

An Overview of Dissolution Porosity Development in the Deep-Burial Environment, With Examples from Carbonate Reservoirs in the Permian Basin*

S.J. Mazzullo¹ and P.M. Harris²

Search and Discovery Article #60028 (2009)

Posted May 22, 2009

*Reprinted from S.J. Mazzullo and P.M. Harris, 1991, An overview of dissolution porosity development in the deep-burial environment, with examples from carbonate reservoirs in the Permian Basin, *in* M. Candelaria, ed., Permian Basin Plays - Tomorrow's Technology Today: West Texas Geological Society (and Permian Basin Section SEPM) Publication no. 91-89, p. 125-138. Appreciation is expressed to both WTGS (<http://www.wtgs.org/Home/tabid/36/Default.aspx>) and PBS-SEPM (<http://www.pbs-sepm.org/mainframe.htm>), and to Paula Mitchell, Executive Director, for permission to post this article.

¹Wichita State University, Wichita, Kansas and geological consultant, Midland, Texas
(salvatore.mazzullo@wichita.edu)

²Chevron Oil Field Research Company, La Habra, California; currently ETC, Chevron, San Ramon, CA, USA. (MitchHarris@chevron.com)

Abstract

Porosity in carbonate reservoir rocks is known to result from subaerial meteoric exposure in eogenetic environment. However, enhancement of pre-existing porosity or creation of new porosity also occurs by dissolution in the deep-burial, mesogenetic environment. Except for porosity along stylolites and hydraulic fractures, pore types formed by mesogenetic dissolution mimic those created in the eogenetic environment. Mesogenetic dissolution likely is effected by fluids, charged with organic acids, carbon dioxide, and hydrogen sulfide, generated relatively late in the history of subsiding basins during organic matter maturation in source rocks and hydrocarbon degradation. The many examples of mesogenetic dissolution porosity known in carbonate reservoir rocks in the Permian Basin attest to the significance of deep-burial diagenesis in reservoir development.

Contents

Introduction

Background

Fluids causing mesogenetic dissolution and porosity increases

Examples of mesogenetic dissolution porosity in Permian Basin reservoirs

Chapman Deep Field

Bone Spring Formation

Lower Permian dolomites, southern Delaware Basin

Griffin Penn Field

Discussion

Conclusions

References

AN OVERVIEW OF DISSOLUTION POROSITY DEVELOPMENT IN THE DEEP-BURIAL ENVIRONMENT, WITH EXAMPLES FROM CARBONATE RESERVOIRS IN THE PERMIAN BASIN

S. J. Mazzullo

Department of Geology, Wichita State University,
Wichita, Kansas and Geological Consultant,
Midland, Texas

and

P. M. Harris

Chevron Oil Field Research Company
La Habra, California

ABSTRACT

Porosity in carbonate reservoir rocks is known to result from subaerial meteoric exposure in the eogenetic environment. However, enhancement of pre-existing porosity or creation of new porosity also occurs by dissolution in the deep-burial, meso-genetic environment. Except for porosity along stylolites and hydraulic fractures, pore types formed by mesogenetic dissolution mimic those created in the eogenetic environment. Mesogenetic dissolution likely is effected by fluids, charged with organic acids, carbon dioxide, and hydrogen sulfide, generated relatively late in the history of subsiding basins during organic matter maturation in source rocks and hydrocarbon degradation. The many examples of mesogenetic dissolution porosity known in carbonate reservoir rocks in the Permian Basin attest to the significance of deep-burial diagenesis in reservoir development.

INTRODUCTION

The significance of diagenetic processes that alter porosity systems in carbonate reservoir rocks in the deep-burial (mesogenetic) environment is becoming widely recognized by geologists (i.e., Bathurst, 1980, 1986; Scholle and Halley, 1985; Choquette and James, 1987; Halley, 1987; Mazzullo and Harris, 1989; Moore, 1989). Deep-burial diagenesis is known to reduce porosity by compaction and cementation, and to increase porosity, through dissolution, by enhancing pre-existing pores or by creating new pores in carbonate rocks. Such diagenetic changes can be related temporally and spatially to the burial depth-temperature-hydrologic history of sedimentary basins and to their hydrocarbon maturation-migration-destruction history (i.e., Moore and Druckman, 1981; Foscolos, 1984; Surdam *et al.*, 1984, 1989; Burruss *et al.*, 1985; Druckman and Moore, 1985; Crossey *et al.*, 1986; Edman and Surdam, 1986; Spirakis and Heyl, 1988; Hutcheon,

1989; Mazzullo and Harris, 1989).

This paper reviews important aspects of deep-burial diagenesis in carbonate rocks as they pertain directly to the evolution of porosity in hydrocarbon reservoirs in the Permian Basin. We discuss the various processes and timing of porosity changes in the mesogenetic environment, with specific emphasis on porosity development through dissolution. Examples of carbonate hydrocarbon reservoirs in the Permian Basin in which porosity has been developed mesogenetically illustrate the relationships of mesodiagenesis to the burial history of those reservoirs.

BACKGROUND

Newly-deposited carbonate sediments are highly porous and permeable, with porosities ranging from 40-75% (Figure 1)(Enos and Sawatsky, 1981). Initial high porosities commonly are reduced somewhat by cementation during and after the mineralogic stabilization of sediments (composed generally of

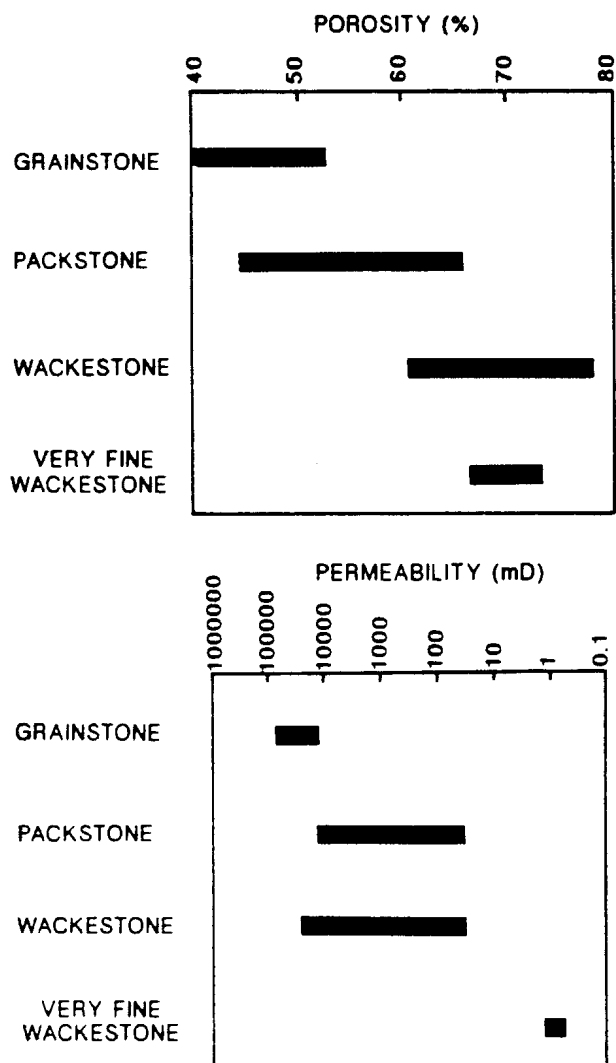


Figure 1. Relationships between depositional textures of modern carbonate sediments and porosity and permeability (modified from Enos and Sawatsky, 1981).

mixtures of aragonite and high-magnesium calcite) to calcite as a result of exposure to meteoric fluids. However, porosity enhancement due to dissolution also may occur to counterbalance this early porosity loss when rocks are exposed subaerially to meteoric fluids in the eogenetic environment (Bathurst, 1975; Longman, 1980; Harris *et al.*, 1985), especially in rocks affected by intense karstification (i.e., James and Choquette, 1984, and Moore, 1989; see papers in James and Choquette, 1988). In the Permian Basin, examples of hydrocarbon reservoirs in which dissolution porosity is believed to have resulted in large part from subaerial karstification include, among others, the San Andres reservoir in Yates Field in Pecos County, Texas (Craig, 1988), various Ellenburger fields along the Central Basin Platform

and in the Midland Basin in Texas (Kerans, 1988; Mazzullo, 1989, 1990a), and some Mississippian reservoirs in the Midland Basin (Mazzullo, 1989). Petroleum geologists quickly embraced the subaerial meteoric exposure model of porosity formation as being widely applicable to the origin of porosity in many carbonate rock reservoirs (see, for example, papers in Roehl and Choquette, 1985). In fact, it virtually became dogmatic that if subsurface carbonates were porous, then they must once have been exposed subaerially. Conversely, many petroleum geologists believed that without subaerial exposure, there likely was little opportunity for carbonate rocks to have substantial porosity developed (notwithstanding that resulting from fracturing and/or dolomitization). Accordingly, the reservoir potential of rocks not exposed subaerially was considered limited and exploration plays for them down-graded. In fact, such a dogmatic approach often extended beyond the limitations of the model as proposed originally. Where basinal limestones were porous, for example, subaerial meteoric exposure commonly was inferred even when such an interpretation clearly was inconsistent with the setting and post-depositional history of the rocks (i.e., see the contrasting opinions of Asquith and Drake, 1985, and Mazzullo and Reid, 1987, concerning some Lower Permian limestone reservoirs in the Midland Basin).

