INTERPRETATION OF DEPOSITIONAL FACIES AND RESERVOIR ROCK QUALITY FROM BOREHOLE, LOGS, SAN ANDRES DOLOMITE, NEW MEXICO

by

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ABSTRACT

The Permian San Andres Formation in three cored wells in the Twin Lakes and Cato fields, New Mexico is composed of five vertically stacked tidal flat sequences. An individual tidal flat sequence consists of evaporite (anhydrite) at the top, followed by supratidal (dolomite, anhydrite and mixtures of anhydrite and dolomite) and subtidal (dolomite or limestone) at the bottom.

The core study shows that dolomite and anhydritic dolomite are the reservoir rocks. Marine and some intertidal dolomites are the most porous and permeable. Porosity is intercrystalline with or without vugs.

Comparison of lithology, porosity, Archie porosity types in the cores with sonic, density, neutron and gamma ray borehole logs shows that lithology, vuggy porosity and tidal flat sequence may be determined from log response alone in the San Andres rocks. Vuggy porosity can be estimated from the reponses of the sonic log compared with that of the density or neutron log. Vuggy dolomites will have an Archie m (cementation exponent) value higher than 2. Calculation of water saturation will be too low and oil and gas calculations too high if the standard value of m = 2 is used in calculations in vuggy intervals.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to the many people who helped make this study possible. I wish to thank Dr. Wayne Ahr for his encouragment and critical review. I also wish to express sincere appreciation to Dr. Denny Loren and Robin Huber of Loren and Associates Inc. for their help in the log interpretations. I wish to give a special thanks to Ramona Sneider for her guidance, critical review and help in typing this paper, and Robert Sneider for his critical review, technical guidance and inspiration. I am grateful to Pelto Oil Company and Shell Oil Company for allowing me to use their cores.

DEDICATION

To my mother and father, who have given me strength and encouragment throughout my life.

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Introduction

Geographic Location of Study Area

The study area is in Cato and Twin Lakes fields in southeast New Mexico, near the Slaughter-Levelland oil field of the Texas panhandle which produces from a stratographically equivalent interval (Figs. 1 & 2).

Stratigraphic Setting

The San Andres Formation is Permian in age (Fig. 3); its rocks are the oldest in the Guadalupian Series. The San Andres is about 1150 feet thick and is overlain by clastic and evaporatic beds of the Artesia Group and is underlain by clastic and evaporite beds of the Yeso Formation. In the study area, the upper part of the San Andres Formation consists mainly of anhydrite and salt. Kelley (1971) divided the San Andres into three members (Fig. 3). The uppermost member, the evaporitic part of the San Andres is the Fourmile Draw Member. This member corresponds to the interval in the subsurface above the so-called P-1 zone. The next lower unit Kelley designated the Bonney Canyon Member, which corresponds to the subsurface P-1 and P-2 zones (also called Slaughter-Levelland zone). Kelley's lowest member is the Rio Bonito, which usually corresponds to the San Andres between the P-3 and the top of the Leonardian, Glorieta Sandstone Member.

The lower San Andres consists of four rock types (lithologies) that range from 40-150 feet in aggregate thickness. The lowermost unit, a thin shale or shaly carbonate bed from 3-10 feet thick, represents the beginning of a depositional cycle. The next unit is a fossiliferous limestone which ranges from 10-50 feet in thickness. The third, or next

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The citations on the following pages follow the style of the American Association of Petroleum Geologists Bulletin.

highest unit is dolomite which is often porous. The uppermost unit in the cycle is an evaporite. The evaporite is anhydrite in the central eastern area of New Mexico but changes to halite to the north. The cycles may be incomplete and commonly may have an evaporite present in the middle.

In the study area, the lower San Andres is composed of five vertically stacked depositional cycles. They are designated from top to bottom as P-1, P-2, P-3, P-4 and P-5. Each cycle represents a shallowing-upwards sequence from a subtidal environment through intertidal and to supertidal (Fig. 4).

North of the area of interest, the P-1 and P-2 consist of anhydrite and salt; southward of this area, anhydrite and salt decrease in abundance, and the amount of dolomite and limestone increases. This is illustrated in figure 4.

The original carbonate deposited was limestone. Dolomite was formed by early secondary processes probably shortly after the original limestone deposition. F. J. Lucia (1972) claims that extensive early dolomitization is characteristic of an evaporitic shoreline.

Structure

The structure on the base of the San Andres in the region containing the Twin Lakes and Cato fields strikes north-south to north-northeast and dips gently eastward at a rate of 40-60 feet per mile or about 1/2 to 2/3 degrees (Fig. 2).

Structural closure in the Slaughter-Levelland-Cato trend is usually minor with maximum closure on the top of the P-1 of 25-30 feet. Hydrocarbon entrapment is generally controlled by porosity and permeability pinchouts updip to the north. This porosity pinchout condition results in part from infill of some of the porosity by secondary anhydrite.

Definition of the Problem

In many fields, like the Twin Lakes and Cato, all wells have borehole logs, but few wells are cored or have cuttings. The objective of this project is to determine if it is possible to determine depositional facies and reservoir rock quality (porosity, permeability and pore type) from logs or a combination of logs and cuttings in the San Andres dolomite reservoir.

Methods and Approach

Cores

Cores from three wells were examined to determine rock texture, composition and sedimentary structure. The Dunham Classification (1962) was used to describe textures and the Archie Classification (1952) was used to describe porosity type and estimate percent porosity.

Logs

Porosity was calculated and the rock types were determined using the methods described in AAPG Basic Well Log Analysis for Geologists by Asquith & Gibson (1982). The reason it is possible to use the sonic, density and neutron logs to determine lithologic rock type, porosity and porosity types is because of the different manner in which each logging tool responds to anhydrite, dolomite and limestone. A combination of the neutron and density logs can identify limestone characterized by a low density (2.75 gm/cc or less). The neutron and density combination cannot distinguish dolomite from anhydrite (both have high density); but, the sonic transit time of anhydrite is much greater than that of dolomite. A comparison of the sonic log response with the density or neutron log response will distinguish dolomite from anhydrite.

The core examination showed that the reservoir rock is dolomite. Because the San Andres consists of mixtures of rock types dominated by dolomite, dolomite was used as the "standard" matrix in the borehole logs, and the lithologies and porosity types were determined by examining combinations of sonic, neutron, density and gamma ray log responses.

When anhydrite is present, porosity calculated from the density and neutron log is nearly zero, but the porosity calculated from the sonic log is about 4%. This discrepancy exists because it is assumed in the calculations that the matrix is pure dolomite with an interval transit time of 43.0 microsec/ft. Because the matrix is not pure dolomite, the sonic log porosity is incorrect. This is further illustrated in the following example:

If one assumes that the interval transit time from the sonic log reads 50.0 microsec/ft and t_{fluid} = 189.0 microsec/ft, then one may use the "sonic porosity" equation shown below:

$$\phi_{sonic} = \frac{\Delta t_{log} - \Delta t_m}{\Delta t_f - \Delta t_m} \text{ X } 100$$

where:

ϕ_{sonic} = sonic derived porosity (%)

Δt_m = interval transit time of the matrix (microsec/ft)

Δt_{log} = interval transit time of formation (microsec/ft)

Δt_f = interval transit time of the fluid in the well bore (microsec/ft)

as it has been assumed that the rock matrix is dolomite:

$$\phi_{sonic} = \frac{50.0 - 43.0}{189 - 43.0} \text{ X } 100 = 4.8\%$$

However the calculation should be:

$$\phi_{sonic} = \frac{50.0 - 50.0}{189 - 50.0} \text{ X } 100 = 0\%$$

The density (ρ) for anhydrite is 2.977 gm/cc whereas the ρ for dolomite in the San Andres is 2.85 gm/cc. If the density of the borehole fluid is taken as 1.0 gm/cc. The equation for porosity (ϕ) from the density log is:

$$\phi_{\rho} = \frac{\rho_m - \rho_{bulk}}{\rho_m - \rho_f} \text{ X } 100$$

where:

