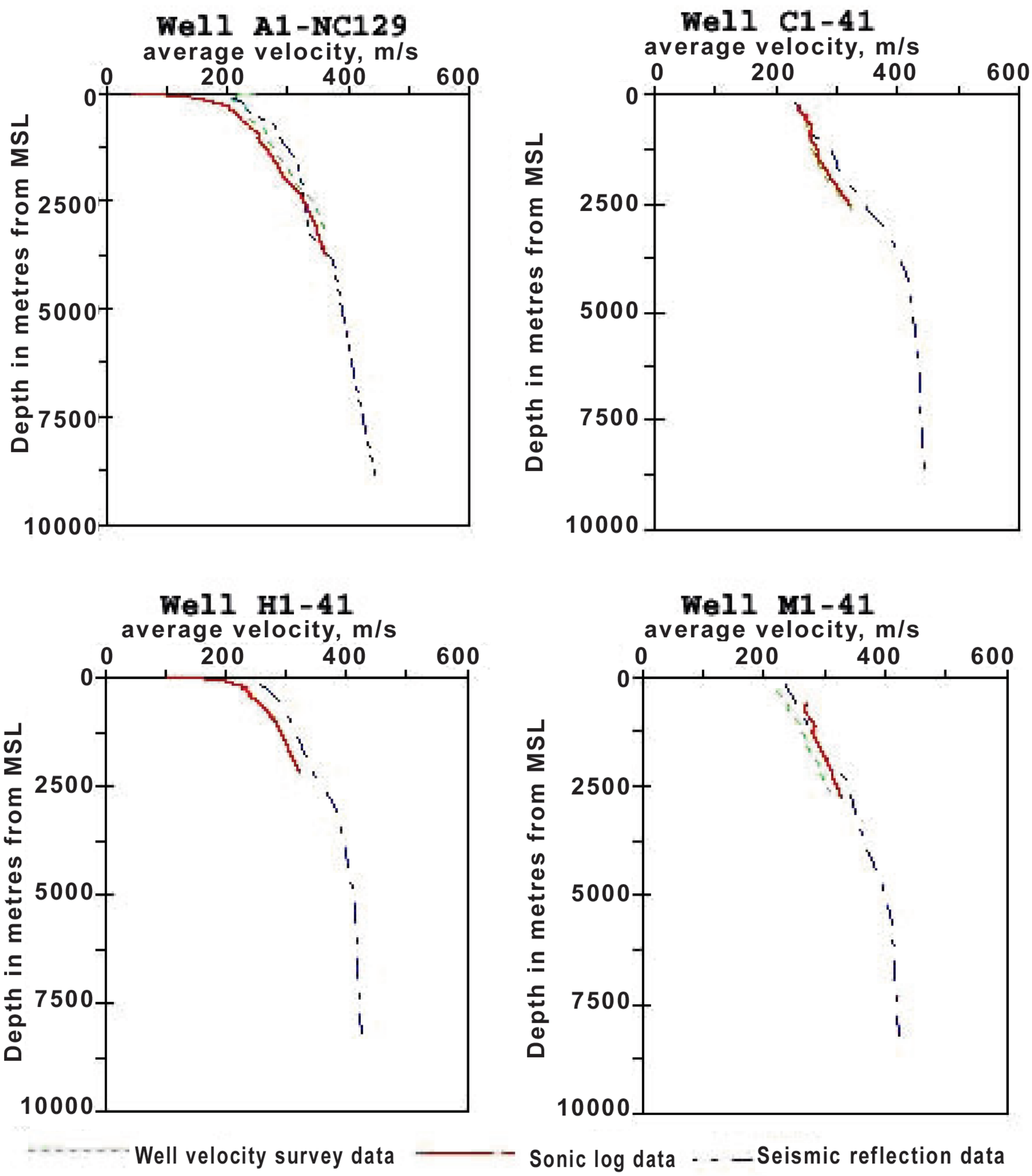


Fig. 6. Comparison of average velocity derived from three sources data; seismic reflection profiles, sonic logging, and well velocity surveys.

percent. This positive drift is consistent with normal dispersion in which the higher frequency waves travel at higher velocities. On the contrary, De *et al*. (1994) concluded that the velocity differences between well velocity surveys and sonic surveys range from +16 to -5 percent, with an average of +6.9 percent. The seismic reflection velocity in this analysis is found higher than the velocity derived from the well velocity surveys and sonic logging in most of the wells. In fact, the true velocity distribution can never be fully recovered by the surface seismic reflection method, due to practical limitations on the resolution of velocity information.

SEISMIC VELOCITY

Interpretation

The average and interval seismic reflection velocities versus two-way time, in the form of seismic section display, have been plotted for preliminary interpretation of the velocity distribution in the study area. The average velocities and the interval velocities were calculated using Dix's equation and are represented in a series of iso-velocity plots.

Figure 7 shows plots of iso-(average seismic reflection velocity) as a function of two-way travel time for selected dip seismic profiles located in the southern part of the area. In these plots, increasing average velocity with depth has been observed. Generally, the average velocity plots are smooth and represent a reasonable correlation with a geological expectation of the subsurface structure. The shallow depths show uniform average velocity distribution. At greater depths, the plots show denser contour lines indicating abrupt changes in velocity. Velocity variation between the platform and the basin is interpreted as arising from changes in lithology between the two areas. The low average velocity at the basinward end of the dip profiles may be correlated with increasing shale percentage towards the deep basin.

Figure 8 shows iso-interval velocity plots of selected dip and strike profiles and their corresponding reflection time. Generally, these

