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Normal and abnormal porosity-depth relationship of tertiary rocks in Soluq depression, NE-Libya.

Saad M. El-Shari

University of Benghazi, Faculty of Science, Earth sciences department. Benghazi
E-mail address: smbelshari@yahoo.com

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ABSTRACT

The principle aim in this analysis is to evaluate and interpret the porosity-depth relationships in the Tertiary rocks in the Soluq Depression. Generally, the porosity in a formation is a function of its present depth only when that depth is its maximum depth of burial. From sonic log interval transit-time for ten wells scattered in the area, the porosity has been estimated, in order to evaluate and analyse the history of burial and erosion in the sedimentary sequences deposited on the western margin of the Soluq Depression.
The comparison of modelled normal compaction trends with actual compaction trends can be used to quantify zones of over-compaction and under-compaction in a rock column. The porosity analysis in this research is basically based on the comparison of the observed shale and limestone regression lines with the normal porosity-depth model. The normal porosity-depth model represents measurements on 'pure' shales and limestones, which are believed to be at their maximum depth of burial. The difference between the two curves may allow any depth of burial anomalies to be identified through the rock columns in the Soluq Depression.

1. Introduction

Porosity is one of the most important physical properties of sedimentary rocks. The value of porosity is principally a function of the interlocking pattern of grains through compaction, contact-solution and redeposition, and cementation. Genetically the porosity in sedimentary rocks is complex, and this complexity is mainly due to the wide range in size and shape of the particles and pores, which build the pore system in the rock, and to diagenesis.

The porosity analysis in this study is not for reservoir potential evaluation. The principle aim is to evaluate and interpret the porosity-depth relationships in the Soluq Depression. From sonic log interval transit-time for ten wells scattered in the area (Fig. 1), the porosity has been estimated, in order to evaluate and analyse the history of burial and erosion in the sedimentary sequences deposited on the western part of the Cyrenaica Platform. To determine the porosity more precisely, very detailed lithology in each well was quantitatively studied from composite lithological logs. This lithological study identifies limestone, shale and dolomite as three major types of sedimentary rocks in the investigated wells.

The maximum depth to which a rock has been buried strongly influences its porosity. This study is based on a comparison between the observed shale and limestone regression lines with regression lines from measurements on 'pure' shales and limestones, which are believed to have normal depth of burial characteristics. The difference between the two curves may allow the identification of any depth of burial anomalies through the rock columns. The reduction in thickness of sedimentary rock units is due to compaction as a result of the increasing weight of younger sediment material that is continually being deposited.

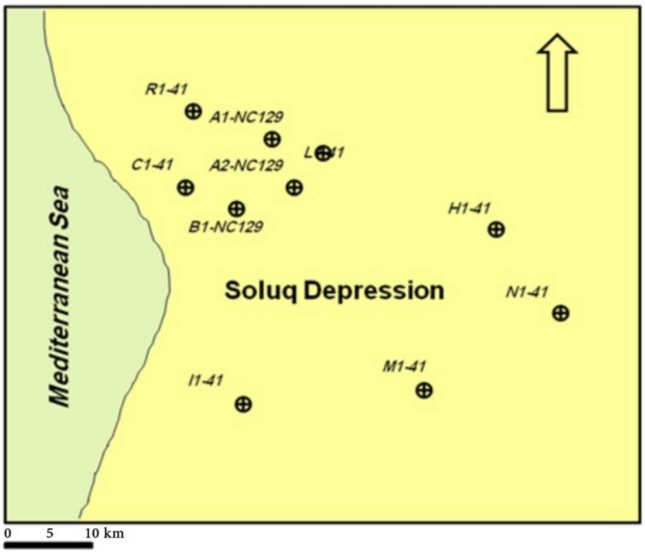

Fig. 1, Location map of the boreholes used in the porosity analysis.

2. Porosity-Depth Relationship In Carbonates And Shales

Generally, carbonates are the predominant rock type in the Soluq Depression (El-Shari, 2008). Fig. 2 shows an exponential porosity decrease with depth in both dolomite and limestone. The porosity in carbonates can be reduced by changes in packing, which take place from a few meters below the sediment surfaces. After deposition of sediments, the two main processes that decrease porosity are compaction and cementation. There are two stages of compaction: mechanical (physical) and chemical compaction. The early compaction, mainly mechanical, occurs after the deposition of overburden sediment load. In carbonates, with increasing physical compaction, a chemical compaction or solution precipitation may take place through the pressure solution process. This process occurs in grains at points of contact, and is considered an important mechanism of porosity reduction (Tucker, 1981).