ϕ_ρ = density derived porosity (%)

ρ_m = matrix density (gm/cc)

ρ_{bulk} = formation bulk density (gm/cc)

ρ_f = fluid density (gm/cc)

Choosing dolomite density instead of anhydrite will lower porosity as dolomite has been assumed to be the matrix:

$$\phi_\rho = \frac{2.85 - 2.90}{2.85 - 1.0} \text{ X } 100 = -2.7\%$$

the matrix is really anhydrite, the calculation should read:

$$\phi_\rho = \frac{2.977 - 2.90}{2.977 - 1.0} \text{ X } 100 = 3.9\%$$

The Schlumberger charts (Fig. 5) indicate that a neutron log will read 1% porosity for a dolomite that would read 3% porosity if it were an anhydrite; therefore, the sonic derived porosity in anhydrite reads high and neutron and density derived porosity values are low. The presence of anhydrite can therefore be determined by the "shift" to the left of the porosity calculated from the sonic log (higher) and a "shift" to the right (lower) of the porosity calculated from the density and neutron logs (Fig. 6).

The presence of limestone can be determined from borehole logs by making similar assumptions. There is an increase in the porosity calculated from the sonic log when compared to the porosity calculated from the neutron log. In the limestones, the observed porosity from the neutron log is about 2% and the porosity from the sonic log varies between 4-6% (Fig. 6).

The presence of dolomite can be determined with logs in the same fashion; but, porosity calculated from the logs are more accurate because dolomite is used as the "standard" rock type.

Separate vugs and intercrystalline porosity can be distinguished by using the sonic log with either the neutron log or the density log. The porosity calculated from the sonic log will be less or shifted to the right of the porosity calculated from the neutron and density logs (Fig. 6). This separation of the porosity derived from the sonic log and the porosity derived from the neutron log and density log corresponds with areas of abundant moldic porosity in the intertidal and marine facies. Separate vugs are associated with high m (cementation factor) values and are the only factor besides gypsum that shifts the porosity from the sonic log to the right (lower porosity) (Traugott, 1970). No gypsum was found in any of the cores examined.

The m value is defined in Archie's equation:

$$\frac{R_o}{R_w} = \phi^{-m}$$

where:

R_o = resistivity of the formation 100% water saturation (ohm-meters)

R_w = resistivity of the formation water (ohm-meter)

ϕ = porosity (%)

m = cementation exponent

The value of m ranges from 1.7 to 3.0 in the Cato field according to Traugott (1970). Higher m values are associated with separate vugs. The m value can be estimated in two ways.

The method described by M. Traugott (1970) uses the sonic log and the sidewall, neutron porosity log. The interval transit time from the sonic log is lain over the prosity from the neutron log. The reading on the sonic log is aligned such that 44.0 microsec/ft is equal to the 0% porosity on the neutron log (assuming a limestone matrix). The deviation of the sonic log readings to the right of the neutron log then directly indicate intervals which contain vuggy porosity. The porosity from the neutron log and the amount of "separation" of the logs can be used to read the appropriate m value from figure 7.

The second method to calculate m values uses the ratio of vuggy porosity to the total porosity called the "vug porosity ratio" (Lucia, 1983). The amount of separate vugs can be estimated visually or calculated using borehole logs. Using the vug porosity ratio the m value can be read off figure 8. The m value can also be calculated directly using the equation of this curve:

$$m = 1.9272236 * e^{0.006977 * \left(\frac{\phi_{vug}}{\phi_{primary}}\right)}$$

where:

m = cementation exponent

ϕ_{vug} = vuggy porosity

$\phi_{primary}$ = intercrystalline porosity

Calculation of water saturation (Sw)

Water saturation is indirectly affected by changes in m. From Archie's equation, Ro can be calculated. An increase in the m value causes an increase in Ro. Because Ro is used to calculate Sw in the equation:

$$Sw = \left[\frac{R_o}{R_t}\right]^{1/n}$$

Sw = water saturation

R_o = resistivity of formation with 100% water saturation (ohm-meters)

R_t = resistivity of formation with less than 100% water saturation (ohm-meters)

n = saturation exponent (most commonly 2)

Increases in Ro are paralleled by increases in Sw; consequently, an increase in the m value will apparently increase the Sw value.

Discussion

Core interpretation

Three cores were examined in this study:

Stevens Oil #7 Citgo State, Twin Lakes Field, Chaves Co., New Mexico
Shell #1 Hodges Federal, Cato Field, Chaves Co., New Mexico
Shell #1-B Hodges Federal, Cato Field, Chaves Co., New Mexico

The lithologies of the cored intervals in the San Andres are anhydrite, dolomite, mixtures of anhydrite and dolomite, and limestone. From the core study and the literature, the San Andres is interpreted to be a tidal flat sequence in the Twin Lake and Cato fields. The tidal flat sequence can be readily divided into four subfacies; the evaporite or sabka, the supratidal, the intertidal, and the subtidal or marine facies (Fig. 9). The subfacies in the depositional cycles of the tidal flat sequence are easily recognized in the cores based on the following depositional sequences and lithologies:

The evaporite or sabka facies is formed in an environment that is only rarely covered with water, but the water that does cover it evaporates leaving behind salt, gypsum or anhydrite. The evaporite facies in the cores studied are composed of almost pure massive anhydrite with a little organic material and minor dolomitic mudstone. The anhydrite has a distinctive nodular texture, making it easy to identify.

The supratidal facies is formed in the region above the normal high tide but is covered by water during storms. The supratidal facies is characterized by well laminated dolomite with abundant anhydrite nodules. The laminae may be algal in origin. The supratidal facies are also characterized by thin interbedded anhydrite zones and by intraclasts of dolomite mudstone.

The intertidal facies is formed in the zone that is covered by the normal high tide and exposed during the normal low tide. It is characterized by dolomitic mudstone to packstone with sparse anhydrite and with well to poorly developed laminations and moderate amounts of burrowing. The uppermost intertidal zone exhibits well laminated beds with some burrows, discontinues laminae and anhydrite infill. Towards the subtidal, the laminae are discontinuous, and the rock is more burrowed. The amount of anhydrite decreases toward the subtidal facies. The intertidal zone is characterized by vuggy porosity that may be infilled with anhydrite.

The subtidal, or marine facies, is formed in the environment that extends seaward from the low tide level. This zone is characterized by highly burrowed dolomitic mudstones to packstones and fossiliferous lime wackestones to packstones. The dolomite is not laminated and has a moderate to high porosity (up to 20%) and commonly contains vuggy and moldic porosity. The limestone has low effective (intercrystalline) porosity. The limestone is usually highly fossiliferous, with most of the fossils having been dissolved to form separate molds. The limestone is probably associated with the deeper marine waters away from the region of dolomitization.

Archie Rock Descriptions

Small pieces of the cores also were described using the Archie pore type classification (Archie, 1952). Rocks in the marine and deeper intertidal zones are predominately fine to very fine crystalline Type III rock. (Crystals or particles are interlocked at different angles allowing for porosity between crystals and these rocks appear sucrosic (sugary) or granular.) Vugs less than 2.0 mm in diameter are also present.

Archie Type I rock (matrix made up of tight interbedded crystals with no visible pores between the crystals) is also found. The amount of Type I rock increases toward the supratidal facies because anhydrite infills the visible pores and cements the rock.

The reservoir rocks are zones of higher porosity and correlate with Type III rock. These rocks are dolomite or slightly anhydritic dolomite. Porosity estimates using the Archie technique closely follow laboratory measurements of porosity of the cores. The best reservoir rock is found to have about 15-18% porosity and permeability of up to 50 md in the Twin Lakes field. In the Cato field, the reservoir has up to 20% porosity and 120 md. permeability.