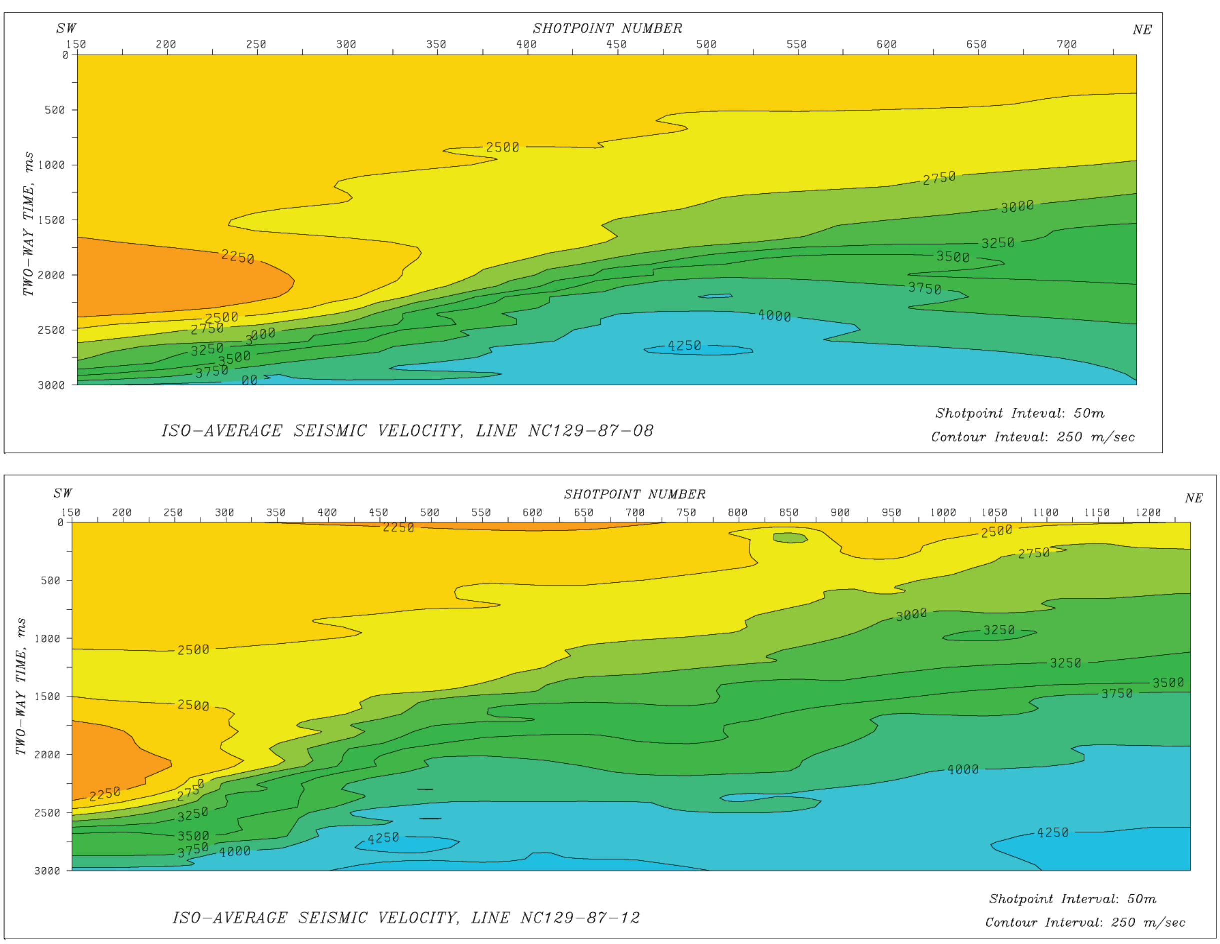


Fig. 7. The iso-average seismic reflection velocity for lines NC129-87-8 and NC129-87-12 (dip lines in the southern part of the area). For lines location see Figure 3.

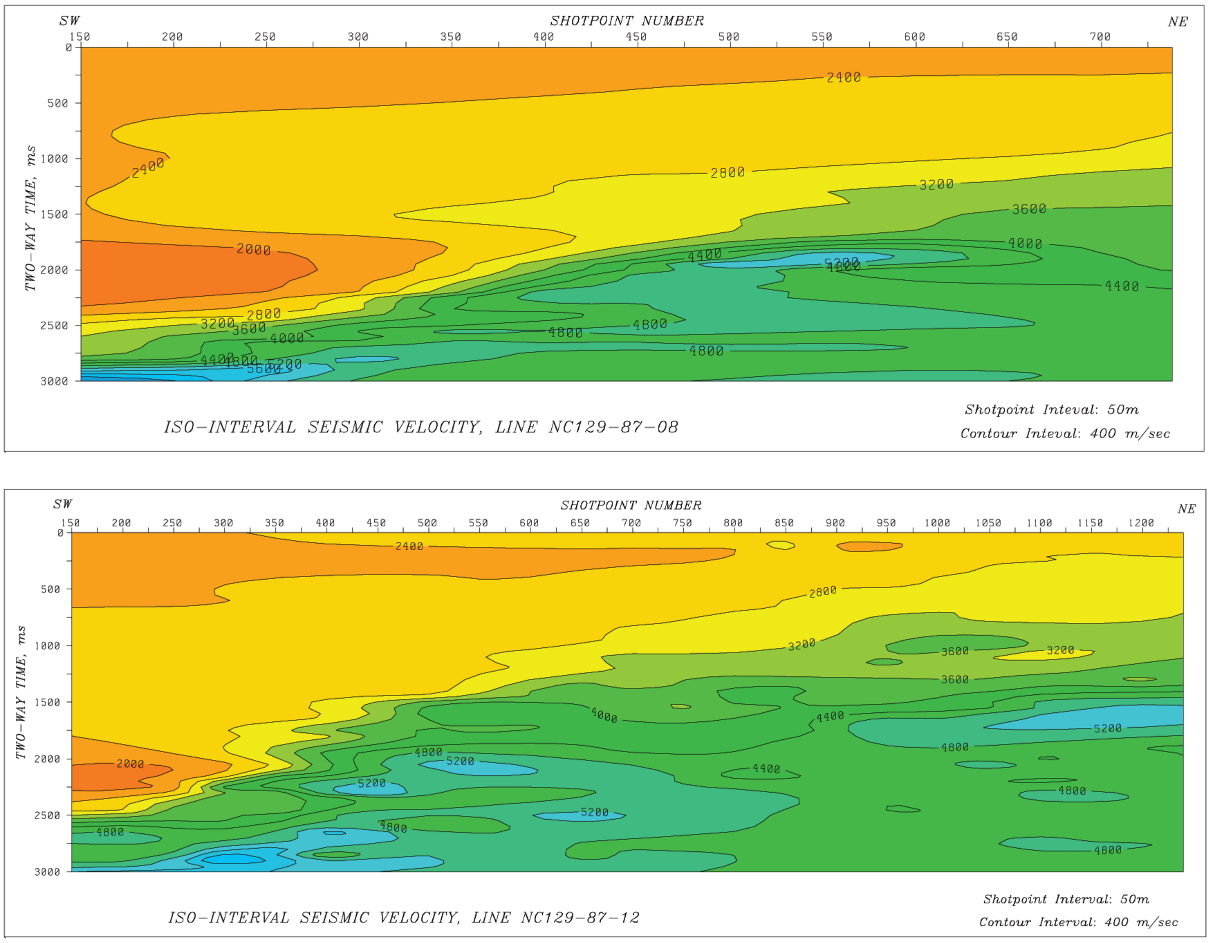


Fig. 8. The iso-interval seismic reflection velocity for lines NC129-87-8 and NC129-87-12 (dip lines in the southern part of the area). For lines location see Figure 3.

contour plots capture the important large-scale velocity behaviour. Lateral variation in the velocity distribution has been observed along these profiles. These velocity anomalies reflect geological conditions related to structural elements and sediment distribution during the Late Cretaceous and Tertiary.

The upper parts of the sections show a uniform increase of interval velocity, consistent with the dip of the section, to a depth of approximately 1.5 sec TWT. Deeper, the interval velocity represents high lateral variations, especially towards the southwest direction. The velocity variation is seen if we compare the right hand side (NE directions) of the dip profiles, NC129-87-8 and NC129-87-12, with the left hand side (SW directions) of the same profiles (Fig. 8). Increasing lithology variation toward the area of a hinge-line is a possible explanation for this lateral interval velocity variation. The relatively highly faulted area may also contribute to these velocity differences. In addition, the development of these faults may affect the depositional environment, which in turn affects the lithology variations of the sediments in those areas. These faults alone, may have an affect on the seismic velocity in those areas.