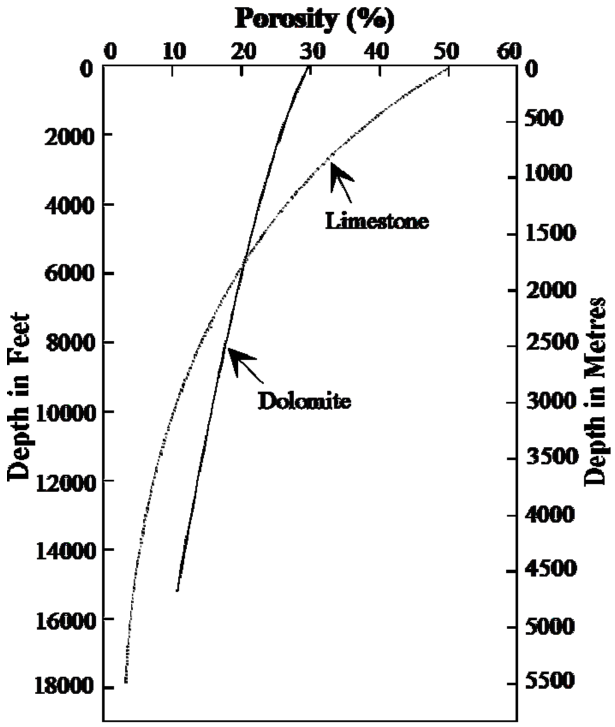

Fig. 2, Exponential porosity depth curves for limestones and dolomites (from Schmoker & Halley, 1982).

The second major rock type in the Soluq Depression is shale. Shale porosity mainly depends on the amount of bound water and impurities, which is highly affected by the compaction processes. The porosity in clay sediments generally shows some differences from that of carbonates. One of these differences is the higher porosity of unconsolidated clays. The porosity of clay on the sea floor is known to be 70 % to 80 %, and decreases rapidly during the early stages of burial (Fig. 3). Magara (1976b) discusses the relationship between porosity and transit time. He suggests that the transit-time value for clay sediments will stay almost constant until porosity falls to 62%. The transit time decreases after this stage as the amount of porosity decreases.

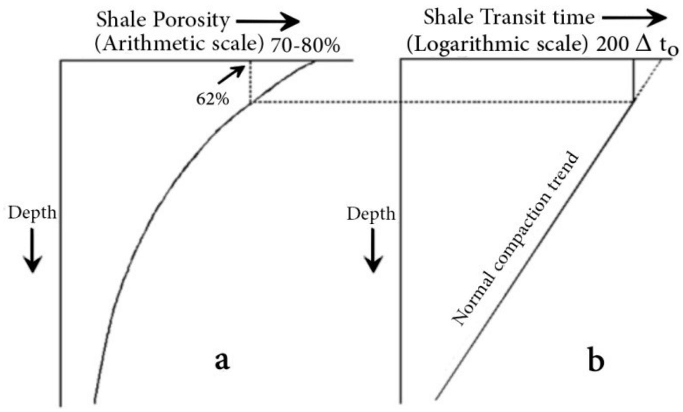

Fig. 3. Schematic diagram showing; **(a)** the shale porosity-depth relation, and **(b)** the corresponding shale transit time-depth relation (after Magara, 1976b).

However, shale is strongly affected by the compaction processes, by which its bulk density increases. Abnormal pressure zones occur due to prevention of the escape of water through compaction processes. Rubey and Hubbert (1959) suggest that two shale sequences at different depths of burial will have the same porosity values if their effective pressures are the same.

3. Normal And Abnormal Porosity-Depth Relationship

The porosity-depth relationship in sedimentary rocks has been subjected to many studies (e.g. Rubey & Hubbert, 1959; Sclater & Christie, 1980; Magara, 1976a & b). Decreasing porosity with depth due to compaction processes is the first thing to be considered when investigating the regional variations of porosity for most sedimentary rocks. Under pressure of the weight of overburden sediments, pore waters escape and the sediment becomes consolidated. The incremental load of sediment is supported by the fluid pressure, and also by the mechanical strength of the grain to grain contacts. Therefore, the average porosity of a rock sequence at a given depth is relatively high in abnormal pressure zones. However, at any depth of burial, the porosity and fluid pressure in the pore spaces are mostly dependent on one another. The rate of porosity loss with depth is consistent if the fluid pressure and overburden pressure increase at a constant rate.