Beginning in the 1970's, however, geologists came to realize that diagenesis may continue beyond the subaerial meteoric realm and into the deep subsurface mesogenetic environment as rocks were buried progressively in subsiding basins. Since that time there has been many studies published which detail various aspects of burial diagenesis in carbonate rocks, including porosity gain and porosity loss (i.e., Bathurst, 1980, 1986; Scholle and Halley, 1985; Choquette and James, 1987; Halley, 1987; Moore, 1989). It is known, for example, that whereas relatively young carbonate rocks may have high initial porosities, the average porosity of most ancient carbonates generally is less than a few percent (Choquette and Pray, 1970). Such porosity loss typically occurs with progressive burial of rocks, to several hundreds to thousands of meters (Figure 2), as a result of cementation and mechanical and chemical compaction (Schmoker and Halley, 1982; Halley and Schmoker, 1983; Scholle and Halley,

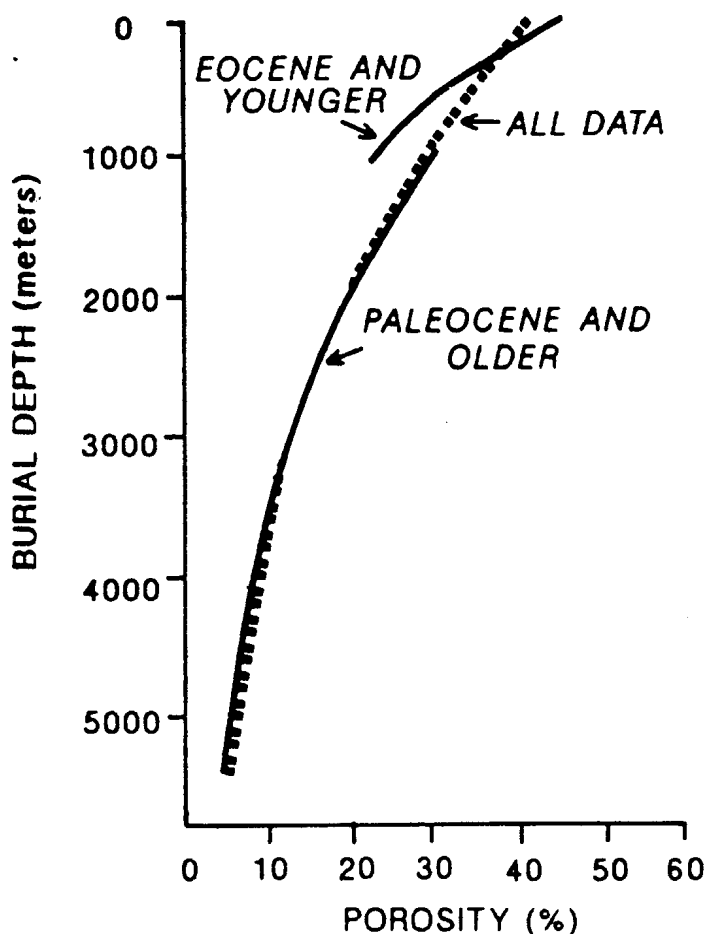


Figure 2. Exponential porosity-depth curves for some South Florida carbonate rocks (modified from Schmoker and Halley, 1982).

1985; Halley, 1987). Indeed, such porosity loss has adversely affected the reservoir potential of many carbonate rocks (i.e., Moore and Druckman, 1981; Friedman *et al.*, 1984; Prezbindowski, 1985; Scholle and Halley, 1985; Walls and Burrowes, 1985; Woronick and Land, 1985; Heydari and Moore, 1989; Kaufman *et al.*, 1990).

However, typical porosities in carbonate reservoirs range from 5-15% (Choquette and Pray, 1970), and average about 13% (data from papers in Roehl and Choquette, 1985). Exclusive of fracturing, this porosity may be: (1) that inherited and preserved from pores created in the depositional environment or pores formed post-depositionally in the subaerial, meteoric diagenetic environment (Halley and Schmoker, 1983; Feazel and Schatzinger, 1985; Harris *et al.*, 1985); (2) due to dolomitization; and (3) that which resulted from dissolution in the

mesogenetic environment, either from enhancement of pre-existing porosity or by creation of new porosity in limestones and/or dolomites. Whereas pre-existing porosity certainly is present in many deeply-buried reservoirs, there are many examples worldwide in which carbonate reservoirs owe part of their porosity to mesogenetic dissolution (see Mazzullo and Harris, 1989; and, for example: Mazzullo, 1981; Moore and Druckman, 1981; Druckman and Moore, 1985; Reijers and Bartok, 1985; Schmidt *et al.*, 1985; Woronick and Land, 1985; Sternbach and Friedman, 1986; Lee and Friedman, 1987; Ye *et al.*, 1987; Dawson, 1988a,b; Fara and Keith, 1988; Machel and Anderson, 1989). These occurrences underscore the significance of mesogenetic dissolution in porosity development and its importance to petroleum geologists exploring for hydrocarbon reservoirs in the deep subsurface.

FLUIDS CAUSING MESOGENETIC DISSOLUTION AND POROSITY INCREASES

Several processes have been proposed which may supply fluids to subsurface hydrologic systems that are capable of causing dissolution in the mesogenetic environment. Some of the most important of these are: (1) fluids generated by deep meteoric recharge in tilted or faulted basins (Toth, 1980); (2) fluids generated during clay mineral transformations, i.e., the conversion of smectite to illite (Foscolos, 1984); (3) fluids derived from reverse weathering reactions (Lundegard and Land, 1986); (4) fluids evolved through evaporite dehydration (Kendall, 1984), and; (5) shale compaction (Hower *et al.*, 1976). Fluids generated by these processes, however, either tend to be expelled relatively early in basin subsidence history, generally prior to significant late dissolution porosity formation, or they appear to result in more porosity reduction by cementation than porosity increase by dissolution (i.e., Foscolos, 1984).

Chemically aggressive fluids evolved during organic diagenesis (organic matter maturation and subsequent hydrocarbon degradation, including thermochemical sulfate reduction) are charged with organic acids, carbon dioxide, hydrogen sulfide, and methane (the breakdown of which provides additional carbon dioxide and hydrogen sulfide) (Orr, 1974; Tissot and Welte, 1978; Surdam *et al.*, 1982, 1984). These fluids likely cause significant dissolution and porosity increase, as well as porosity

reduction by cementation, in the mesogenetic environment (Schmidt and McDonald, 1979; Surdam *et al.*, 1982, 1984, 1989; Spirakis and Heyl, 1988; Moore, 1989). For example, carbon dioxide combines with pore waters to produce carbonic acid, and hydrogen sulfide combines with pore waters to form sulfuric acid. Meshri (1986) reported that organic acids may be more effective in causing dissolution in the subsurface than carbonic acid. Thermochemical sulfate reduction during hydrocarbon degradation may result in porosity occlusion by cementation (i.e., Heydari and Moore, 1989) or porosity increase by dissolution (i.e., Machel, 1989). The process involves generation of sulfuric acid and the breakdown of methane which contributes additional carbon dioxide, and hence carbonic acid, to pore fluids.

According to some of these above-mentioned workers, periods of carbonate dissolution and porosity increase may alternate with periods of cementation and porosity decrease, depending to some extent on relative amounts of organic acids and carbon dioxide in subsurface fluids (i.e., Surdam *et al.*, 1982, 1984, 1989; Lundegard and Land, 1986; Spirakis and Heyl, 1988; Leach *et al.*, 1991). Such contrasting diagenetic processes may be related temporally to the progressive burial of carbonate reservoirs associated with hydrocarbon source rocks as the rocks sequentially enter the zones of organic matter maturation and then hydrocarbon degradation. Likewise, these processes are related to the length of time that a carbonate reservoir and associated source rocks reside in a given temperature region because organic diagenesis is time- and temperature-dependent (Waples, 1980). Hence, insofar as diagenesis is related to levels of thermal maturity of organic matter and hydrocarbons, mesodiagenesis is in turn related to the burial depth- temperature history of sedimentary basins as shown in Figure 3. Likewise, fluids capable of causing dissolution or porosity reduction via cementation may migrate into shallower horizons, above depths at which organic diagenesis occurs (Figure 3).