Porosity in the San Andres in eastern New Mexico and west Texas is facies controlled. Good quality reservoir rock occurs in the lower intertidal and marine dolomites as intercrystalline porosity with or without vugs.

San Andres porosity has been severely affected by diagenetic alteration. Porosity seems to have been created by dolomitization of lime mud. Anhydrite infill has reduced some of the porosity in the dolomites observed in the study area.

Log Interpretation

Two main zones of porosity in the San Andres can be determined using logs. They are the P-1 (uppermost) and the P-2 (lower) zones which are analogues to the Slaughter-Levelland reservoir zones in west Texas.

A combination of the gamma ray, neutron, density and sonic logs can be used to distinguish rock type, porosity type, P-1 Zone from P-2 Zone, and the environment of deposition. Assumptions for coefficients used in the log calculations have been picked because they fit lab data and are listed in the appendix.

The P-1 and P-1 zones can be distinguished by the more regular gamma ray response for the P-1 zone than the P-2 zone. The most distinctive characteristic to distinguish the P-2 zone is a large gamma ray "kick" at the base of the P-2 zone (Fig. 6).

The evaporite or sabka facies is the easiest to distinguish. The anhydrite sabka facies porosity calculated from the sonic log (assuming a dolomite matrix) gives a porosity of about 4%. Porosity determined from the neutron log, calibrated, for dolomite, shows that that anhydrite with an "actual" porosity of about 3% will "read" 0-1% porosity on the dolomite scale. The evaporite facies can easily be distinguished as seen in figures 10 & 11.

The supratidal facies can be distinguished by its low (1-3%) porosity readings by all logs (Figs. 10 & 11). The sonic log may indicate a porosity slightly higher than that indicated on the neutron and density logs because of the "distortion" due to the presence of anhydrite.

The intertidal facies is characterized by both low porosity dolomite and high porosity dolomite. The porosity indicated by the sonic log may be slightly higher for some of the lower porosity zones because of the presence of anhydrite. In higher porosity dolomites, vuggy porosity is identified by a separation (departure) of the calculated porosities determined from two different logs. That is, the porosity indicated by the sonic log will be less than that indicated by the neutron and density logs. The difference in the porosity calculated from the sonic log and that from the neutron log or density log will equal the amount of vuggy porosity (Figs. 10 & 11).

The marine facies is characterized by moderate to high porosity dolomite often with vuggy porosity present or by tight, fossiliferous limestone (Figs. 10 & 11).

It is very difficult to distinguish marine dolomite from porous intertidal dolomite using logs alone. The location of the dolomite in the tidal flat sequence or juxtaposition with limestone can be used to distinguish marine dolomite from intertidal dolomite.

Limestone exhibits a characteristic sonic log trace from which a higher porosity value is calculated than that determined by calculations based on the neutron log. The anomalously high porosity can be confused with the anhydritic zones because the sonic log derived porosity there is also about 4%. The neutron log derived porosity is not zero as it is with anhydrite; but it remains at about 2% in the limestone zone. The density log may be used to distinguish anhydrite from limestone. In limestone, the density log indicates anomalously high porosity in the same way as the sonic log. In anhydrite, the density log will indicate zero porosity along with the neutron log. The gamma ray reading in limestone will be higher than it is in anhydrite (Figs. 10 & 11).

Water Saturations (Sw)

Water Saturation is the percent of the pore volume in a rock which is occupied by formation water. Water saturation is important because the hydrocarbon saturations of a reservoir can be determined by subtracting the water saturation from the value, one (where 1.0 = 100% Sw).

In general, water saturations in the P-1 zone tended to be lower than the water saturation in the P-2 zone.

In zones with a high percentage of vuggy porosity, water saturations calcuated assuming m=2 were as much as 40% too low when compared to Sw calculated using higher m values associated with vuggy porosity (Fig. 12). When calculating Sw in vuggy rocks, it is important to take into account the higher m value or the Sw will be too low.

Conclusion

In the Twin Lakes and Cato fields, the San Andres Formation in the three cored wells is composed of anhydrite, dolomite, mixtures of dolomite and anhydrite and limestone.

The San Andres cores are interpreted to be vertically "stacked" tidal flat sequences. Individual sequences consist of (from the top downwards) evaporite (anhydrite); supratidal (dolomite, anhydrite and mixtures of anhydrite and dolomite), intertidal (dolomite and anhydritic dolomite) and subtidal or marine (dolomite or limestone).

Dolomite and anhydritic dolomite are the reservoir rocks as determined from core analyses and Archie porosity classification of core chips. The porosity is intercrystalline (sucrosic) with or without vugs and its distribution is controlled by facies patterns. Marine and intertidal dolomite are the most porous and permeable facies.

Comparison of lithology, calculated porosity values and pore types in the three cored wells along with sonic, density, neutron and gamma ray borehole logs shows that it is possible to identify lithology, vuggy porosity and depositional environment from log response alone. One may determine lithology, porosity and pore types from a combination of the sonic, density and neutron logs by capitalizing on the different way in which each log responds to these features.

From a combination of borehole porosity logs and described pore types from rock cuttings, it may be possible to predict the spacial distributions of depositional facies in the San Andres Formation. Permeability can be inferred from borehole logs by comparing porosity and pore type to rocks of similary porosity and pore type of known permeability.

Using the standard value of $m = 2$ in zones with vuggy porosity will affect the water saturation (Sw) calculations so that the calcualted Sw will be too low with the consequence that the calculated amount of oil and gas will be too high. By estimating the value of vuggy porosity present using borehole logs, the correct value of m can be found by using the method of Lucia (1983) or Trauggot (1970).