4. The Observed Porosity In The Area

Ten boreholes have been used in porosity analysis in the Soluq Depression (Fig. 1). The porosity-depth plots for composite sections of different lithology in the area are shown in Fig. 4. For the purposes of easy identification, different symbols and colours represent each rock type in these plots. In these plots, some irregularity in porosity values has been observed. The porosity deviation seems to be strongly dependent on lithology, physical and chemical differences in the rock matrix. Also, this deviation could be due to the subjection of these lithologies to different strengths of diagenatic processes. However, these plots represent a generally consistent loss of porosity as the depth of burial increases. It is clear that the exponential function is the best fit for the porosity-depth relationship in all investigated wells, and that seems to represent the normal porosity-depth trend for any mixed lithology.

The porosity-depth plots in Fig. 4, generally show a rapid porosity loss at shallower depths, but slowly in the deeper. The significant loss of porosity in most wells took place mainly within the first 1000 m (3000 ft.). The observed rapid decline in porosity, in this depth interval, may result from decreasing primary porosity with depth. However, porosity scattering is relatively higher at the shallower parts of the wells. This scattering may be attributed to freshwater dissolution processes and the development of scattered secondary porosity in the form of cavities, holes and other karstic features. Leaching of near surface carbonate and precipitation at depth in a closed circulation system, is another reason for decreasing porosity with depth. In order to investigate the porosity distribution in the area, the following sections represent the porosity analysis of each rock type in the analysed wells.

Limestone: From the porosity versus depth curves in the limestone intervals, two main phases of porosity reduction have been observed. Phase (i), which is characterised by wider range of porosity values, span from about 65% near the surface to about 30% at depth of 1000 m (3000 ft.). This phase represents relatively high rate of porosity reduction of (3.5% per 100 m). In this interval mechanical compaction was probably the most important mechanism contributing to this fast porosity reduction. Phase (ii), in which the porosity values show a narrower variation deeper than 1000m (3000 ft.). This phase is characterised by a lower rate of porosity reduction (approximately 1.5% per 100m). Cementation and precipitation of materials from chemical compaction may have been an important factor responsible for the majority of the porosity loss in this phase, where mechanical compaction made little contribution to porosity loss once the rock was buried to this depth.