EXAMPLES OF MESOGENETIC DISSOLUTION POROSITY IN PERMIAN BASIN RESERVOIRS

Hydrocarbon reservoirs in limestones and dolomites in which mesogenetic dissolution is believed to have played a role in porosity enhancement or creation occur throughout the Permian Basin (Figure 4). The depositional setting of reservoirs affected by mesogenetic diagenesis ranges from shallow shelf and peritidal to deep-basinal marine, and their ages from Ordovician to Permian. In these examples, mesogenetic dissolution affected rocks with either pre-existing porosity or little to no pre-existing porosity. Undoubtedly, additional fields will be added to this list as our understanding and recognition of mesogenetic porosity development progresses. Four examples, three from the Delaware Basin and one from the Midland Basin, illustrate some important relationships among progressive burial, mesogenetic porosity modifications, and basin evolution.

CHAPMAN DEEP FIELD

Pennsylvanian limestones in Chapman Deep (Atoka) Field (Figure 5), presently buried to a depth of about 3965 meters (13,000 ft) produce gas from shelf margin reef and oolite facies. Mazzullo (1981) suggested that most, if not all, of the primary porosity created in the post-depositional, subaerial meteoric environment in these rocks was occluded prior to significant burial. A main episode of porosity creation along fractures and stylolites occurred late, after compaction, and may have coincided with initial hydrocarbon generation during Permian time. Timing of porosity creation is constrained by paleotemperature estimates calculated from oxygen isotopic compositional data for saddle dolomite emplaced after compaction and prior to porosity formation. It occurred at depths of about 3000-4000 meters (9843-13,124 ft), possibly during latest Permian to earliest Triassic time, at temperatures of about 55° C to 100° C. Fluids responsible for dissolution likely were derived from organic diagenesis in associated shale source rocks that were in the hydrocarbon-generating window at this time. Porosity types formed include grain-moldic, cement-moldic, and vuggy pores, and dissolution-enlarged fractures. Porosity developed along stylolites is an important component of this reservoir, as it is in

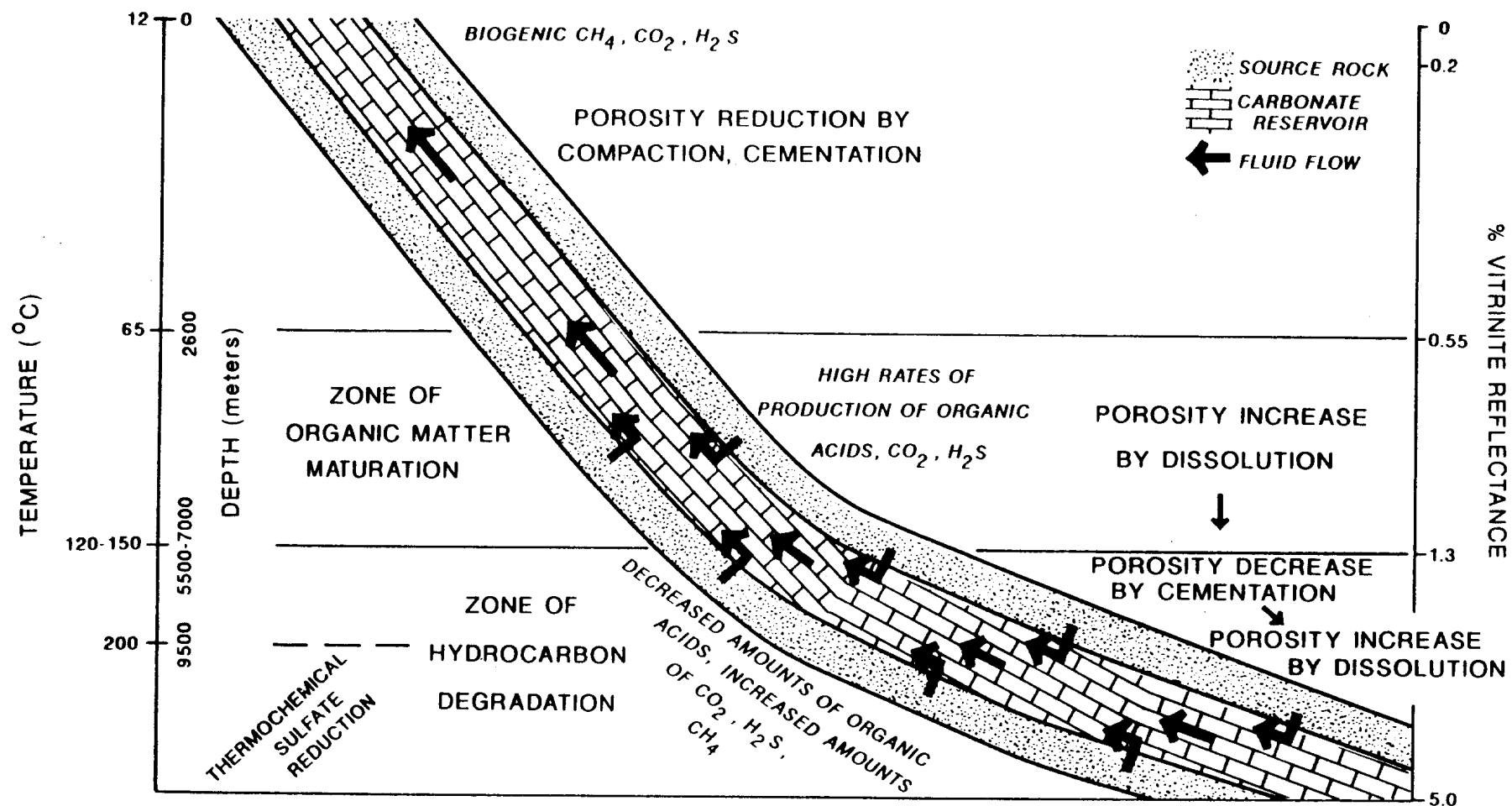


Figure 3. Model of relationship of organic diagenesis to possible mesodiagenetic processes. Depths shown are based on a geothermal gradient of $20^\circ C/km$ ($= 1.2^\circ F/100 ft$), and are meant as an example only; depths corresponding to onset of maturation and degradation are time- and temperature-dependent (Waples, 1980), and vary according to rates of subsidence, geothermal gradient, nature of kerogen present, and time.