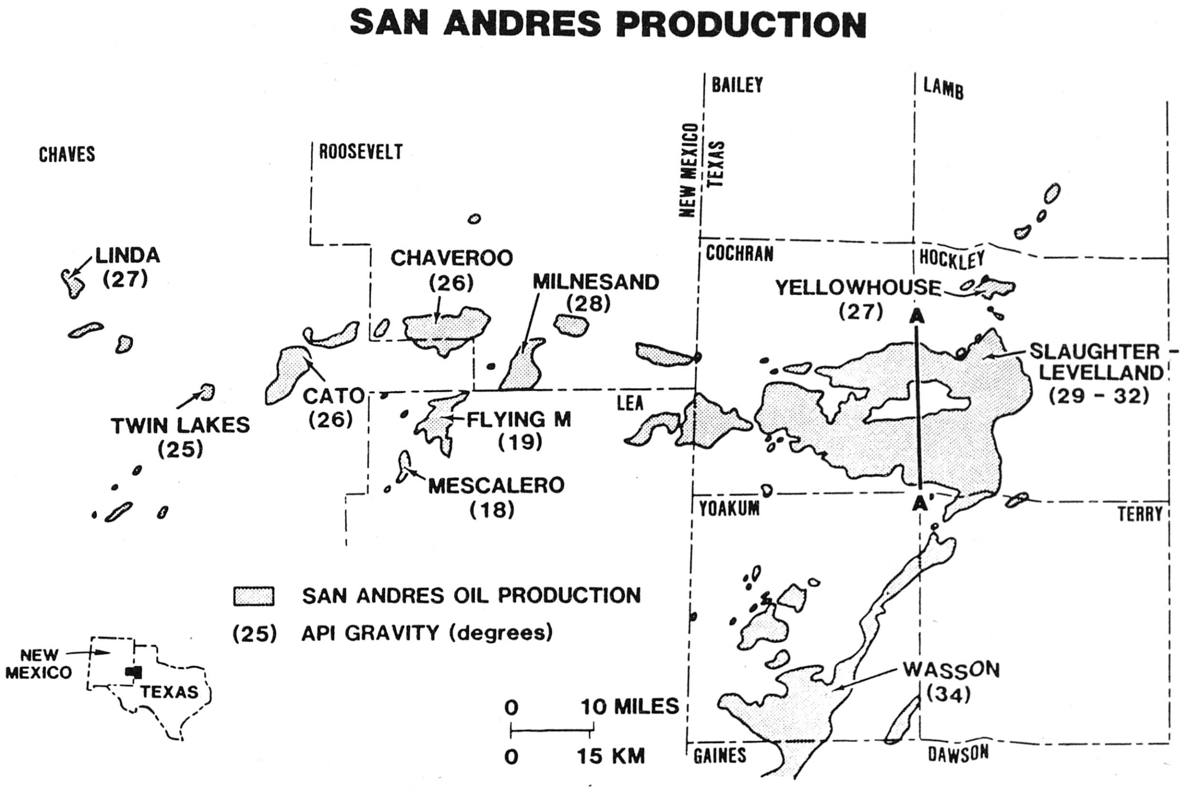
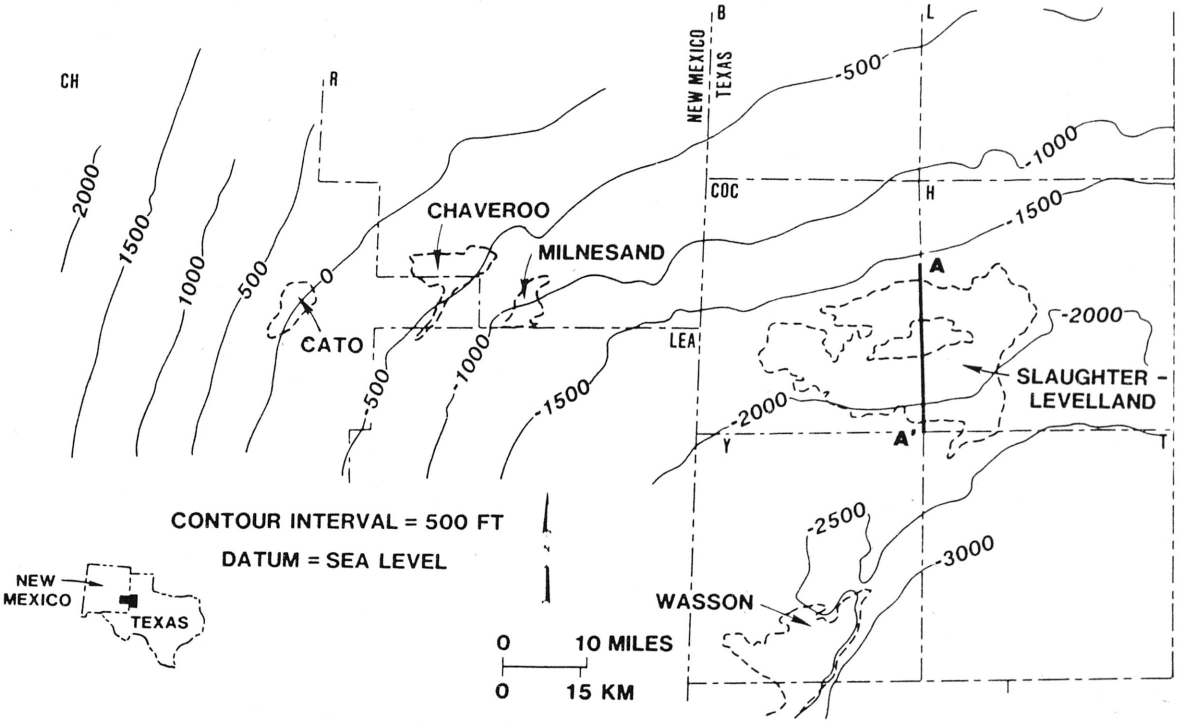


Figure 1 - Map of study area and San Andres production. (After Sneider, 1985.)



STRUCTURE MAP, BASE OF SAN ANDRES FORMATION

Figure 2 - Structure map of the San Andres Formation in the study area. (After Sneider, 1985.)

PERMIAN (248 mybp - 286 mybp)

- **Ochoan Series**
- **Guadalupian Series**
  - **Salado-Castile Fm**
  - **Seven Rivers Fm**
  - **Queen Fm**
  - **Grayburg Fm**
  - **San Andres Fm**
    - **Fourmile Draw Member**
    - **Bonney Canyon Member**
    - **Rio Bonito Member**
- **Leonardian Series**
- **Wolfcampian Series**

Figure 3 - Time units of the Permian Period.

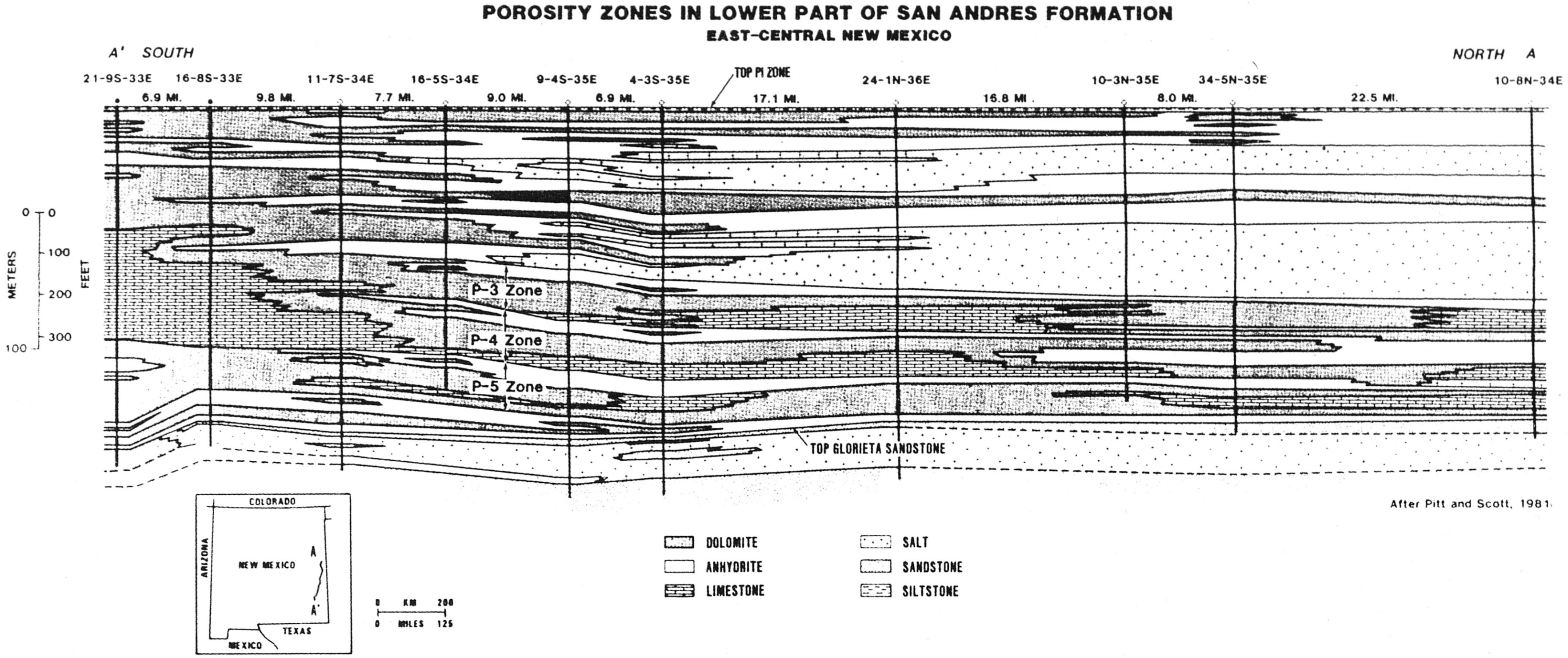


Figure 4 - Cross section showing the porosity zones and the increase of salt and anhydrite to the north. (After Pitt and Scott 1981.)