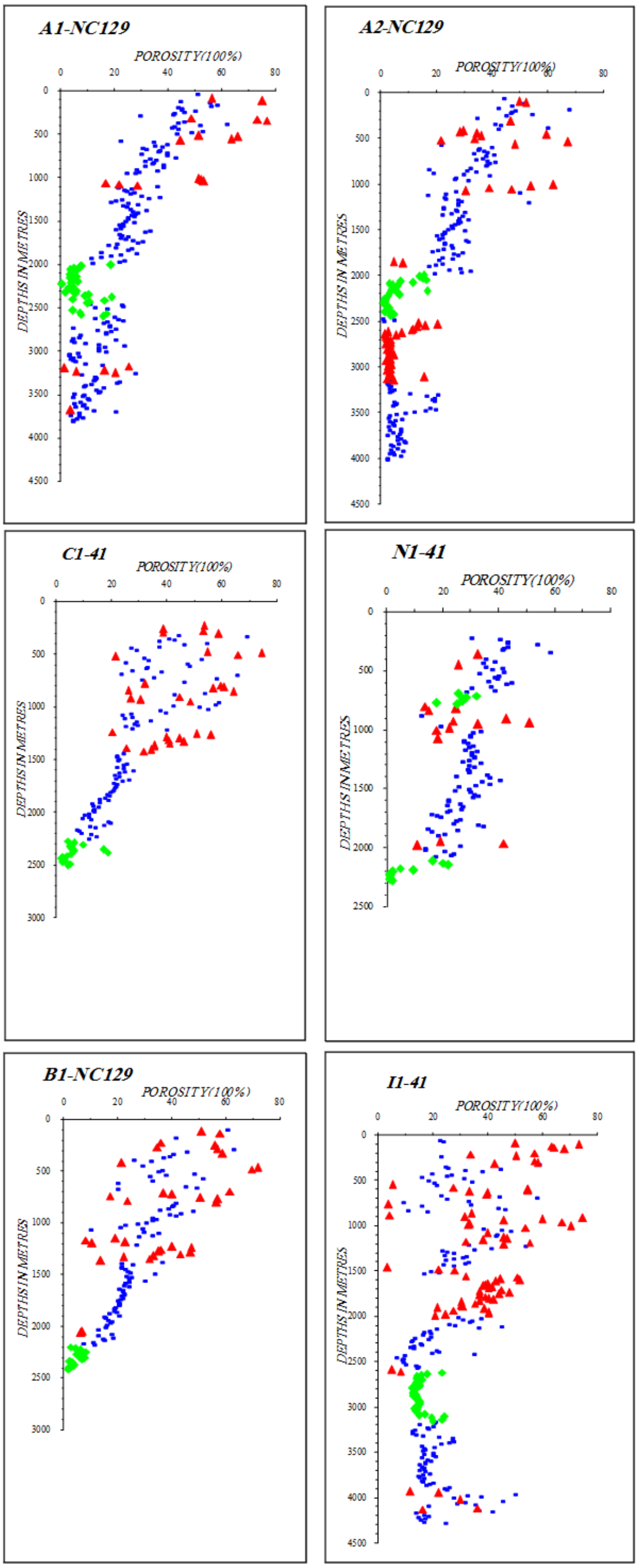

Fig. 4. Porosity versus depth plots for the composite lithological sections in wells in the Soluq Depression.

Shales: The shale intervals represent a considerable range of porosity values in the Soluq Depression. The variation in their porosity-depth relationship makes some difficulty in determining the shale porosity reduction rates. The environment in which the shale was deposited, and the response to subsequent diagenatic processes such as compaction and their resultant pressure condition, is considered to be the main controlling factors affecting the variation in shale porosity values. Also, the differences in silt content makes for a considerable variation in porosity values in shales (Schlumberger, 1974).

Dolomites: The dolomites in the investigated wells are characterised by a very narrow range of low porosity values on average of 6%. However, well I1-41 exhibits considerably higher porosity values (approximately 16%). In the investigated wells, the dolomite does not represent a rapidly decreasing rate in porosity with depth as in limestone. This may be attributed to the fact that the dolomite crystal is more resistant to the compaction process than limestone. However, the dolomite porosity in the area appears lower than the limestone porosity. Halley and Schmoker (1982) observed that in the study of Cenozoic carbonate porosity of South Florida the amount of porosity loss in dolomites is largely due to the dolomite-forming mechanism.

5. Exponential Models For Normally Compacted Rocks

Unfortunately, there is no published study on porosity analysis in the area. Consequently, the porosity-depth model in this area was not known before the present study. In order to evaluate whether the rock sequence is under- or over-compacted within the rock column through the porosity-depth relation in the studied wells, a model of normal compaction trends has been built to compare them with the observed trends .

For the equilibrium compaction condition, an exponential function has been established to represent the porosity-depth relationship. Rubey and Hubbert (1959) confirmed a general equation representing the porosity-depth relationship in normally pressured shale and mudstone, and it is written as follows:

$$\Phi_n = \Phi_0 e^{-cz} \qquad (1)$$

where: ϕ_n is the porosity at any depth of burial *z*, ϕ_0 is the average original porosity at the time of deposition, and *c* is the compaction coefficient which determines the slope of the porosity-depth curve. The constant value *c,* for each type of lithology, can be established from a number of porosity measurements. The exponential function has been fitted to the normal porosity-depth relationship in different lithologies. An exponential model of porosity, as a function of depth, is found in chalks from the North Sea (Scholle, 1977), and in limestones and dolomites of South Florida (Schmoker & Halley, 1982; Halley & Schmoker, 1982). Sclater and Christie (1980) established an exponential curve in normal pressured sections in the central North Sea for chalk, shale, sand and shaly sandstone.

In this analysis, the porosity at the time of deposition (without any compaction), and the compaction coefficient which controls the slope of each curve, are determined from the published data for each lithology type. By using equation 1, an exponential relationship between the porosity of each rock type and the depth of burial is calculated. Based on this calculation, a model for porosity as a function of depth has been constructed. The values of parameters of depositional porosity ϕ_0 and compaction coefficient c are shown in Table 1. The resulting porosity versus depth exponential fitted curves set up for limestone and shale in the investigated wells are shown in Fig. 5.