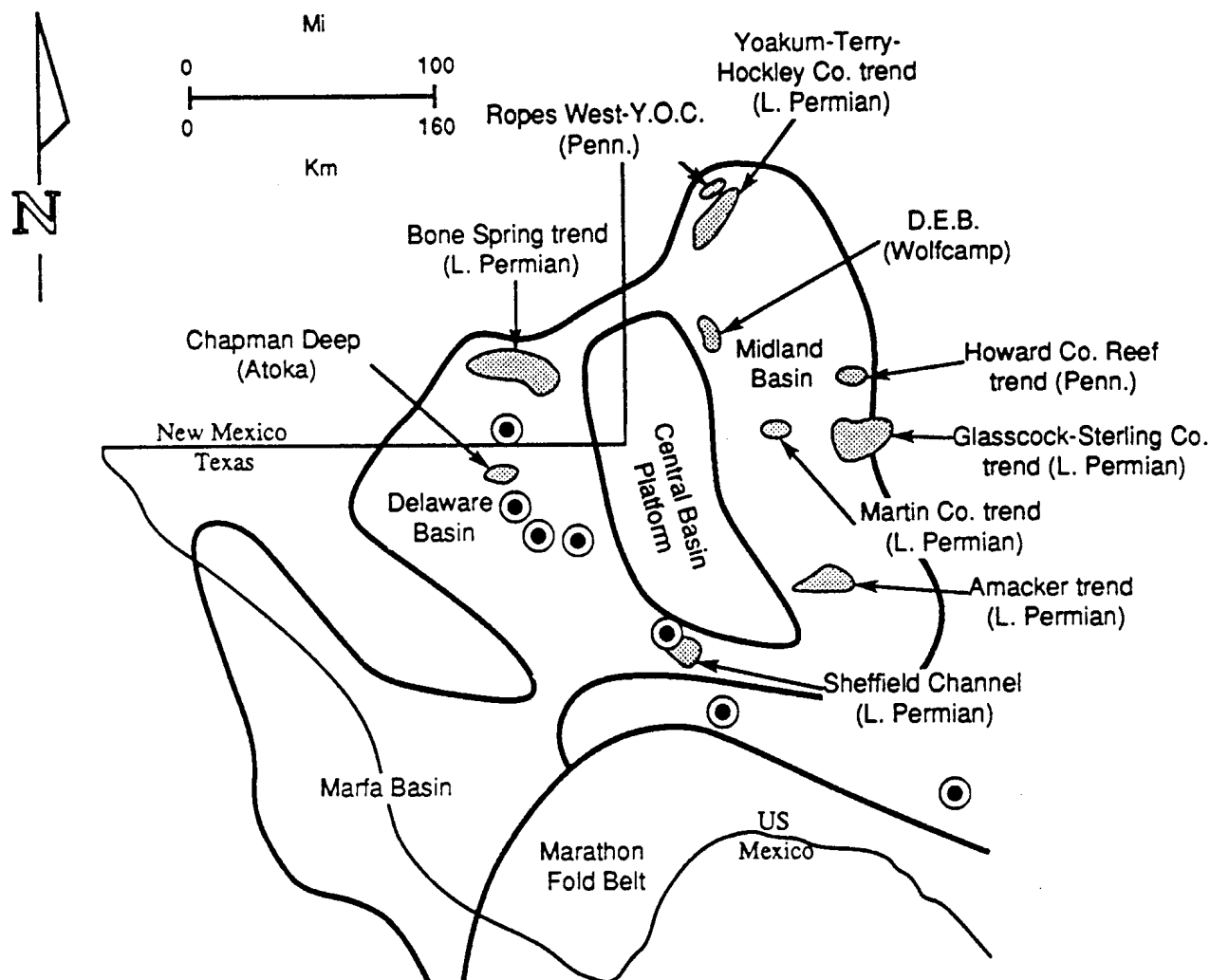


Figure 4. Locations of fields in the Permian Basin in which mesogenetic dissolution has contributed to reservoir porosity. Circled dots are wells studied by Lee and Friedman (1987).

other carbonate reservoirs elsewhere (i.e., Dawson, 1988a, b). Mesogenetic porosity later was occluded partially by coarse crystalline calcite and another generation of saddle dolomite, and gas was emplaced into the reservoirs then or immediately thereafter. Mesogenetic dissolution accounts for 3% to 14% porosity in these rocks.

BONE SPRING FORMATION

The diagenesis of some oil reservoirs in Lower Permian Bone Spring Formation dolomites deposited in foreshelf environments (Figure 6) was examined by Wiggins and Harris (1985) and also by Saller *et al.* (1989). According to Wiggins and Harris (1985), the main episode of porosity development in prior-formed (eogenetic) dolomites occurred in the shallow mesogenetic environment at burial depths of 500-1000 meters (1640-3281 ft), probably in latest

Permian time, at temperatures at or less than 35° C. Because associated source rocks were not yet in the oil-generating window at this time, it is likely that the fluids responsible for dissolution were derived from organic diagenesis in older, more deeply-buried source rocks. Porosity formed then included grain-molds, vugs, intercrystalline pores, and dissolution-enlarged fractures. This diagenetic stage was followed by dolomite replacement, partial occlusion of porosity by dolomite cements, and silicification at about 1000 meter (3281 ft) depths. Later precipitation of anhydrite cement and its subsequent calcitization occurred during maximum burial of 3500-3800 meters (11,483-12468 ft), corresponding to a temperature of about 100° C, and oil may have been emplaced during the late Permian to early Triassic.

CHAPMAN DEEP FIELD

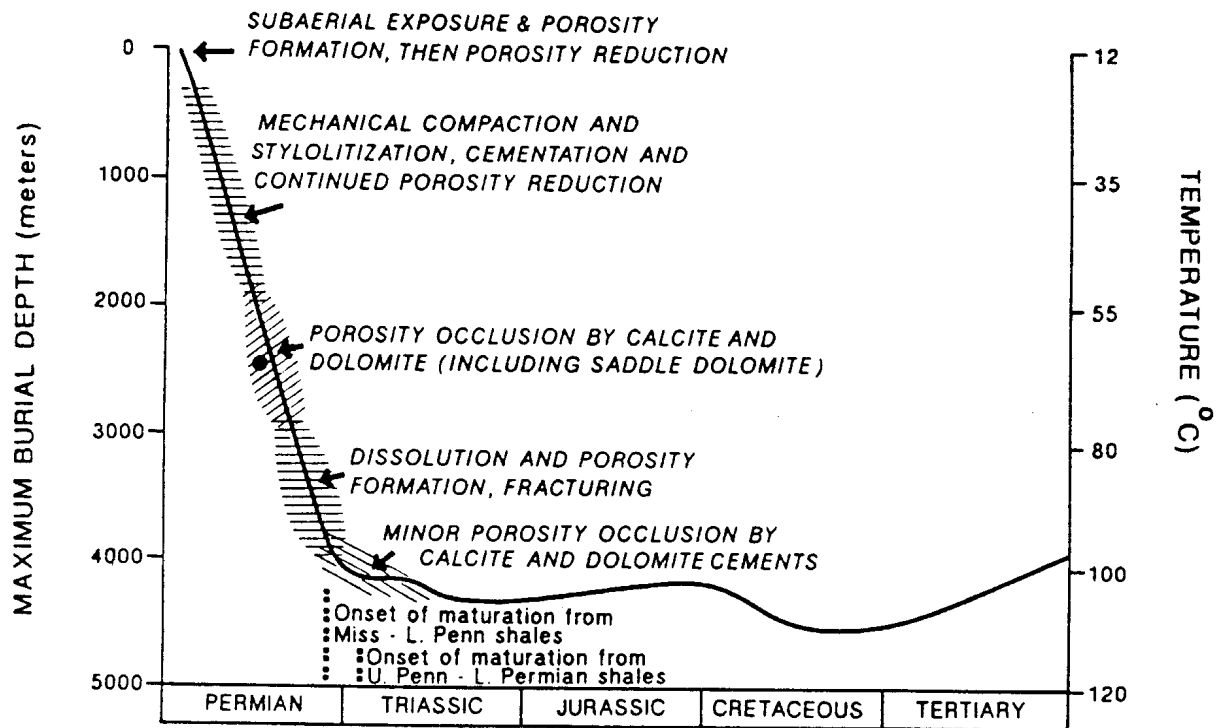


Figure 5. Burial depth-temperature curve and paragenetic sequence in Chapman Deep (Atoka) field (from Mazzullo, 1981). Maximum burial depth is present burial depth plus approximately 610 meters of removed overburden (from Mazzullo, 1986). Temperature on the basis of a geothermal gradient of 20° C/km (= 1.2 F/100 ft) (from Mazzullo, 1986). Onset of organic matter maturation from Horak (1985). Black dot in cementation stage immediately prior to mesogenetic dissolution stage is location of saddle dolomite cement with delta composition of -8.0 o/oo PDB, corresponding to a paleotemperature of about 67° C.