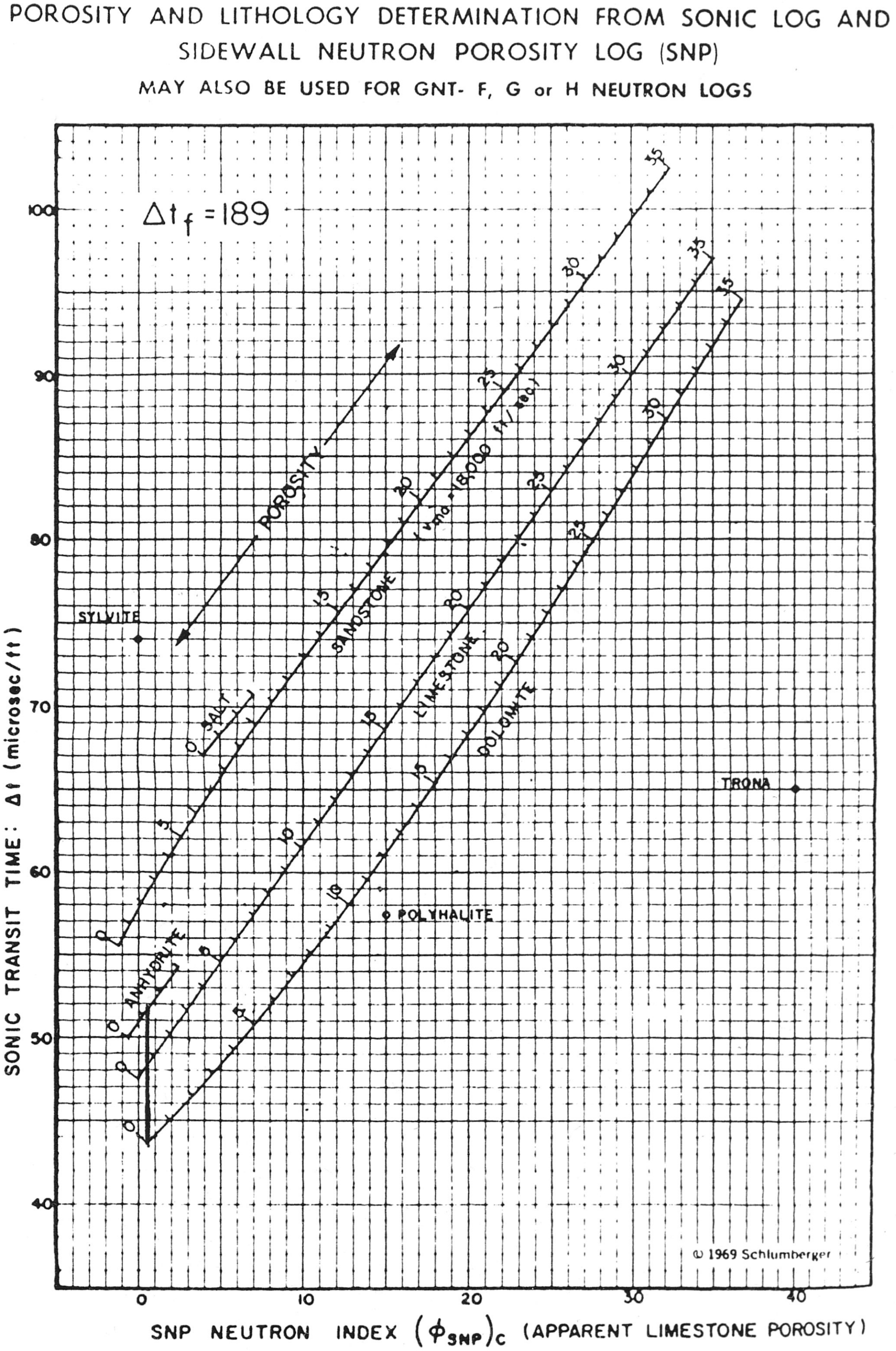


Figure 5 - Schlumberger chart showing the relationship between sonic transit time and SNP neutron index calibrated for limestone. Heavy line illustrates the affect of assuming dolomite in an anhydrite zone. (After Schlumberger, 1969.)

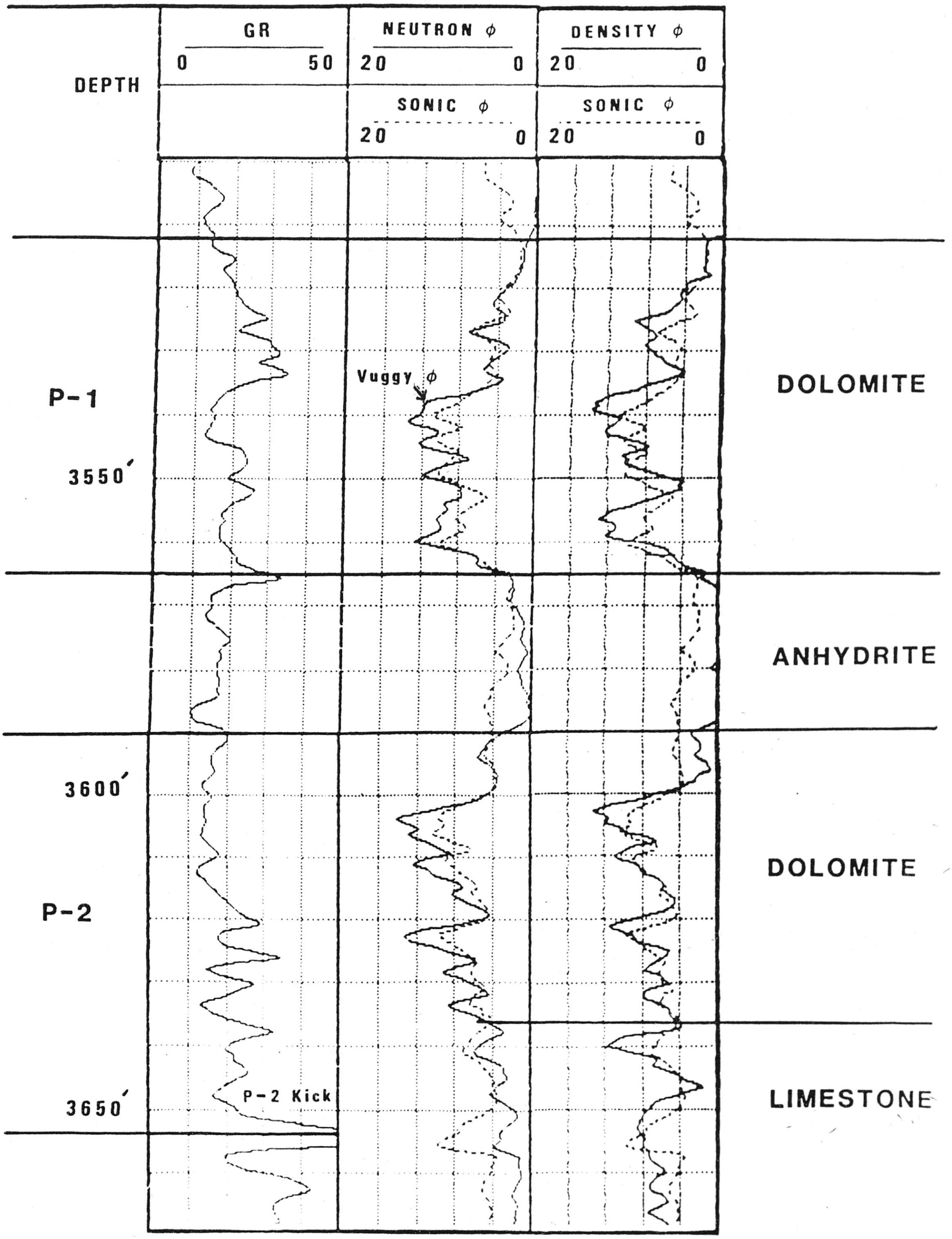


Figure 6 - Comparison of the neutron, sonic and density derived porosities and the gamma ray log to the P-1 and P-2 zones, the rock type and porosity type.