Velocity Calibration

Determination of velocities from well survey methods is important, since they give the only true check on the precision of the same velocities derived from other sources. Any mature exploration area shows that wells tend to be concentrated in clusters around hydrocarbon discoveries. Also, because hydrocarbons migrate updip, and accumulate towards the climax of the prospect, the locations of the wells tend to be concentrated towards the structural highs. Since few wells have been drilled in structural lows, this drilling represents a significant influence in the sampling of seismic velocities. Also, the structural highs are commonly characterised by apparent thin or missing geological sections. This, commonly combined with large lithological variation from structural highs to lows, contributes to make the estimation of velocities away from well control a slightly uncertain operation.

The final step in this velocity analysis is to compute an accurate velocity function for the entire study area. The well velocity survey is used to calibrate the initial seismic reflection velocity. It is often very useful to calibrate the velocity field, estimated from exploration seismic data, with the other well velocity sources. However, this method depends on the degree of velocity variation, the amount of well control, and the quality and density of velocity information from seismic data. The seismic reflection velocities have been calibrated using velocities derived from the well data to remove unrealistic variations. The idea of calibration is based on calculated velocity values from a number of widely separated wells, which are averaged and then used to correct the seismic reflection velocities.

VELOCITY MAPPING

In sedimentary rocks, the *P*-wave velocity is dependent upon the wave velocity in the rock matrix, the porosity and the velocity in the fluid filling the pore spaces. Also, the velocity depends on the strength of rock, which reflects the consolidation and sedimentation, both of which tend to increase with age and depth of burial. The rock density generally increases while porosity decreases with burial. In general, the lithology, porosity and depth of burial are considered the most prominent factors affecting the velocity of sediments.

In the Soluq Depression, an interpretation of the seismic information has been made, and well information has been used to correlate seismic reflection horizons with stratigraphy and to estimate the gross interval velocities between horizons. Information from lithologic well logs indicate that the subsurface geology, and hence velocity distribution, of most sedimentary sections is likely to be complex. From the well information, it is recognised that the sedimentary column of the area is composed mostly of an alternation of limestone, shale, and dolomites (Fig. 2).

Average Velocity Maps

The average velocity is usually given as a function of depth and can be considered as a vertical variation in velocity. The average velocity maps have been constructed for the sequences from the top of the Upper Cretaceous sequence to the top of the Lower Miocene sequence which is the shallowest horizon boundary identified in this study. In the average velocity maps, increasing velocity with depth has been observed. The compaction process, and consequent loss of porosity, is the primary cause for the increase of velocity with depth. The significant difference in the average velocity of individual sequences mostly occurs between the area toward the deep basin and the platform.

Figure 9a displays the average velocity above the top of Upper Cretaceous sequence. In general, the contour pattern in this map shows some irregularity in the velocity distribution. The complexity of the velocity at this level may be attributed to the decrease in quality of velocity data. In the lower depositional sequences (the Palaeocene sequence and the Lower Eocene sequence), the average velocity distribution is generally unsystematic (Figs. 9b and 9c). However, a general increase of velocity has been observed towards the southwest, consistent with an increasing depth of burial towards the basin. The Middle Eocene sequence and all overlying sequences are characterised by increased velocity towards the east and southeast (Fig. 9d). Limestones and shales are the predominant lithologies in these sequences, with a considerable increase in shale percentage, towards the deep basin. The increased shale percentage towards west and southwest is the most reasonable explanation of decreasing velocity towards that direction.

Interval Velocity Maps

The interval velocity maps represent the pattern of velocity variation within the sequences and reflect the controlling variables of lithological variation and depth of burial. Particular details of velocity structure and an investigation of the lateral velocity variation provide parameters such as depositional environment, source area location, burial history, structural style and structural position. In general faults cause discontinuities in the interval velocity data. The interval velocity maps are constructed for the entire Tertiary sedimentary succession in the Soluq Depression.

The Palaeocene Sequence

Figure 10a shows contour plotting of the interval velocity within the Palaeocene sequence. The contour patterns generally have an irregularity in their