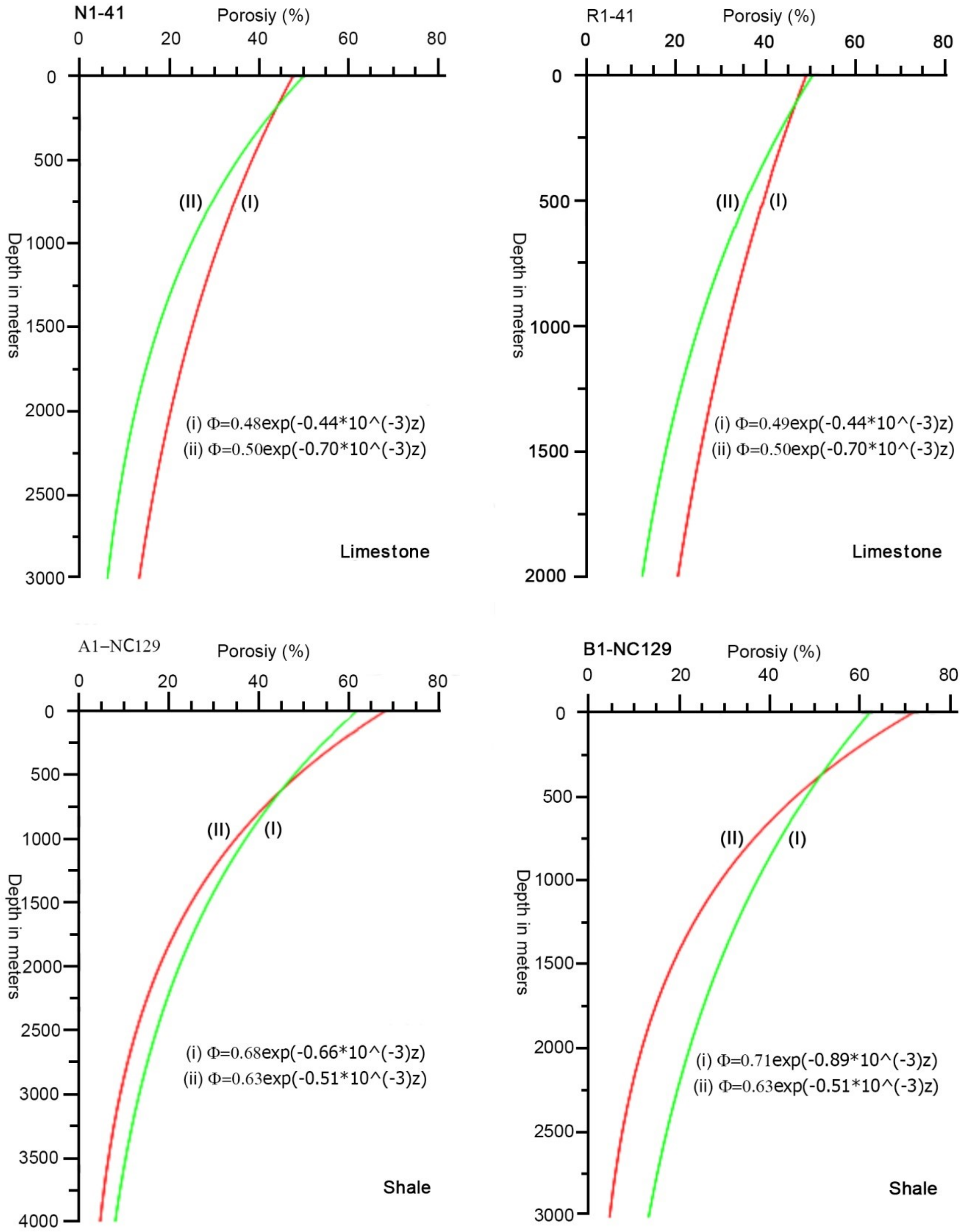

Fig. 5. The porosity-depth plots for individual lithologies; limestones, shales and dolomites, in the Soluq Depression, with the comparison of observed porosity-depth trend (curve i) with the exponential normal porosity models (curve ii). Note the different depth scale.