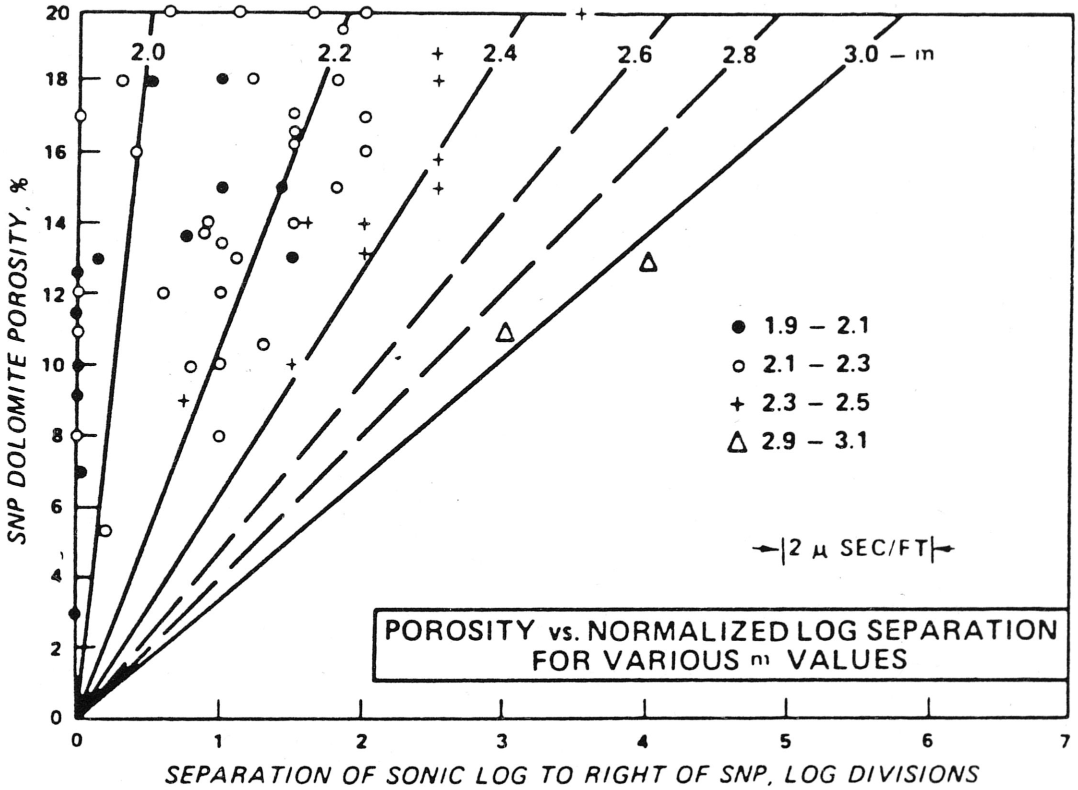


Figure 7 - Graph to find the value of m using the Traugott method. (After Traugott, 1970.)

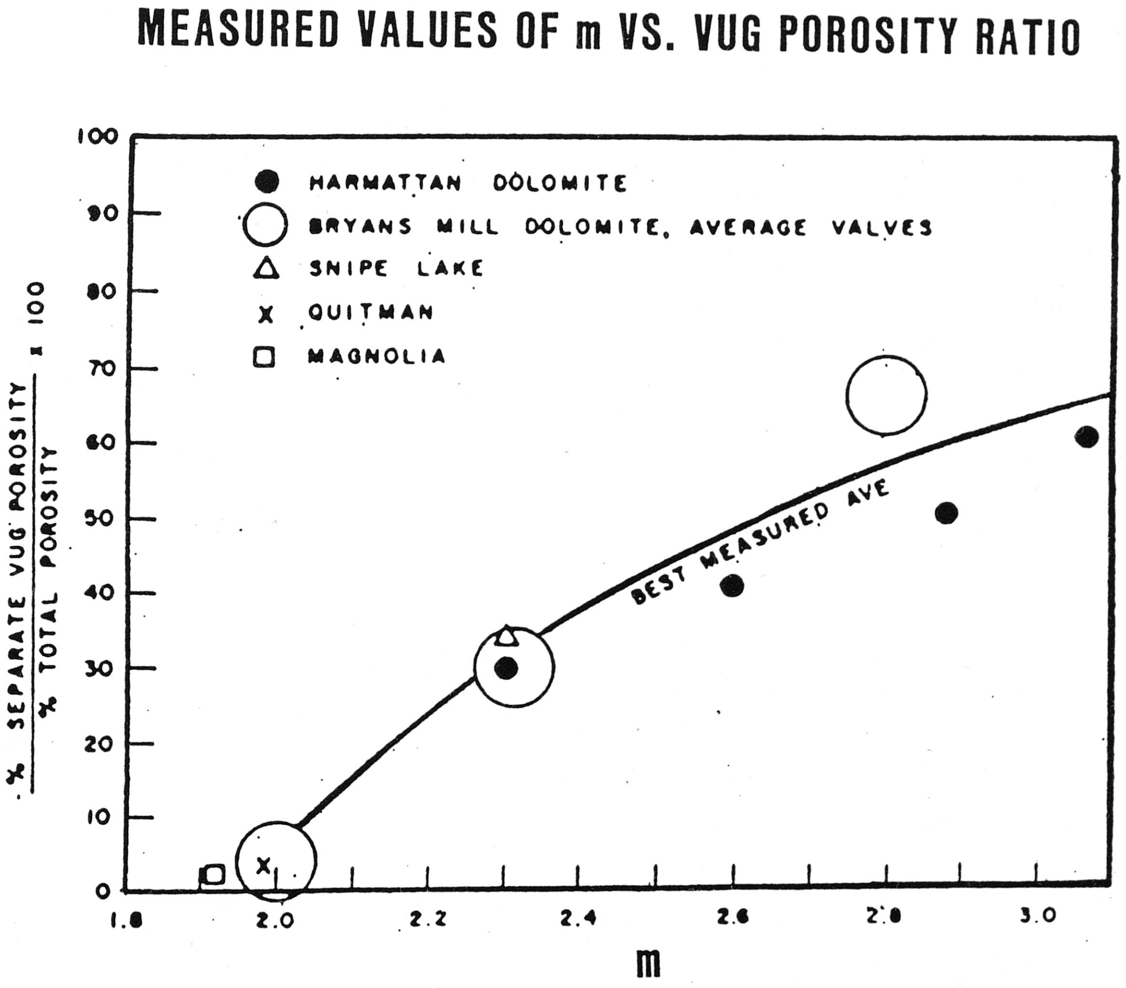


Figure 8 - Graph to find the value of m using the Lucía method. (After Lucia, 1983.)