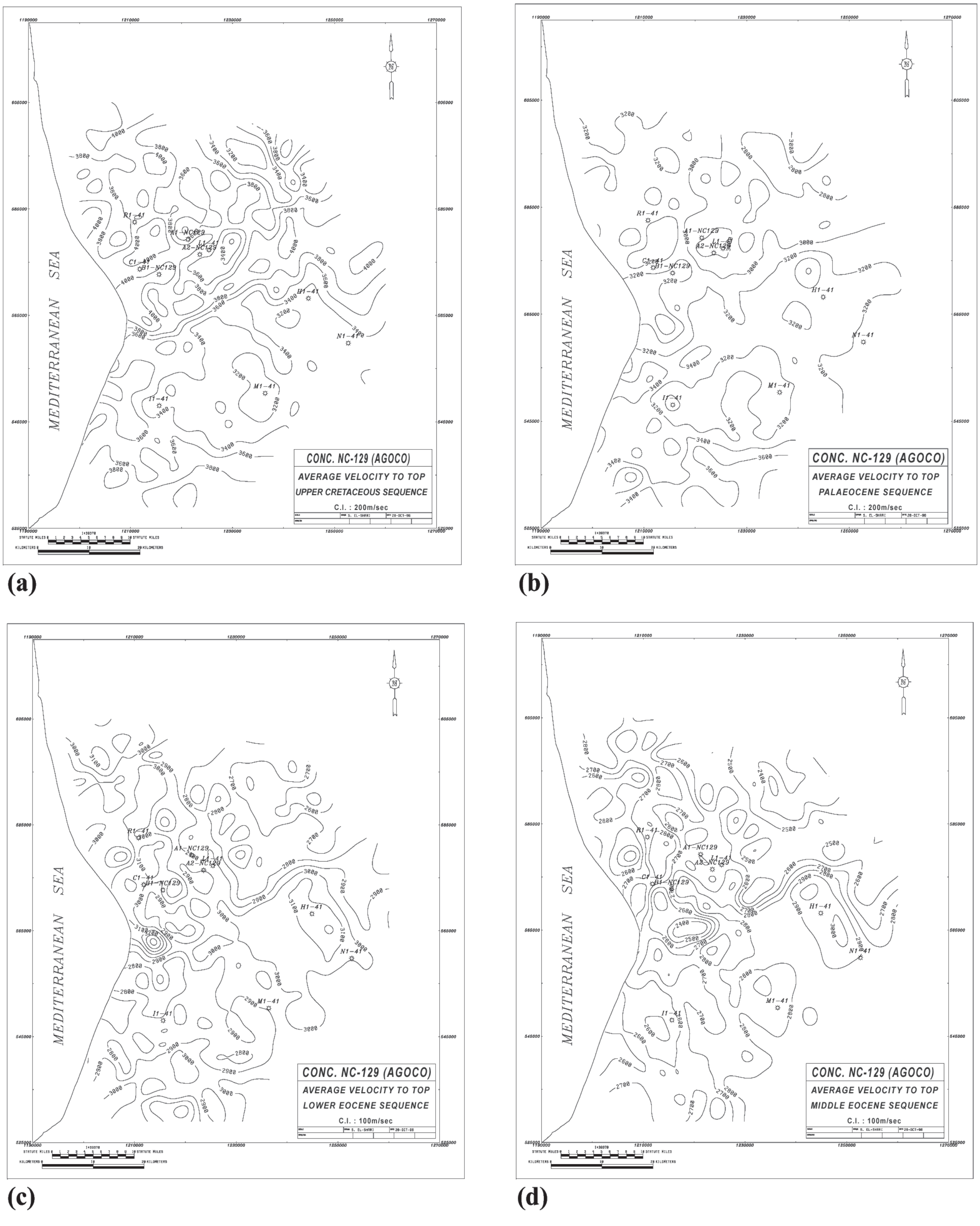


Fig. 9. Average velocity contour map to top of; a) Upper Cretaceous (b) Palaeocene, (c) Lower Eocene, and (d) Middle Eocene sequences.

measurement in that area. However, the lateral velocity variation in the Lower Eocene sequence is interpreted as controlled by sedimentary facies variation, and the effect of the fault structures. The variation of depth of burial throughout the sequence may also effect the interval velocity distribution.

The Middle Eocene Sequence

The interval velocity distribution within the Middle Eocene sequence (Fig.10c) shows a different appearance from that of the previous sequences (The Palaeocene sequence and the

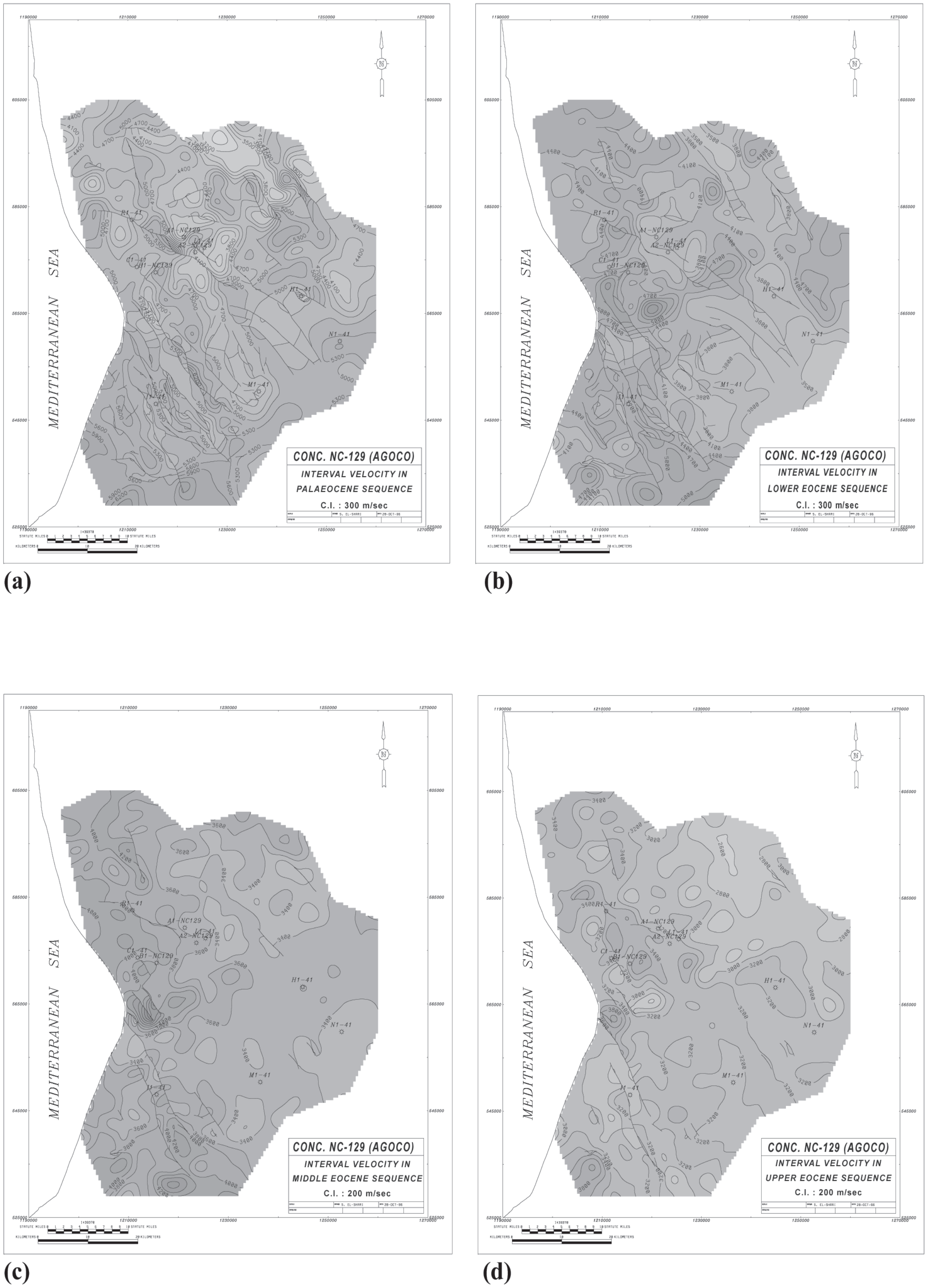
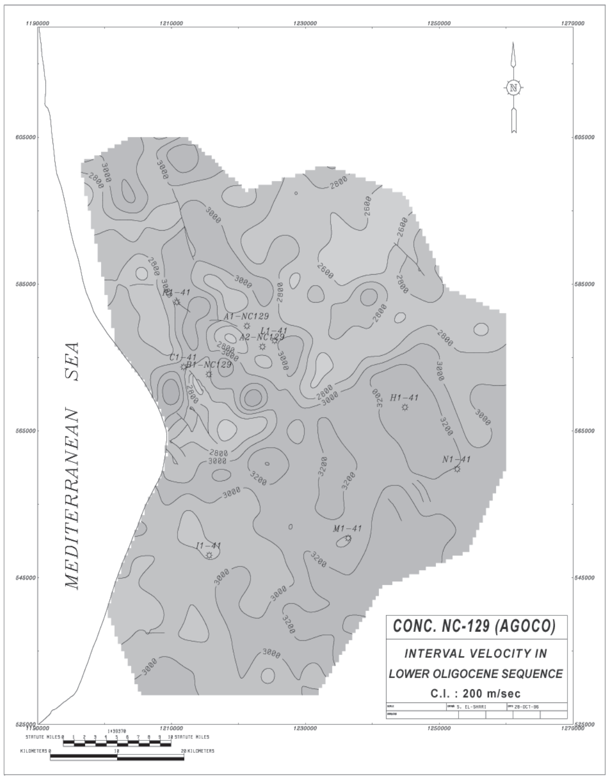
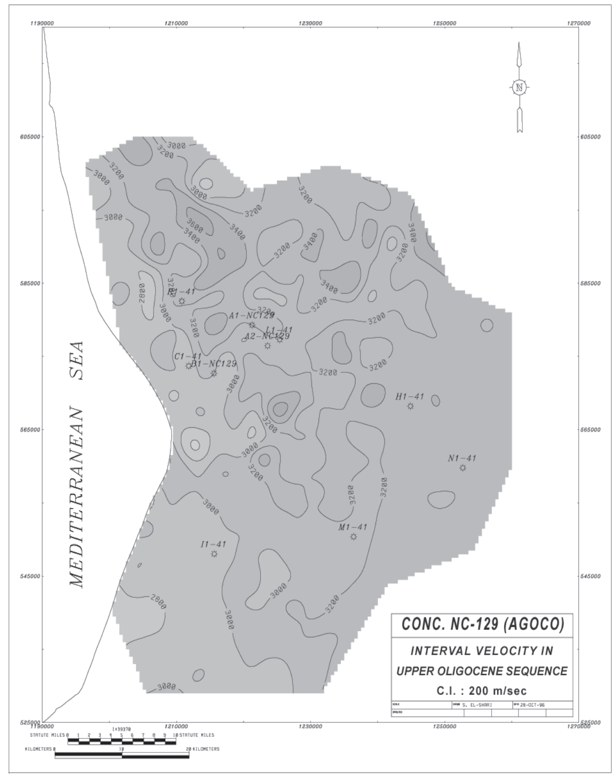