BONE SPRING, NO. DELAWARE BASIN

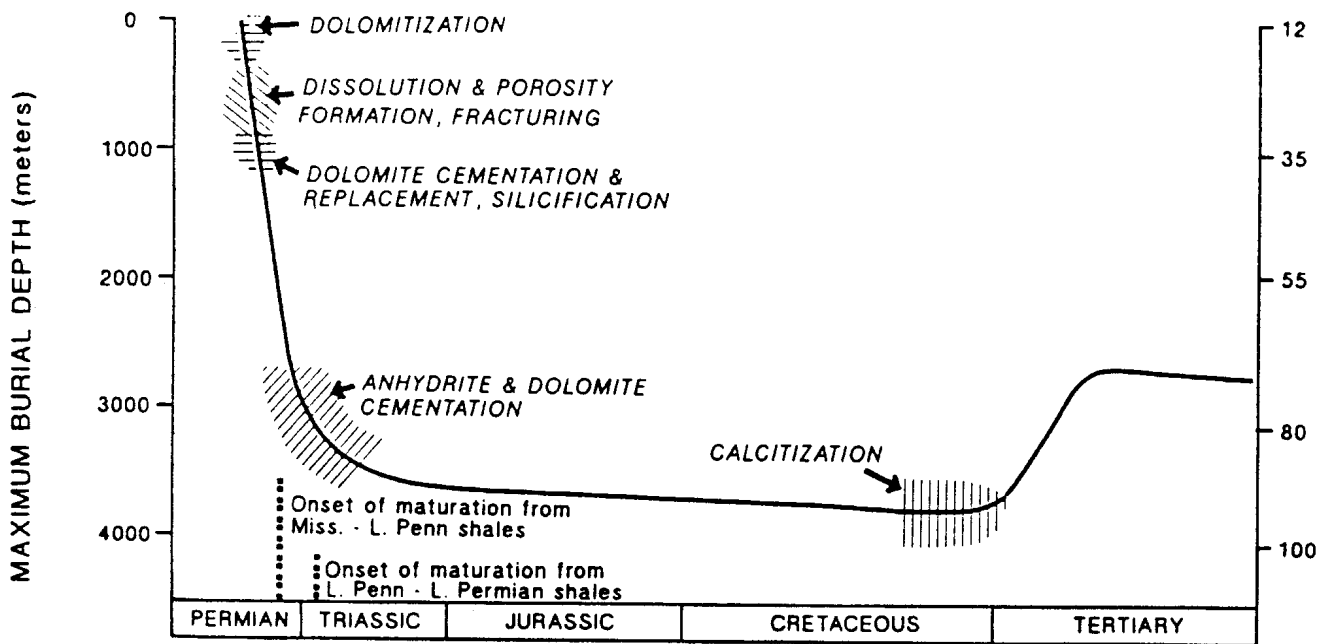


Figure 6. Burial depth-temperature curve and paragenetic sequence in Bone Spring Formation dolomites, northern Delaware Basin (from Wiggins and Harris, 1985). Maximum burial depth is present burial depth plus approximately 610 meters of removed overburden (from Mazzullo, 1986). Temperature on the basis of a geothermal gradient of 20 C/km (= 1.2 F/100 ft) (from Mazzullo, 1986). Onset of organic matter maturation from Horak (1985). Earliest formed dolomite has the following isotopic compositions: delta O = -1.2 to -3.0 o/oo PDB, delta C = +2.6 to -2.7 o/oo PDB; for earliest dolomite cement delta O = -2.7 to 3.6 o/oo PDB, delta C = -0.1 to +2.3 o/oo PDB; for later dolomite cement delta O = -4.6 to -6.6 o/oo PDB, delta C = 0.5 to +2.2 o/oo PDB; for calcites formed in latest calcitization stage delta O = -10.5 o/oo PDB, no data for C.

LOWER PERMIAN DOLOMITES, SOUTHERN DELAWARE BASIN

Mazzullo (1986) described the paragenetic sequence of Lower Permian, shelf margin dolomites associated with Mississippi Valley-type sulfides in the southern Delaware Basin (Sheffield Channel) (Figure 7). Enhancement of pre-existing porosity as a result of mesogenetic dissolution appears to have occurred at burial depths of about 1500-3000 meters (4922-9843 ft), corresponding to temperatures of 45° C to 75° C. Because coeval source rocks were not in the oil-generating window at this time, fluids responsible for dissolution likely were derived from organic diagenesis in older, more deeply-buried source rocks and migrated upward along fault conduits. Dissolution and sulfide emplacement were, at least in part, contemporaneous. Data from fluid inclusions and sulfur isotopes of associated sphalerite and galena suggest that the fluids responsible for dissolution and sulfide mineralization were as hot as 96° C to 122° C (Mazzullo, 1986). These data support the idea of diagenetic fluids derived from depth. Porosity types formed include vugs and intercrystalline pores. Average oxygen isotopic composition of latest stage calcite in the sequence is more depleted than associated limestones, and gives a calculated paleotemperature of about 55° C. The fluids responsible for precipitating this calcite may have been derived essentially in-situ.

GRIFFIN PENN FIELD

Griffin Penn Field (Figure 8), located in Howard County, Texas in the Midland Basin (Figure 3), produces oil from upper Pennsylvanian reefs and associated bank facies deposited during sea level lowstands on former deeper-water slopes (Reid *et al.*, 1990). Present depth of burial is 2380-2450 meters (7809-8038 ft). Eodiagenesis included secondary porosity development during post-depositional subaerial exposure, much of which was occluded at this time by calcite cements. With progressive burial, remaining porosity was occluded by compaction (Mazzullo, 1990b). Later mesogenetic dissolution likely occurred at or near maximum burial depths of 3100 meters (10,170 ft), at temperatures of about 80° C, and resulted in an average of as much as 11% newly created, secondary porosity (Mazzullo, 1990b). Fluids responsible for dissolution likely were

derived from organic diagenesis in associated, or perhaps, slightly deeper shale source rocks. Mesogenetic pores transect earlier cements and compaction features, and include grain-molds, cement-molds, and vugs. Dissolution-enlarged fractures (Figure 9) are interpreted as hydraulic fractures that formed in the mesogenetic environment, and which facilitated the movement of chemically aggressive fluids into the reservoir. Some of the mesogenetic pores were later partially occluded by calcite and saddle dolomite cements. Cementation was followed by another period of stylolitization.

DISCUSSION

These four examples, and those shown in Figure 4, illustrate several important points about deep-burial diagenesis in carbonate rocks:

I. Mesodiagenesis is continuous during the progressive burial of carbonate rocks, and occurs on a basin-wide scale. In the examples described above, mesodiagenesis, including porosity increases due to dissolution, operated early at depths from about 500 meters (1640 ft), to later at depths of 4000 meters (13,120 ft) (Figures 5-8). In the Permian Basin, deep-burial diagenesis and associated dissolution porosity development are known to have occurred in carbonate rocks buried to depths in excess of 7000 meters (23000 ft) (Lee and Friedman, 1987; Amthor and Friedman, 1991), and deeper occurrences may yet be confirmed. Worldwide, burial depths at which mesogenetic dissolution and/or porosity occlusion by cementation may occur range from 200 to 9150 meters (660-30,000 ft).

II. Mesogenetic dissolution may affect rocks deposited on shallow-water platforms (i.e., Chapman Deep Field and southern Delaware Basin) or in former deeper-water slope environments during lowstands (i.e., Griffin Penn Field), that were exposed to meteoric fluid in the eogenetic environment and later buried in the mesogenetic realm. Likewise, it may affect rocks deposited in slope and basin settings that were not exposed subaerially (i.e., Bone Spring Formation, northern Delaware Basin, and other Lower Permian slope and basin reservoirs shown in Figure 4).

III. Fluids responsible for mesogenetic dissolution may be derived from source rocks associated directly with the deeply-buried carbonate reservoirs (i.e.,