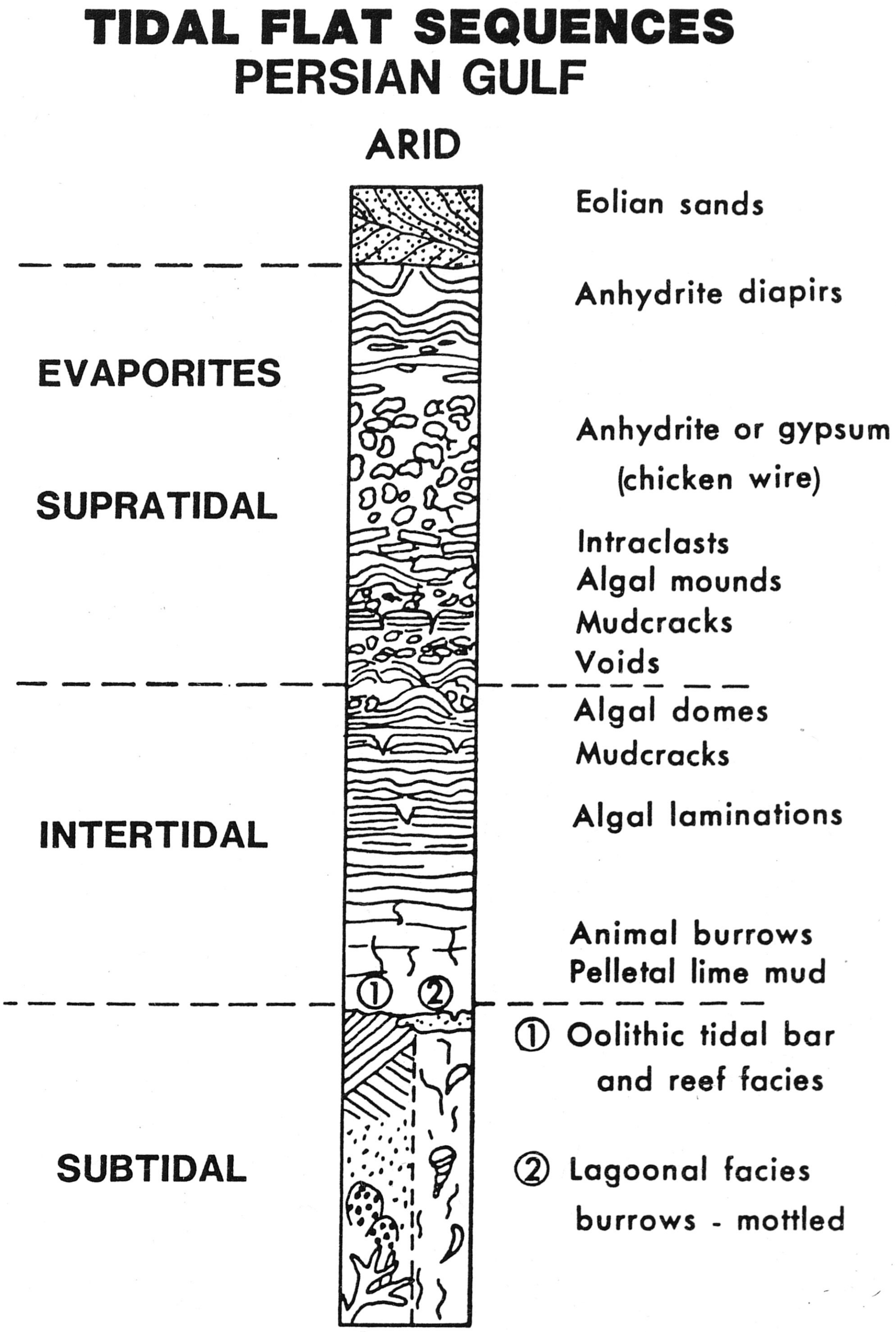


Figure 9 - Typical tidal flat sequence in an arid environment. (After Sneider, 1985.)

SHELL #1 Hodges Federal

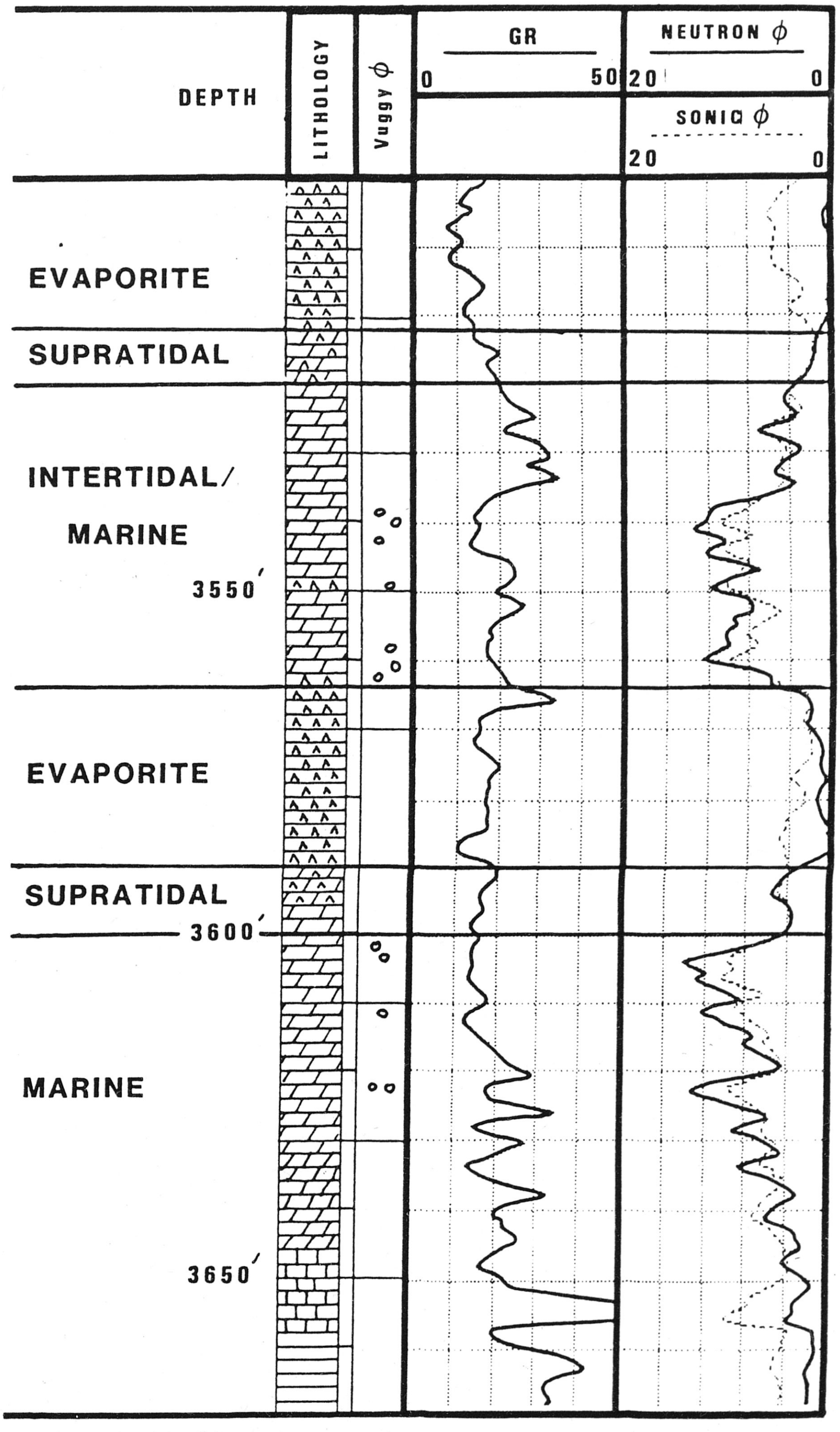


Figure 10 - The Shell #1 Hodges Federal from the Cato field. The lithology, facies and vuggy porosity has been determined from the core. The behavior of the gamma ray (GR), and the porosity derived from the neutron and sonic logs are unique to each environment. (Lithology symbols are in the appendix)