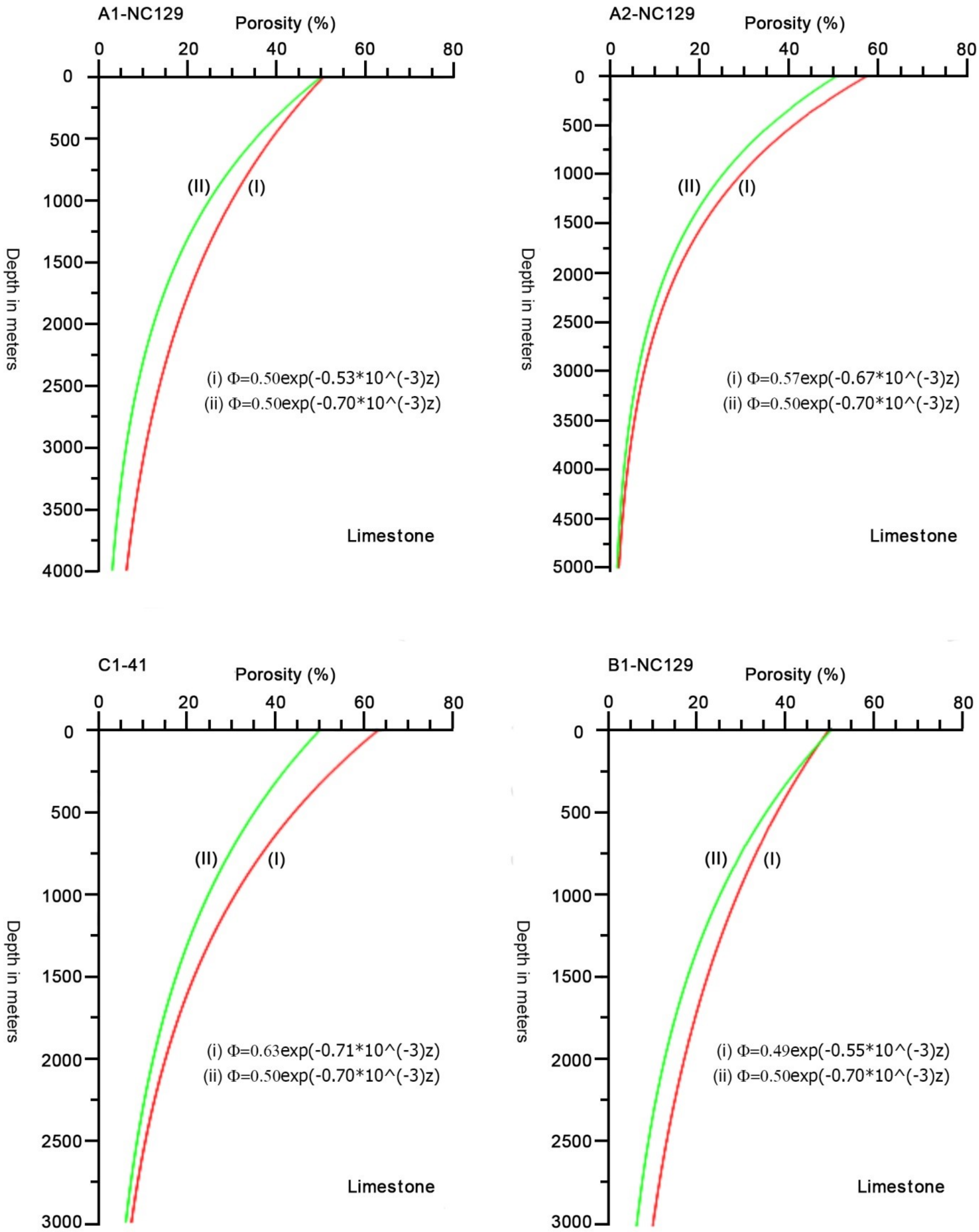

Fig. 5 continued

Table 1: Parameters used for construction of the exponential model for normal porosity as a function of depth (from Sclater & Christie, 1980 and Angevine et al., 1990).