LOWER PERMIAN, SO. DELAWARE BASIN

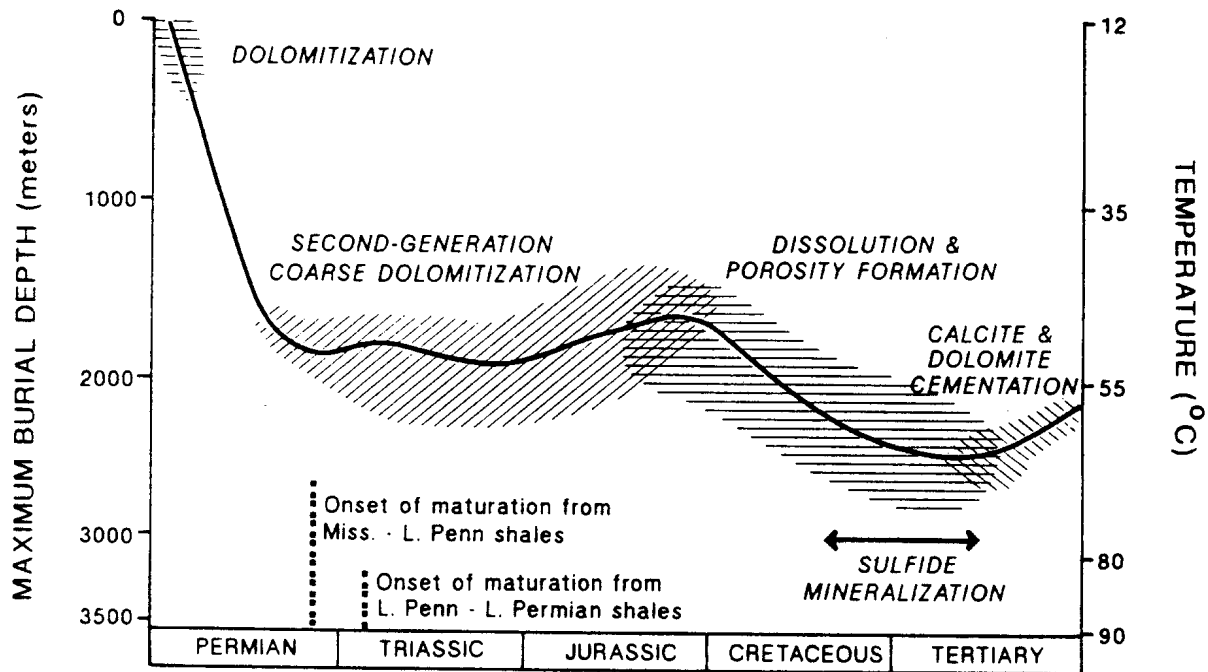


Figure 7. Burial depth-temperature curve and paragenetic sequence in Lower Permian dolomites, southern Delaware Basin (from Mazzullo, 1986). Maximum burial depth is present burial depth plus approximately 610 meters of removed overburden. Temperature on the basis of a geothermal gradient of 20 C/km (= 1.2 F/100 ft). Onset of organic matter maturation from Horak (1985). Fluid inclusion data, and delta S = +4.1 o/oo CDT for sphalerite and -1.2 o/oo CDT for galena indicate temperature of sulfide mineralization of 96°-122° C. The average isotopic compositions of latest stage calcite cements are: delta O = -8.0 o/oo PDB, delta C = -2.3 o/oo PDB. Isotopic compositions of associated limestones are: delta O = -2.0 o/oo PDB, delta C = +1.2 o/oo PDB (isotopic data courtesy of Carol Hill).

GRIFFIN PENN FIELD

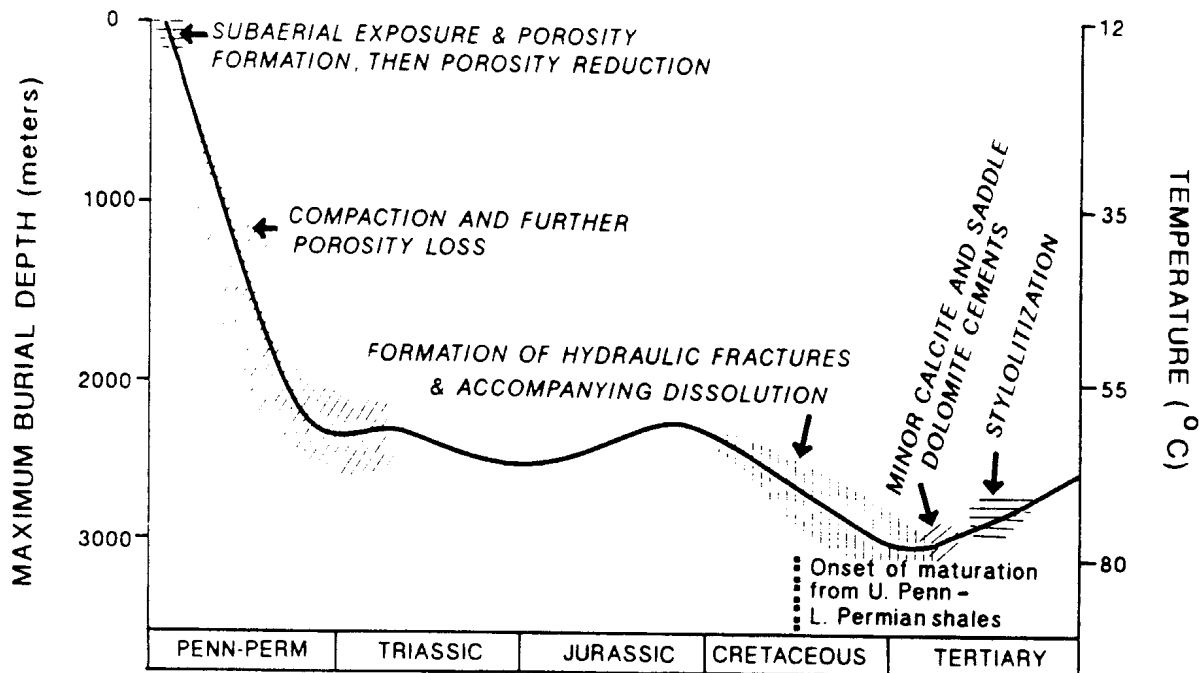


Figure 8. Burial depth-temperature curve and paragenetic sequence in Griffin Penn Field. Maximum burial depth is present burial depth plus approximately 610 meters (2000 ft) of removed overburden. Temperature on the basis of a geothermal gradient of 20° C/km (= 1.2° F/100 ft). Onset of organic matter maturation from Horak (1985).

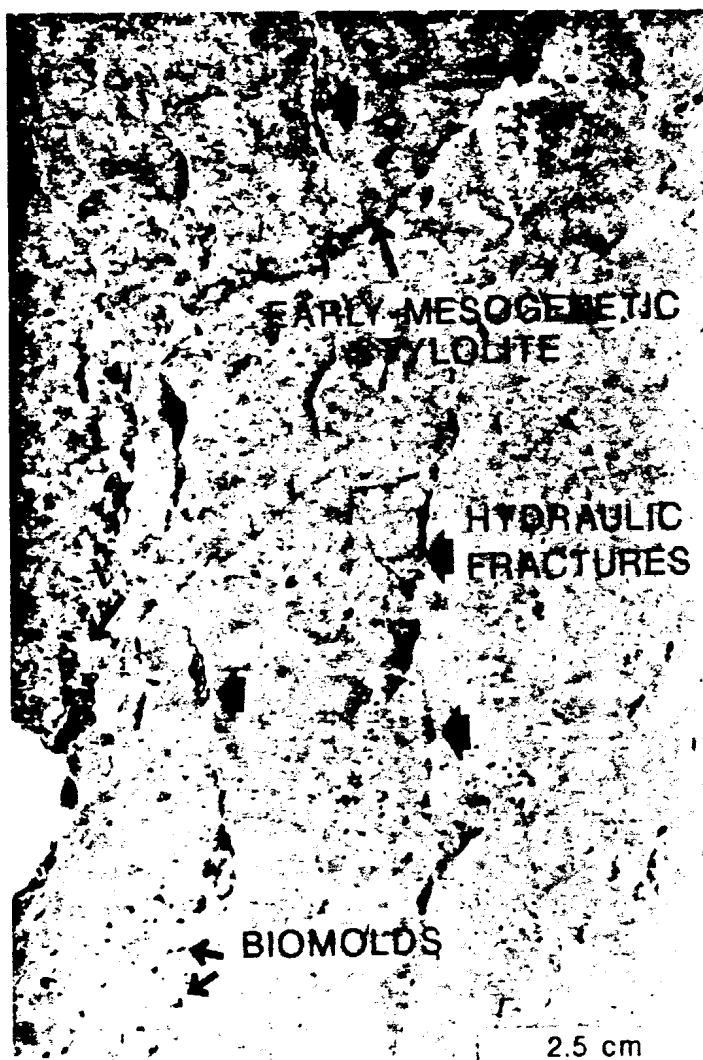


Figure 9. Core of Pennsylvanian limestone from Griffin Penn field showing stylolites, and hydraulic fractures and associated moldic porosity formed in the mesogenetic environment.

Chapman Deep and Griffin Penn Fields), or from more deeply buried source rocks from which fluids migrated into reservoirs above the zone of organic diagenesis (Bone Spring Formation, northern Delaware Basin and Lower Permian in the southern Delaware Basin).

IV. Mesogenetic dissolution affects rocks with pre-existing porosity as well as those with little or no inherited porosity. Porosity increase as a result of mesogenetic dissolution can be considerable (Mazzullo and Harris, 1989). In the examples of carbonate reservoirs discussed above, mesogenetic porosity is as high as 14%.

V. With the exception of porosity along stylolites and hydraulic fractures, mesogenetic pore types are similar to those formed in eogenetic and telogenetic environments with which they can be confused (Mazzullo and Harris, 1989).

VI. A recognizable sequence of diagenetic processes and products commonly is preserved as decipherable signatures of mesodiagenesis. In the Permian Basin examples, there is a recurring theme of: (1) porosity loss due to compaction and early cementation, followed by; (2) progressive burial with porosity gain due to dissolution (and commonly, fracturing); and then (3) minor porosity loss due to cementation (Figures 5-8). Such a theme is typical of many other deeply-buried carbonate rocks (Mazzullo and Harris, 1989), and may be related to the burial depth-temperature-organic diagenesis history of subsiding basins (Figure 3). The relative amounts of porosity gain or loss, and the timing and duration of dissolution and/or cementation may differ from basin to basin depending on such factors as amount of pre-existing porosity, burial depth, geothermal gradient, type of original organic matter, and the nature of fluid migration.