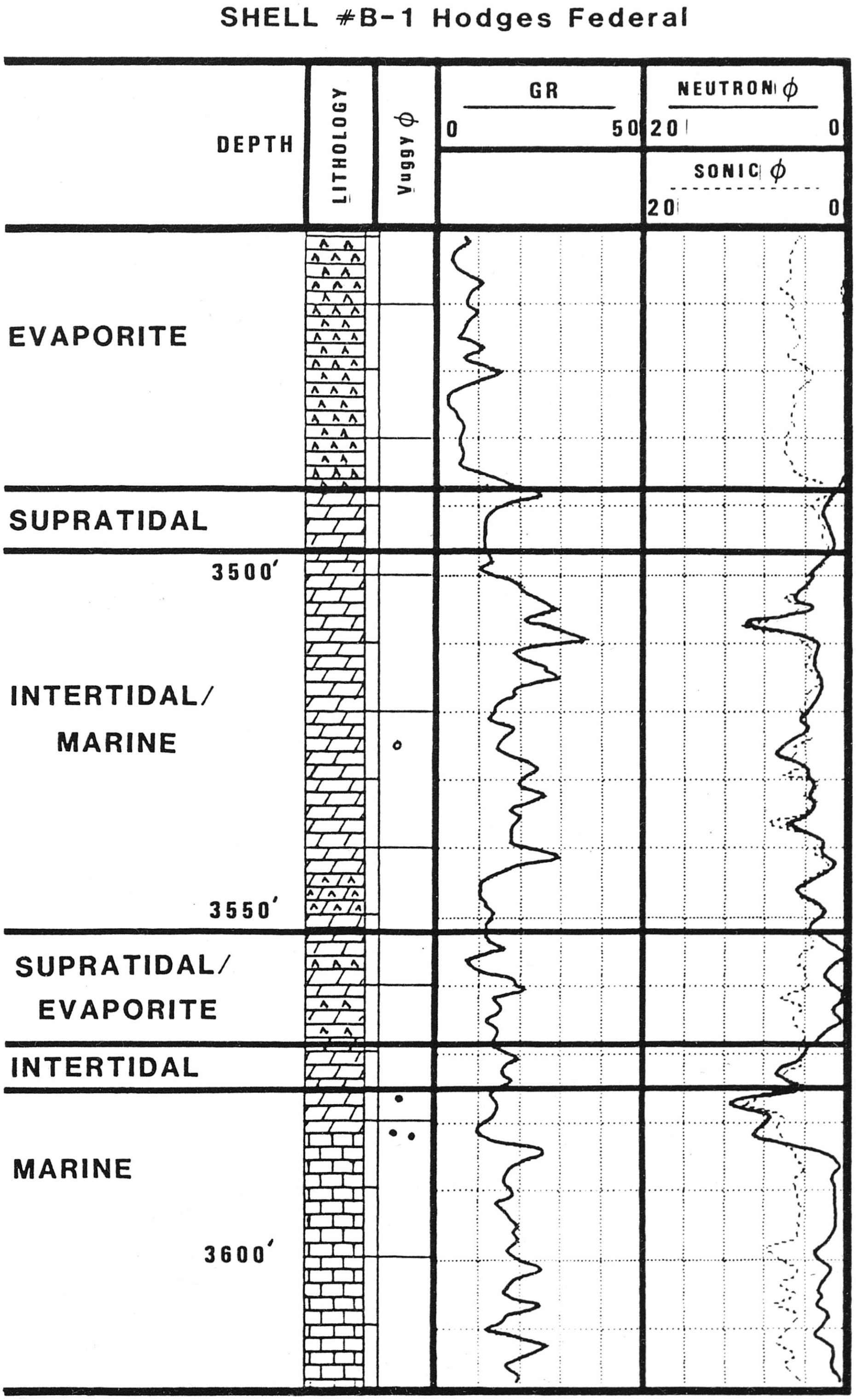


Figure 11 - The Shell #B-1 Hodges Federal from the Cato field. The lithology, facies and vuggy porosity has been determined from the core. The behavior of the gamma ray (GR), and the porosity derived from the neutron and sonic logs are unique to each environment. (Lithology symbols are in the appendix.)

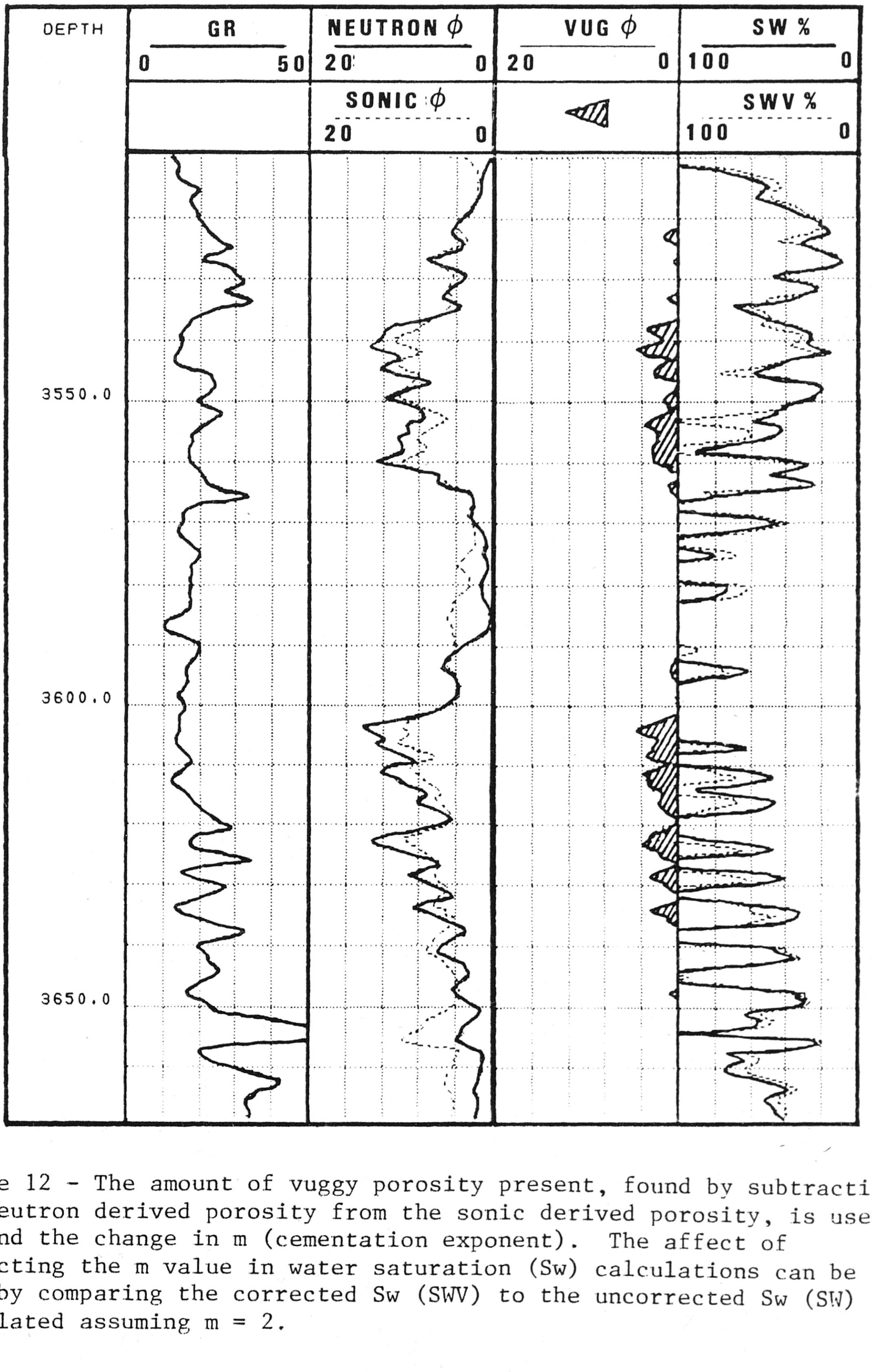


Figure 12 - The amount of vuggy porosity present, found by subtracting the neutron derived porosity from the sonic derived porosity, is used to find the change in m (cementation exponent). The affect of correcting the m value in water saturation (Sw) calculations can be seen by comparing the corrected Sw (SWV) to the uncorrected Sw (SW) calculated assuming m = 2.

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APPENDIX

Assumptions for Log Calculations

Δt_f = 183 microsec/ft (interval transit time for fluid)

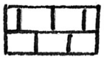
Δt_m = 43.0 microsec/ft (interval transit time for dolomite)

ρ_m = 2.85 gm/cc (density of dolomite)

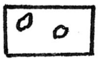
Lithology Symbols

Anhydrite

Dolomite



Limestone



Vuggy Porosity