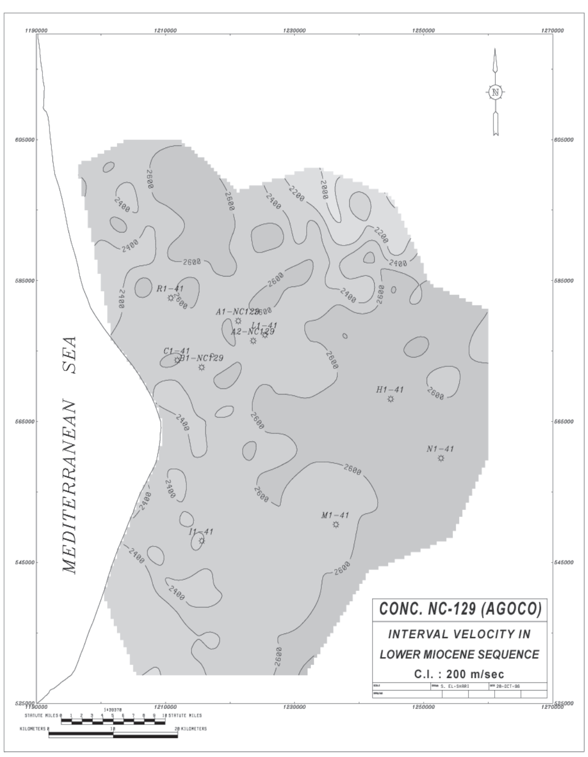
Fig. 10. Interval velocity contour map within the depositional sequences in the Soluq Depression; (a) the Palaeocene, (b) the Lower Eocene, (c) the Middle Eocene, (d) the Upper Eocene.



(e)



(f)



(g)

Fig. 10. Interval velocity contour map within the depositional sequences in the Soluq Depression; (e) the Lower Oligocene, (f) the Upper Oligocene, and (g) the Lower Miocene.

Lower Eocene sequence). The contour pattern in this map shows wider contour line spacing over most of the area, which indicates some uniformity in velocity distribution. The interval velocity in the northern and eastern areas only ranges between 3400 and 3600 m/sec. However, the faulted areas around and northwest of well I1-4 show relatively dense contours, which suggest a sudden change in interval velocity within the sequence occurring in these areas. The maximum interval velocity in the faulted areas reaches a value of about 4200 m/sec.

The Middle Eocene sequence is composed of relatively uniform lithology throughout the area (Fig. 2). The well information of M1-41, N1-41, H1-41 and C1-41 shows that argillaceous limestone, interbedded occasionally with shale beds, is the dominant lithology. The map shows increasing velocity towards the west and southwest. Generally, the velocity increase gradually, but have relatively steep gradients where the shelf margin is present at the area of well I1-41. Based on well data, the increasing velocity trend may be consistent with an increase of relatively dense carbonates towards the basin. The sequence depth of burial increases toward the southwest and is more significant beyond the shelf margin area, which accounts for increasing interval velocity toward the southwest where porosity reduction and compaction might be expected with increasing depth.

The Upper Eocene Sequence

Figure 10d is a contour plot of the interval velocity within the Upper Eocene sequence. The velocity in this map is in the ranges from 3000 to 3400 m/sec. Well data in the Soluq Depression shows lateral lithofacies changes in the sequence. It mainly consists of argillaceous limestones interbedded with shales. Lithological logs from wells located in the northwestern (A1-NC129, B1-NC129 and C1-41) show that chalky and argillaceous limestones are the common rock types. The limestone interbeds with shale in the western and southern wells (N1-41 and H1-41). In general, the velocity gradually increases towards the west. The areas towards the basin show relatively close contour patterns, indicating sudden changes in the distribution of the interval velocity within the sequence.

The Lower Oligocene Sequence

The interval velocity distribution in the Lower Oligocene sequence is shown in Figure 10e. The velocity contours in this map show some irregularity, especially in the northwestern area, which reflects some lateral interval velocity variation. Velocity in the range is 3000 - 3200 m/sec is the most dominant. Lower velocity values are encountered in the western and northeastern parts of the area, where slightly increasing velocity generally marks the sequence southeastwards. The well information shows that the Lower Oligocene sequence represents lateral changes in lithofacies throughout the Soluq Depression. Limestone and shale interbedded with some marl beds are the predominant lithologies in the sequence. A thick shale sequence was deposited in the west and southwest, while interbedded shales and carbonates were deposited in the east. There are only a few normal faults of NW-SE orientation marked on the map. However, these faults appear to be without any significant affect on the interval velocity distribution. Therefore velocity distribution within the sequence may be controlled by the lateral lithological variation.

The Upper Oligocene Sequence

Figure 10f shows the interval velocity map of the Upper Oligocene sequence. The map of this sequence shows a different appearance from that of the previous sequences. The contour patterns in this map generally display a uniform velocity distribution within the sequence. The dominant interval velocity range is 3000- 3200 m/sec. The general increasing velocity trend is toward the east. The well data shows limestone interbedded with some beds of shale and marl as the predominant lithology in the sequence (Fig. 2). Dolomitic limestone and anhydrite beds occasionally occur within the sequence. In southern areas, the lithology of the sequence is mainly fossiliferous limestone interbedded with shale (wells; I1-41, M1-41, N1-41 and H1-41). The dolomitic limestone and anhydrite percentage increases in the eastern wells. In the northern areas, fossiliferous limestone interbedded with marls is the predominant rock type. This lithology variation may be correlated with the interval velocity distribution in the sequence. No fault structures appear in this level, and the lithology may be the main cause of velocity variation.