Lithology Type	*Depositional Porosity (ϕ_0)*	*Compaction Coefficient (C)*
Limestone	50%	0.70×10^{-3} m^{-1}
Shale	63%	0.51×10^{-3} m^{-1}
Dolomite	51%	0.50×10^{-3} m^{-1}

6. Comparison Of Porosity-Depth Trend With Models

The porosity in a formation is a function of its present depth only when that depth is its maximum depth of burial. The comparison of modelled normal compaction trends with actual compaction trends can be used to quantify zones of over-compaction and under-compaction in a rock column (Magara, 1976a & b). The porosity analysis in this chapter is basically based on the comparison of the observed shale and limestone regression lines with the normal porosity-depth model. The normal porosity-depth model represents measurements on 'pure' shales and limestones, which are believed to be at their maximum depth of burial. The difference between the two curves may allow any depth of burial anomalies to be identified through the rock columns in Soluq Depression.

Fig. 5. shows plots of porosity data for individual wells in the area. In order to remove the effect of the lithology differences on the porosity-depth trend, the limestone, dolomite, and shale have been separated. These plots represent the observed porosity versus depth of burial trends, for each rock type, with their best fitted exponential curves. The observed porosity-depth curves are also overlaid by the established exponential normal porosity-depth trend for each lithology. The observed porosity-depth curves carry the symbol (i), and the model curves are carrying the symbol (ii).

In the majority of wells, there is a good match in the limestone intervals between the observed and model curves even though there is a lower correlation coefficient recorded for some wells. The shale plots show lower correlation between the two curves. The absence of a thick sequence of shale in many wells may affect the fitted observed porosity-depth curve. Dolomite zones in the most wells represent one continuous interval (see Fig. 4). The absence of any dolomite intervals at shallow depths makes curve-fitting a difficult task. The dolomites generally represent a uniform porosity-depth trend through the wells. However, dolomite porosity is not used for evaluating the compaction and overpressured sequences, because dolomite formed under different conditions and was subjected to a greater extent by diagenetic processes.

6.1 The Surface Porosities, ϕ_0 Comparison

The uppermost depositional sequences in the Soluq Depression mainly consist of limestone deposited in the Lower and Middle Miocene periods. The comparison diagrams (Fig. 5) show the surface porosity, ϕ_0, in the limestone to be very close to the average depositional porosity in the normal compacted sequence, commonly within 5%. The surface porosity of the limestone in the area is expected to show a lower value compared with the porosity at the time of deposition. This is because it is Miocene in age and may have been subjected to compaction during burial. However, the development of secondary porosity through dissolution of the limestone is very active near the surface, which acts in a direction opposite to compaction. In this case, the development of secondary porosity compensates for the loss of porosity due to compaction. Moreover, in sonic logging, usually the wells are not logged in the upper parts, and therefore the surface porosity is found only by extrapolation.

6.2 The Apparent Under-Compaction Of Lower Oligocene Sequence

The Lower Oligocene sequence shale displays a higher observed porosity value when compared with the normal compaction trend for the majority of the wells in the area. Fig. 6 shows the porosity-depth plots of the Lower Oligocene shales in selected wells. Anomalously high porosity has been noticed near the upper boundary of the sequence. Above this boundary the porosity values decrease again to approximate the normal compaction trend throughout the sequence. In these wells, relatively low porosity values have been observed in the Upper Oligocene sequence. In well M1-41, the Upper Oligocene sequence represents a slightly low interval velocity (El-Shari,2005a). However, well data show that shallow marine fossiliferous limestone is the predominant lithology in the sequence (El-Shari, 2008). Secondary porosity in this interval may constitute a significant part of the total porosity. Therefore, the sonic log may reflect in lower porosity than the real formation porosity, by ignoring the secondary porosity effects.

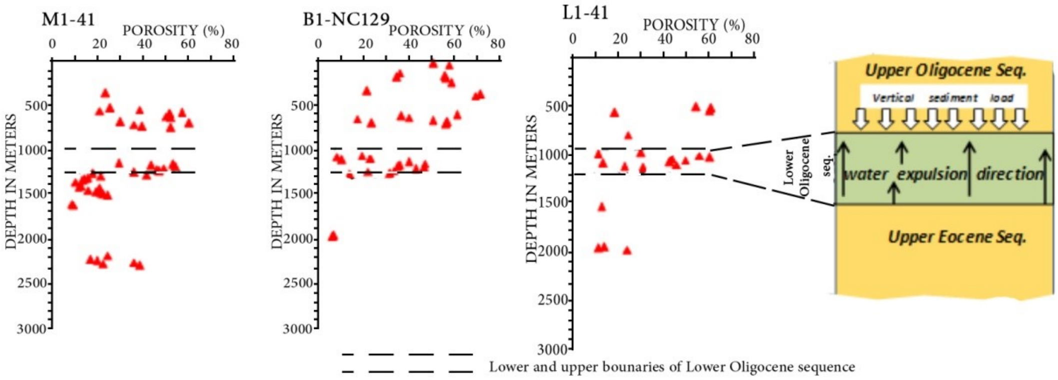

Fig. 6. Porosity-depth plots of shale of the lower Oligocene Sequence in wells M1-41, B1-NC129 and L1-41, with possible explanation of the high porosity values in the sequence.