CONCLUSIONS

Interpretations concerning the evolution of porous hydrocarbon reservoirs in Permian Basin carbonate rocks need not be restricted to porosity formation as a result of subaerial meteoric exposure. Indeed, many examples in the Permian Basin demonstrate the importance to reservoir occurrence of porosity development by dissolution-enlargement of pre-existing pores and creation of new pores in the deep-burial environment. The most likely culprits responsible for mesogenetic dissolution are fluids charged with organic acids, carbon dioxide, and hydrogen sulfide generated during organic matter maturation and hydrocarbon destruction. As such, although the occurrence of mesogenetic porosity can not yet be predicted, it can be related to the burial depth-temperature history of subsiding basins through organic matter diagenesis.

REFERENCES

- Amthor, J.E., and G.M. Friedman, 1991, Dolomite-rock textures and secondary porosity development in Ellenburger Group carbonates (Lower Ordovician), west Texas and southeastern New Mexico: *Sedimentology*, v. 38, p. 343-362.
- Asquith, G.B., and J.F. Drake, 1985, Depositional history and reservoir development of a Permian *Fistulipora-Tubiphytes* bank complex, Blalock

- Lake East Field, west Texas, *in* P.O. Roehl and P.W. Choquette, eds., Carbonate Petroleum Reservoirs: Springer-Verlag, p. 309-316.
- Bathurst, R.G.C., 1975, Carbonate Sediments and Their Diagenesis: Elsevier, Developments in Sedimentology 12, 658 p.
- Bathurst, R.G.C., 1980, Deep crustal diagenesis in limestones: Revista del Instituto de Investigaciones Geologicas, Universit of Barcelona, p. 89-100.
- Bathurst, R.G.C., 1986, Carbonate diagenesis and reservoir development: conservation, destruction, and creation of pores: Quarterly Colorado School of Mines, v. 81, p. 1-25.
- Burruss, R.C., K.R. Cercone, and P.M. Harris, 1985, Timing of hydrocarbon migration - evidence from fluid inclusions in calcite cements, tectonics and burial history, *in* N. Schneidermann and P.M. Harris, eds., Carbonate Cements: SEPM Special Publication No. 36, p. 277-289.
- Choquette, P.W., and N.P. James, 1987, Diagenesis 12: Diagenesis in limestones - 3. The deep burial environment: Geoscience Canada, v. 14, p. 3-35.
- Choquette, P.W., and L.C. Pray, 1970, Geological nomenclature and classification of porosity in sedimentary carbonates: AAPG Bulletin, v. 54, p. 207-250.
- Craig, D.H., 1988, Caves and other features of Permian karst in San Andres Dolomite, Yates Field reservoir, west Texas, *in* N.P. James and P.W. Choquette, eds., Paleokarst: Springer-Verlag, p. 342-363.
- Crossey, L.J., R.C. Surdam, and R. Lahann, 1986, Application of organic/inorganic diagenesis to porosity prediction, *in* D.L. Gautier, ed., Roles of Organic Matter in Sediment Diagenesis: SEPM Special Publication No. 38, p. 147-156.
- Dawson, W.C., 1988a, Ismay reservoirs, Paradox Basin: diagenesis and porosity development: Rocky Mountain Association Geologists, 1988 Symposium, p. 163-174 and 441-443.
- Dawson, W.C., 1988b, Stylolite porosity in carbonate reservoirs: AAPG Bulletin, v. 72, p. 176.
- Druckman, Y., and C.H. Moore, 1985, Late subsurface porosity in a Jurassic grainstone reservoir, Smackover Formation, Mt. Vernon Field, southern Arkansas, *in* P.O. Roehl and P.W. Choquette, eds., Carbonate Petroleum Reservoirs: Springer-Verlag, p. 371-383.
- Edman, J.D., and R.C. Surdam, 1986, Organic-inorganic interactions as a mechanism for porosity enhancement in the Upper Cretaceous Ericson Sandstone, Green River Basin, Wyoming, *in* D.L. Gautier, ed., Roles of Organic Matter in Sediment Diagenesis: SEPM Special Publication No. 38, p. 85-109.
- Enos, P., and L.H. Sawatsky, 1981, Pore networks in Holocene carbonate sediments: Journal of Sedimentary Petrology, v. 51, p. 961-985.
- Fara, D.R., and B.D. Keith, 1988, Depositional facies and diagenetic history of the Trenton Limestone in northern Indiana, *in* B.D. Keith, ed., The Trenton Group (Upper Ordovician Series) of Eastern North America - Deposition, Diagenesis, and Petroleum: AAPG Studies in Geology No. 29, p. 277-298.
- Feazel, C.T., and R.A. Schatzinger, 1985, Prevention of carbonate cementation in petroleum reservoirs, *in* N. Schneidermann and P.M. Harris, eds., Carbonate Cements: SEPM Special Publication No. 36, p. 97-106.
- Foscolos, A.E., 1984, Diagenesis 7. Catagenesis of argillaceous sedimentary rocks: Geoscience Canada, v. 11, p. 67-75.
- Friedman, G.M., J. Cattafe, and B. Borak, 1984, Deep-burial diagenesis of the Hunton (Late Ordovician to Early Devonian) carbonates in the Anadarko Basin, *in* N.J. Hyne, ed., Limestones of the Mid-Continent: Tulsa Geological Society, p. 183-199.
- Halley, R.B., 1987, Burial diagenesis of carbonate rocks: Quarterly Colorado School of Mines, v. 82, p. 1-15.
- Halley, R.B., and J.W. Schmoker, 1983, High porosity Cenozoic carbonate rocks of South Florida: progressive loss of porosity with depth: AAPG Bulletin, v. 67, p. 191-200.
- Harris, P.M., C.G. St.C. Kendall, and I. Lerche, 1985, Carbonate cementation - a brief review, *in* N. Schneidermann and P.M. Harris, eds., Carbonate Cements: SEPM Special Publication No. 36, p. 79-95.
- Heydari, E., and C.H. Moore, 1989, Burial diagenesis and thermochemical sulfate reduction, Smackover Formation, southeastern Mississippi salt basin: Geology, v. 17, p. 1080-

- 1084.
- Horak, R.L., 1985, Tectonic and hydrocarbon maturation history in the Permian Basin: Oil and Gas Journal, v. 83, no. 21, p. 124-129.
- Hower, J., E.V. Eslinger, M.E. Hower, and E.A. Perry, 1976, Mechanism of burial and metamorphism of argillaceous sediment: 1. mineralogical and chemical evidence: GSA Bulletin, v. 87, p. 725-737.
- Hutcheon, I.E., ed., 1989, Short Course in Burial Diagenesis: Mineralogical Association of Canada, Short Course Handbook v. 15, 409 p.
- James, N.P., and P.W. Choquette, 1984, Diagenesis 9. Limestones - the meteoric diagenetic environment: Geoscience Canada, v. 11, p. 161-194.
- James, N.P., and P.W. Choquette, eds., 1988, Paleokarst: Springer-Verlag, 416 p.
- Kaufman, J., W.J. Meyers, and G.N. Hanson, 1990, Burial cementation in the Swan Hills Formation (Devonian), Rosevar Field, Alberta, Canada: Journal of Sedimentary Petrology, v. 60, p. 918-939.
- Kendall, A.C., 1984, Evaporites, in R.G. Walker, ed., Facies Models: Geoscience Canada, Reprint Series 1, p. 259-298.
- Kerans, C., 1988, Karst-controlled reservoir heterogeneity in Ellenburger Group carbonates of west Texas: AAPG Bulletin, v. 72, p. 1160-1183.
- Leach, D.L., G.S. Plumlee, A.H. Hofstra, G.P. Landis, E.L. Rowland, and J.G. Viets, 1991, Origin of late dolomite cement by CO₂-saturated deep basin brines: evidence from the Ozark region, central United States: Geology, v. 19, p. 348-351.
- Lee, Y.I., and Friedman, G.M., 1987, Deep-burial dolomitization in the Ordovician Ellenburger Group carbonates, west Texas and southeastern New Mexico: Journal of Sedimentary Petrology, v. 57, p. 544-557.
- Longman, M.W., 1980, Carbonate diagenetic textures from near surface diagenetic environments: AAPG Bulletin, v. 64, p. 461-487.
- Lundegard, P.D., and L.S. Land, 1986, Carbon dioxide and inorganic acids: their role in porosity enhancement and cementation, Paleogene of the Texas Gulf Coast, in D.L. Gautier, ed., Roles of Organic Matter in Sediment Diagenesis: SEPM Special Publication No. 38, p. 129-146.
- Machel, H.G., 1989, Relationships between sulfate reduction and oxidation of organic compounds to carbonate diagenesis, hydrocarbon accumulations, salt domes, and metal sulphide deposits: Carbonates and Evaporites, v. 4, p. 137-151.
- Machel, H.G., and J.H. Anderson, 1989, Pervasive subsurface dolomitization of the Nisku Formation in central Alberta: Journal of Sedimentary Petrology, v. 59, p. 891-911.
- Mazzullo, S.J., 1981, Facies and burial diagenesis of a carbonate reservoir: Chapman Deep (Atoka) Field, Delaware Basin, Texas: AAPG Bulletin, v. 65, p. 850-865.
- Mazzullo, S.J., 1986, Mississippi Valley-type sulfides in Lower Permian dolomites, Delaware Basin, Texas: implications for basin evolution: AAPG Bulletin, v. 70, p. 943-952.
- Mazzullo, S.J., 1989, Subtle traps in Ordovician to Permian carbonate petroleum reservoirs, Permian Basin: an overview, in J.E. Flis, R.C. Price, and J.F. Sarg, eds., Search for the Subtle Trap, Hydrocarbon Exploration in Mature Basins: West Texas Geological Society Publication No. 89-85, p. 155-180.
- Mazzullo, S.J., 1990a, Karst-controlled reservoir heterogeneity in Ellenburger Group carbonates of west Texas: discussion: AAPG Bulletin, v. 74, p. 1119-1123.
- Mazzullo, S.J., 1990b, Recognition and contribution of deep-burial diagenesis to porosity evolution in carbonate reservoir rocks: AAPG Bulletin, v. 74, p. 219-220.
- Mazzullo, S.J., and P.M. Harris, 1989, Porosity formation in the deep-burial environment: an overview, with examples from the Permian Basin: AAPG Bulletin, v. 73, p. 388.
- Mazzullo, S.J., and A.M. Reid, 1987, Basinal Lower Permian facies, Permian Basin: Part II - Depositional setting and reservoir facies of Wolfcampian-Lower Leonardian basinal carbonates: West Texas Geological Society Bulletin, v. 26, p. 5-10.
- Meshri, I.D., 1986, On the reactivity of carbonic and organic acids and generation of secondary porosity, in D.L. Gautier, ed., Roles of Organic