The Lower Miocene Sequence

The interval velocity within the Lower Miocene sequence is displayed in the contour map of Figure 10g. On this map, no significant sudden change in interval velocity marked the horizon, and consistent lateral variation in velocity distribution can be seen. The well data shows the Lower Miocene sequence is mainly composed of shale and argillaceous limestone throughout the basin. The shale is the predominant lithology in the lower part of the sequence and fossiliferous limestone interbedded with some intervals of shales appears in the middle part. In the upper part, the lithology of this unit is primarily shale with some argillaceous limestone. The shale percentage increases towards the west and southwest. The interval velocity distribution largely reflects the gradual lithological variation within the sequence. The velocity in the sequence is generally consistent with the shale-increasing trend.

Time to Depth Conversion

One of the significant results in this project is to determine reliable depths to the top of each depositional sequence in the Soluq Depression. The time to depth conversion in this research was carried out using velocities derived from surface seismic data calibrated by well velocity data. Time to depth conversion for complicated geological models including laterally variable velocities and reflector structure strictly requires more accurate velocity consideration. The calibrated average velocities together with the two-way travel times, to the top of each depositional sequence, have been used to calculate the depths of these sequences.

Depth Map of Upper Cretaceous Sequence

Figure 11a shows the depth contour map of the Upper Cretaceous depositional sequence. In general, the depth gradually increases towards the southwest. Close contour spacing in the map, which is concentrated west of well I1-41, indicates a sudden increase in sequence depth at the shelf margin. The general trend of normal faults dissecting the Upper Cretaceous sequence is NW-SE. Differential subsidence across the hinge-line between the Sirt Basin and Cyrenaica Platform, together with the effect of the fault displacement, are the main reasons for the sudden increase in depth towards the deep basin. The Upper Cretaceous sequence in the Soluq Depression is only penetrated in wells A1-NC129, I1-41 and M1-41. The comparison of the sequence depths in these wells with the constructed depth map shows misties especially in well I1-41. However, this disagreement is expected at this level due to the following reasons:

(a) The Upper Cretaceous Sequence is the most intensively faulted horizon. These faults have a detrimental effect on the accuracy of both picking horizon times and velocity measurements.

(b) The decreasing seismic resolution with depth affects the precise picking of the horizon time on the seismic profile.

(c) Lower accuracy of seismic reflection velocity estimation with increasing travel time.

(d) Less control points for seismic velocity calibration as the horizon is only penetrated in a few wells.

Depth Maps of Palaeocene, Lower Eocene and Middle Eocene Sequences

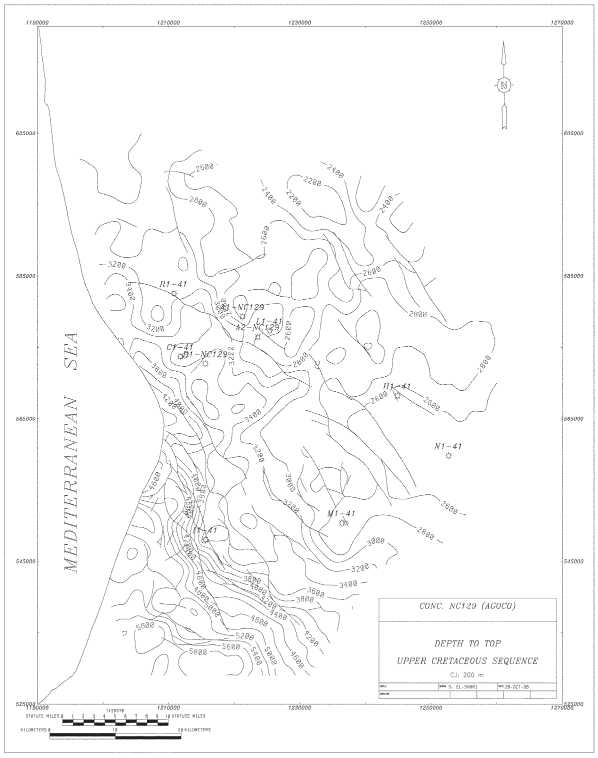
The depth maps of these sequences are shown in Figures 11b, 11c and 11d respectively. In general these maps show slightly increasing depth generally marks the sequences southwestwards. An exception is the shelf margin at well I1-41, where sudden increases in depth are observed. The sequences are intensively dissected by many normal faults dipping mainly southwards. The main faults in the sequences appear to be concentrated in a belt roughly tending NW-SE, where some of them have a WNW-ESE trend. These faults may have an influence in the irregularity of the depth contours. Close contours on these maps are seen to the west of well I1-41, indicating a sudden increase of depth to the southwest. The location of the area on a hinge-line may be the main reason for the abrupt increase in depth towards the deep basin. Subsidence, which is expected to increase towards the deep basin, as well as the displacement of normal faults, may be the most plausible reasons for this change in the depth gradient towards the southwest. However, the shape of the contour pattern in the Middle Eocene sequence is more regular. This may be attributed to decreasing of the fault structures in this horizon compared with the underlying horizons.

Depth Maps of Upper Eocene, Lower Oligocene, Upper Oligocene and Lower Miocene Sequences

The depth structure maps of these depositional sequences are shown in Figures 11e, 11f, 11g and 11h respectively. In general, the contour pattern in these maps represent gradual and uniform increasing in depth of the sequences towards the southwest. A very gentle increase in depth has been observed up to the area of well I1-41. To the west of this well the contour line spacing indicates an abrupt increase in depth towards the deep basin. Here again the increasing depth gradient toward the southwest indicates increasing basin subsidence as we move southwestwards. Thermal subsidence of post-rift sequences in the basin is expected to be the main reason for the increasing depth gradient in this direction because there are no major effects of fault displacement in these sequences. However, the gradient of increasing depth southwestward in the Upper Oligocene and Lower Miocene sequences is obviously lower than the increasing depth gradient in the underlying sequences in the same trend. This may be interpreted as a decrease of the effect of the basin thermal subsidence with time.