The observed porosity anomalies in the Lower Oligocene shale sequence may be attributed to the mechanism of bound water expulsion after deposition. The amount of water expelled from the sediment, due to mechanical compaction, affects the porosity distribution in the rock column. If a thick shale sequence has reached a normal compaction condition, but an additional load of sediment is deposited above this sequence, a higher pore-pressure is developed. The compaction is continuous from the lower part to the upper part, with expulsion of the pore water until the normal compaction condition is again reached. Magara (1976a) studied the movement of the expelled water during sedimentation in the Tertiary sequence in the Gulf Coast area, and constructed models to determine the movement direction of pore water in interbedded sand-shale and massive shale sequences. He concluded that the main direction of water movement in the thick continuous shale is vertically upward. In the equilibrium condition, the compaction of the sediment is increased if the pore water can escape from the sediment, i.e. if there is sufficient permeability. In the case of no or little permeability, increasing pore pressure will occur to support the extra vertical stress, i.e. the horizon becomes overpressured. Rubey and Hubbert (1959) suggested that under conditions of extremely rapid loading, the fluid pressure-overburden ratio increases with depth when the rate of escape of pore water is negligible compared with rate of application of new sedimentary load.

In the Lower Oligocene sequence, the pore water may have moved from a higher-pressure zone at the base of the shale sequence to the upper parts. There will be no significant water expulsion, if it is prevented from escaping by the rapid deposition of the overlying thick continuous limestone of the Upper

Oligocene sequence. In a backstripping analysis, the sediment accumulation rates calculation (Elshari, 2005b), indicate a high sedimentation rate during Late Oligocene time. This process causes the lower section of the Lower Oligocene sequence to lose a significant part of its porosity and thus become more compacted and consolidated than the upper part.

7. Discussion and Conclusion

In this study, porosity analysis was undertaken to evaluate and analyse the history of deposition of the sedimentary sequences in the Soluq Depression. An identification of under- and over-compacted sequences in the area was also undertaken. The porosity-depth plots of the composite sections and individual lithologies generally follow published model trends. However, the observed surface porosity, and subsurface values, in the area represent higher values than would be expected of a rock deposited in the Middle Miocene. A reasonable explanation of the higher porosity in this interval may the development of secondary porosity through the dissolution of limestone, which is usually very active near the surface. The development of secondary porosity compensates for the loss of porosity due to compaction in the subsurface.

The observed porosity-depth trend correlates closely with the normal ideal compacted sequence of each lithology type. In the limestone porosity plots, both curves are in good agreement. The close match between the actual data trend and the model generally indicates normal compaction in the rock column. This result suggests that there has been no significant uplift and no deep effective erosion that might have created abnormal pressure zones in the rock column. Therefore, one of the most important and significant conclusions that are drawn from this analysis is that the results encourage the use of the published porosity-depth curves for the purpose of decompaction in any backstripping analysis.

Positive porosity anomalies relative to model trends are observed in the Lower Oligocene sequence in some wells, and reflect an overpressured zone in the sequence. The porosity values in the sequence show a slightly high porosity near the upper boundary of the sequence, higher than a normal compaction trend. This higher porosity value can be explained as being due to the expulsion of pore water during deposition, which has moved from a zone at the base of the shale sequence to the upper part of the sequence. The overpressure ultimately develops when the pore water in the rock is sealed in at the top of the formation. The rock is unable to compact because the pore water cannot escape at the same rate as load is added to the overburden of the rock. The additional load is supported by pore water, and a pressure higher than hydrostatic pressure occurs. The rapid sedimentation of the Upper Oligocene limestones may be responsible for termination of the water expulsion from the pore spaces in the Lower Oligocene shale sequence.

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