- Matter in Sediment Diagenesis: SEPM Special Publication No. 38, p. 123-128.
- Moore, C.H., 1989, Carbonate Diagenesis and Porosity: Elsevier, Developments in Sedimentology 46, 338 p.
- Moore, C.H., and Y. Druckman, 1981, Burial diagenesis and porosity evolution, Upper Jurassic Smackover, Arkansas and Louisiana: AAPG Bulletin, v. 65, p. 597-628.
- Orr, W.L., 1974, Changes in sulfur content and isotopic ratios of sulfur during petroleum maturation - study of Big Horn Basin Paleozoic oils: AAPG Bulletin, v. 58, p. 2295-2318.
- Prezbindowski, D.R., 1985, Burial cementation - is it important? A case study, Stuart City trend, south central Texas, *in* N. Schneidemann and P.M. Harris, eds., Carbonate Cements: SEPM Special Publication No. 36, p. 241-264.
- Reid, A.M., S.T. Reid, and S.J. Mazzullo, 1990, Lowstand carbonate reservoirs: Upper Pennsylvanian sea level changes and reservoir development adjoining Horseshoe Atoll: AAPG Bulletin, v. 74, p. 221.
- Reijers, T.J.A., and P. Bartok, 1985, Porosity characteristics and evolution in fractured Cretaceous carbonate reservoirs, La Paz Field area, Maracaibo Basin, Venezuela, *in* P.O. Roehl and P.W. Choquette, eds., Carbonate Petroleum Reservoirs: Springer-Verlag, p. 407-423.
- Roehl, P.O., and P.W. Choquette, eds., 1985, Carbonate Petroleum Reservoirs: Springer-Verlag, 622 p.
- Saller, A.H., J.W. Barton, and R.E. Barton, 1989, Slope sedimentation associated with a vertically building shelf, Bone Spring Formation, Mescalero Escarpe Field, southeastern New Mexico, *in* P.D. Crevello, J.L. Wilson, J.F. Sarg, and J.F. Read, eds., Controls on Carbonate Platform and Basin Development: SEPM Special Publication no. 44, p. 275-288.
- Schmidt, V., and D.A. McDonald, 1979, The role of secondary porosity in the course of sandstone diagenesis, *in* P.A. Scholle and P.R. Schluger, eds., Aspects of Diagenesis: SEPM Special Publication No. 26, p. 175-207.
- Schmidt, V., I.A. McIlreath, and A.E. Budwill, 1985, Origin and diagenesis of Middle Devonian pinnacle reefs encased in evaporites, "A" and "E" pools, Rainbow Field, Alberta, *in* P.O. Roehl and P.W. Choquette, eds., Carbonate Petroleum Reservoirs: Springer-Verlag, p. 140-160.
- Schmoker, J.W., and R.B. Halley, 1982, Carbonate porosity versus depth: a predictable relation for South Florida: AAPG Bulletin, v. 66, p. 2561-2570.
- Scholle, P.A., and R.B. Halley, 1985, Burial diagenesis: out of sight, out of mind!, *in* N. Schneidemann and P. M. Harris, eds., Carbonate Cements: SEPM Special Publication No. 36, p. 309-334.
- Spirakis, C.S., and A.V. Heyl, 1988, Possible effects of thermal degradation of organic matter on carbonate paragenesis and fluorite precipitation in Mississippi Valley-type deposits: Geology, v. 16, p. 1117-1120.
- Sternbach, C.A., and G.M. Friedman, 1986, Dolomites formed under conditions of deep burial: Hunton Group (Upper Ordovician to Lower Devonian) in the deep Anadarko Basin of Oklahoma and Texas: Carbonates and Evaporites, v. 1, p. 69-73.
- Surdam, R.C., S.W. Boese, and L.J. Crossey, 1982, Role of organic and inorganic reactions in development of secondary porosity in sandstones: AAPG Bulletin, v. 66, p. 635.
- Surdam, R.C., S.W. Boese, and L.J. Crossey, 1984, The chemistry of secondary porosity, *in* D.A. McDonald and R.C. Surdam, eds., Clastic Diagenesis: AAPG Memoir 37, p. 127-149.
- Surdam, R.C., T.L. Dunn, H.P. Heasler, and D.B. MacGowan, 1989, Porosity evolution in sandstone/shale systems, *in* I.E. Hutcheon, ed., Short Course in Burial Diagenesis: Mineralogical Association of Canada, Short Course Handbook v. 15, p. 61-134.
- Tissot, B.P., and D.H. Welte, 1978, Petroleum Formation and Occurrence: A New Approach to Oil and Gas Exploration: Springer-Verlag, 538 p.
- Toth, J., 1980, Cross-formational gravity-flow of groundwater: a mechanism of the transport and accumulation of petroleum (the generalized hydraulic theory of petroleum migration), *in* W.H. Roberts and R.J. Cordell, eds., Problems of Petroleum Migration: AAPG Studies in Geology No. 10, p. 121-167.
- Walls, R.A., and G. Burrowes, 1985, The role of

- cementation in the diagenetic history of Devonian reefs, Western Canada, in N. Schneidermann and P.M. Harris, eds., Carbonate Cements: SEPM Special Publication No. 36, p. 185-220.
- Waples, D.W., 1980, Time and temperature in petroleum formation: application of Lopatin's method to petroleum exploration: AAPG Bulletin, v. 64, p. 916-926.
- Wiggins, W.D., and P.M. Harris, 1985, Burial diagenetic sequence in deep-water allochthonous dolomites, Permian Bone Spring Formation, southeast New Mexico, in P.D. Crevello and P.M. Harris, eds., Deep-Water Carbonates — A Core Workshop: SEPM Core Workshop No. 6, p. 140-173.
- Woronick, R.E., and L.S. Land, 1985, Late burial diagenesis, Lower Cretaceous Pearsall and lower Glen Rose formations, South Texas, in N. Schneidermann and P.M. Harris, eds., Carbonate Cements: SEPM Special Publication No. 36, p. 265-275.
- Ye, D.S., S.H. Lui, Z.D. Zeng, and Y.B. Chen, 1987, Diagenesis and porosity evolution of Yongningzheng Formation grainstones (Lower Triassic) in southwest Guizhou, China: SEPM Annual Midyear Meeting Abstracts, v. 4, p. 94.