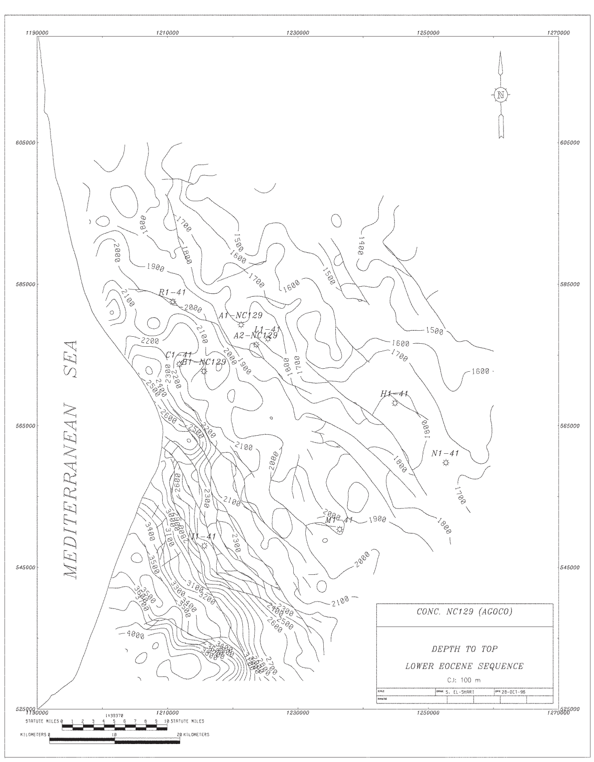
CONCLUSIONS

Analyses of true velocity variation are very useful for local stratigraphic interpretation and lithologic evaluation, and for conversion of time to depth for each sequence in the subsurface of the Soluq Depression. In order to satisfy these objectives, the velocity analysis done in this research was based on

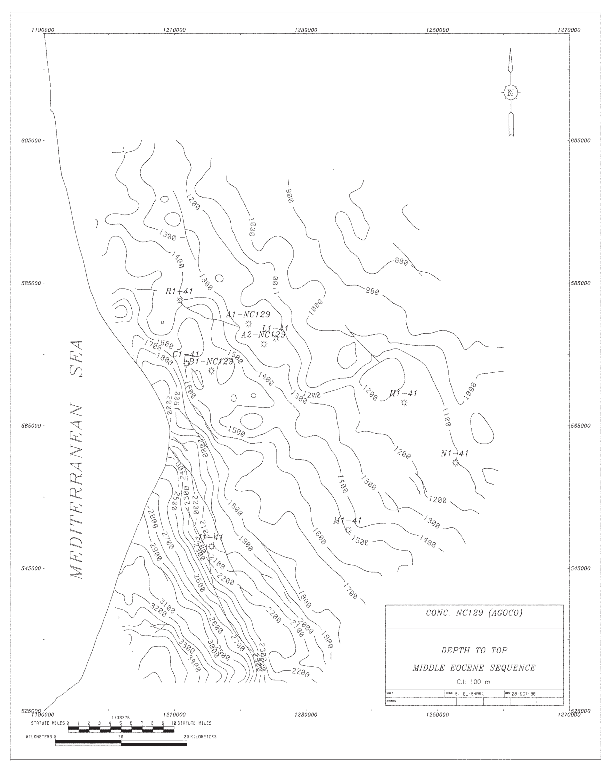


(a)

(b)



(c)



(d)

Fig. 11. Depth structural contour map of the depositional sequences in Soluq Depression; (a) top Upper Cretaceous (b) top Palaeocene, (c) top Lower Eocene, (d) top Middle Eocene.

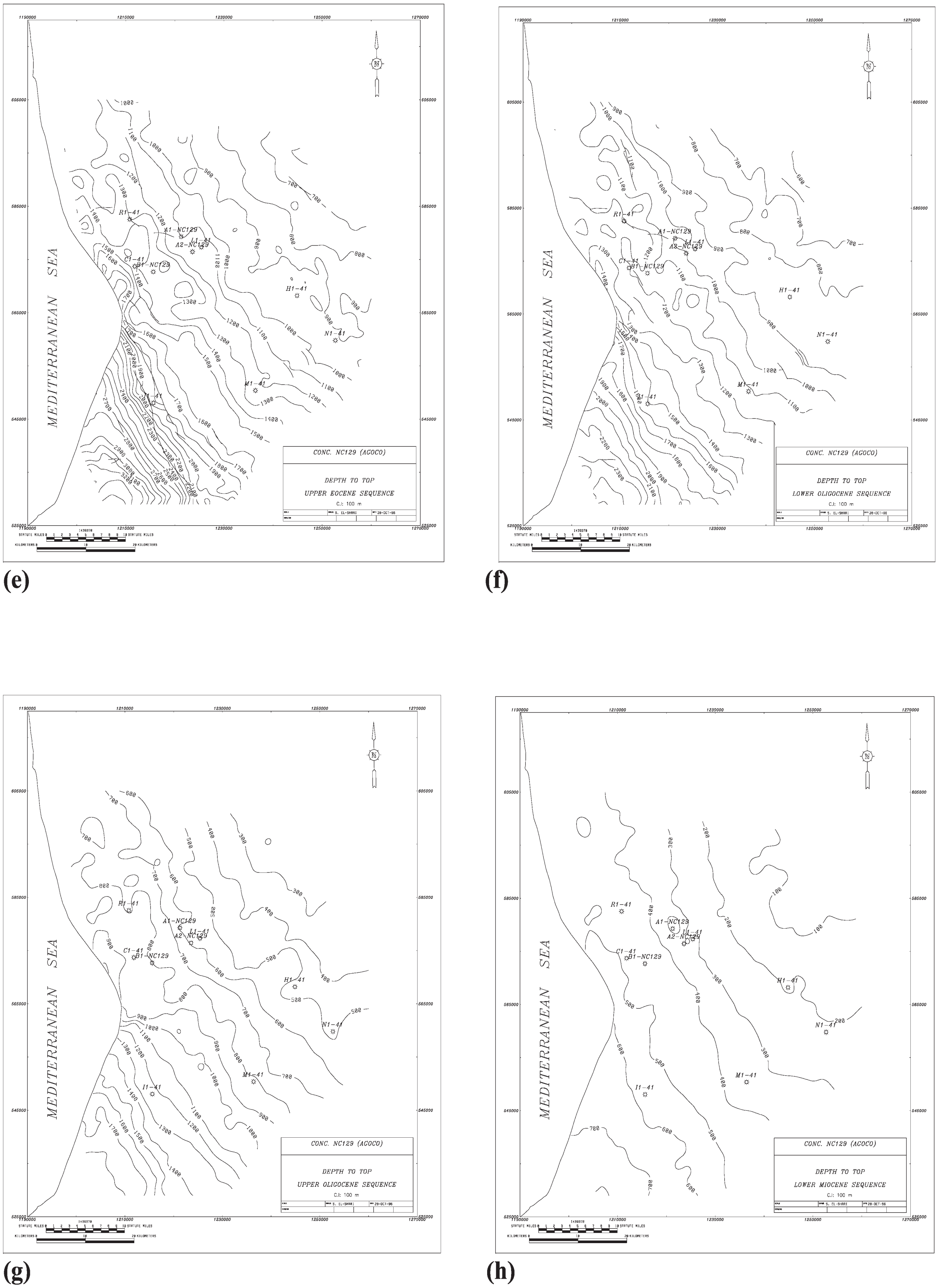


Fig. 11. Depth structural contour map of the depositional sequences in Soluq Depression; (e) top Upper Eocene, (f) top Lower Oligocene, (g) Upper Oligocene, and (h) top Lower Miocene.

velocities extracted from three data sources: well velocity surveys, sonic logs, and seismic reflection measurements. Contour plotting of the seismic reflection average velocities shows a general increasing velocity with depth, as expected with normal compaction.

The velocity comparison indicates that the seismic reflection data consistently shows a higher velocity than that measured from well data. The comparison also shows that the velocities derived from sonic logs were consistently higher than those from well surveys. To obtain a realistic velocity value, well data were used as a reference in a calibration operation to smooth the seismic reflection velocities. Seismic reflection velocity should not be used directly to infer true subsurface velocities for time to depth conversion if accuracy is important.

Between the deep basin and the platform areas, there are significant differences in the average velocity to the tops of most sequences. In general, increases of average velocity have been observed towards the southwest for the Palaeocene and Lower Eocene sequences. This is consistent with increasing depth of burial basinward. A decrease in velocity towards the west and southwest direction is characteristic of the Middle Eocene sequence, and all the overlying sequences. The most reasonable explanation of this trend is the increasing shale percentage in the same direction.

The patterns of velocity variation within the sequences are represented on the interval velocity maps, and reflect the controlling variables of lithological variation and depth of burial. Lateral changes in velocity have been observed in the Palaeocene and the Lower Eocene sequences. Determination of interval velocity is made more complicated here by the effect of faults on the accuracy of seismic velocity estimation and also, in some instances, the control of those faults on the lateral facies distribution. Transfer zones between these faults may act as conduits for local sediment transport in basin stratigraphy.

The interval velocity maps generally display relatively less irregularity in velocity distribution in the Middle Eocene and Upper Eocene sequences. The main factors affecting velocity distribution are variations of both lithology and depth of burial. For the Lower Oligocene sequence and above, the interval velocity maps generally display uniform velocity distribution, decreasing towards the southwest. The lateral lithofacies variation largely controls the velocity distributions in these sequences. The main reason for velocity decreasing towards the southwest direction is the deposition of thick sequences of shale in the same direction.

The final results of the depth conversion are depth maps with perfect well ties, and with reasonable depth estimates away from wells. All of the depositional sequences display surfaces dipping towards the southwest (basin direction). In the southwest, the dip gradient is much steeper. Fault displacement and thermal relaxation in the post-rift period are two main reasons for gradients towards the centre of the basin. The development of a hinge-line between the Cyrenaica Platform and the Sirt Basin may explain why the increase in dip is more significant beyond the area of the shelf-slope break. The increasing gradient toward the southwest may be due to increasing thermal subsidence in the post-rift period towards the deep basin, compared with the platform.

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REFERENCES

Al-Chalabi, M., 1974. An analysis of stacking, rms, average, and interval velocities of horizontally layered ground. *Geophysics. Prosp.,* **22**, 458-475.

Al-Chalabi, M., 1979. Velocity determination from seismic reflection data. *In:* A. A. Fitch (*ed.*), *Developments in Geophysical Exploration Method*, **1**, 1-68.

Anketell, J. M. and Ghellali, S. M., 1991. A palaeogeographic map of the Pre-Tertiary surface in the region of the Jifarah plain and its implication to the structural history of northern Libya. *In:* M. J. Salem, A. M. Sbeta, and M. R. Bakbak, (*eds.*). *The Geology of Libya,* Elsevier, **6**. 2407-2416.

Banik, N. C., 1984. Velocity anisotropy of shales and depth estimation in the North Sea basin. *Geophysics*, **49**.1411-1419.

Barr, F. T., 1972. Cretaceous stratigraphy and planktonic foraminifera of Libya. *Palaeont*., **18**.1-46.

Berggren, W. A., 1969. Biostratigraphy and planktonic foraminifera zonation of the Tertiary system of the Sirte Basin of Libya. North Africa. *In*: P. Bornnimann and H. H. Renzi (*eds.*). *Proc. 1st Int. Conf. Plank. Microfossils*, **1**, 104-120.

Berggren, W. A., 1974. Palaeocene benthonic foraminiferal biostratigraphy, biogeography and palaeoecology of Libya and Mali. *Micropalaeontology.* **20**, 449-465.

Burke, K. and Dewey, J. F., 1974. Two plates in Africa during the Cretaceous?. *Nature*, **249**,313-316.

De, G. S., Winterstein, D F. and Meadows, M. A., 1994. Comparison of P- and S-wave velocities and Q's from VSP and sonic log data. *Geophysics,* **59**, 1512-1529.

Dobrin, M. B. and Savit, C. H., 1988. *Introduction to Geophysical Prospecting* (Forth Edition). McGraw-Hill book company.

El-Arnauti, A. and Shelmani, M., 1985. Stratigraphic and structure setting. *In*: B. Thusu and B. Owens (*eds*.), Palynostratigraphy of Northeast Libya. *J. Micropalaeontology*, **4**, 1-10.

El-Shari, S. M., 2004. Stratigraphic effects and tectonic implications at hinge-zone area between Sirte Basin and Cyrenaica Platform, NE Libya. *G*eology of East Libya, *Sedimentary Basins of Libya,* Third Symposium (abstract).

Levin, F. K., 1978. The reflection, refraction and diffraction of waves in media with an elliptical velocity dependence. *Geophysics*, **46,** 528-537.

Lindseth, R. O., 1982. *Digital Processing of Geophysical Data, a Review,* Continuing Education Program, Society of Exploration Geophysics, Tulsa, 278p.

O'Brien, P. N. S. and Lucas, A. L., 1971. Velocity dispersion of seismic waves. *Geophysical Prospecting*, **19**, 1-26.

Peikert, E. W., 1985. Stratigraphic velocity interpretation; national petroleum reserve-Alaska. *In*: O. R. Berg and D. G. Woolverton (*eds*.), Seismic stratigraphy II: An integrated approach to hydrocarbon exploration. *Am. Assoc. Petrol. Geol. Memoir* **39**, 209-222.

Rohlich, P., 1974. Geological Map of Libya. 1:250000 Sheet NI 34-15, *Al-Bayda Explanatory Booklet*. Ind. Res. Cent. Tripoli, 70p.

Sheriff R. E. and Geldart L. P., 1995. *Exploration Seismology* (Second Edition). Cambridge. 592p.

Sola, M. and Ozcick, B., 1990. On the hydrocarbon prospectivity of the north Cyrenaica region, Libya. *Petrol. Res. J*., **2**, 25-41.

Stewart, R. R., Huddleston P. D. and Kan K. K., 1984. Seismic versus sonic velocities: A vertical seismic profiling study. *Geophysics*, **49**(8), 1153-1168.

Van Houten, F. B., 1983. Sirte Basin, north central Libya; Cretaceous rifting above a fixed mantle hotspot?. *Geology*, **11**, 115-118.

Yanilmaz, E.; Ahmed S. and Amsaad, I., 1989. *Regional Geology of Cyrenaica* (*Northeast Libya*). Internal report, AGOCO, Exploration Department.