EFFECT OF CO_2 FLOODING ON DOLOMITE RESERVOIR ROCK DENVER UNIT, WASSON (SAN ANDRES) FIELD, TEXAS

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ABSTRACT

This report documents results of a study to determine whether brine and CO_2 injection significantly changes total porosity in a dolomite reservoir. Pre- and postpilot cores from closely-spaced wells in the Shell Western E&P Inc. Denver Unit CO_2 pilot provided the necessary data. We concluded that only minor porosity enhancement resulted from brine dissolution of anhydrite.

Detailed petrographic examination of thin sections provided the modal composition (bulk mineralogy, total porosity and pore types) of 112 samples. This data was evaluated by statistical methods (t test) to determine the significance of any change in porosity at a given confidence level.

Large vugs, channels or other evidence of high permeability thief zones, created by carbonic acid dissolution of the dolomite, were not observed in the postpilot core located 25 feet from the pilot injection well. However, minor anhydrite dissolution is documented from both chemical analyses of the pilot flood water and thin sections. These results are significant when one considers the large brine and CO_2 injection volumes (approximately 90 pore volumes of brine and 30 pore volumes of CO_2) that contacted the postpilot core. In addition, minor amounts of solid hydrocarbon were observed to occlude porosity in seven thin sections from the postpilot core.

As a result of anhydrite dissolution, total point-counted porosity is slightly higher in the postpilot core but not statistically significant. Our results appear to refute Chevron's (SACROC) concerns that carbonic acid would aggravate reservoir heterogeneities and cause channeling detrimental to areal sweep.

INTRODUCTION

The implementation of a CO_2 pilot project in the Denver Unit by Shell Western E&P Inc. (SWEPI) led to a need for a detailed geologic model of the San Andres reservoir in the pilot area (Figs. 1 and 2). Earlier work by SWEPI geologists documented the general geologic framework of the Wasson San Andres reservoir.

Between January and June 1977, five closely-spaced wells were cored in the CO_2 pilot area (Fig. 3). The prepilot core provided an opportunity to make a detailed study of the reservoir on a scale usually not possible. Between June and December 1979, five additional wells were pressure cored in the CO_2 pilot area. The postpilot core allowed us to document any significant changes in reservoir rock characteristics as a result of brine and CO_2 injection during the pilot project.

The purposes of this investigation were to (1) construct a detailed geologic model of the CO_2 pilot area, (2) determine whether total porosity changed during fluid injection, and (3) statistically document any changes in total porosity or amounts of specific pore types as a result of fluid injection.

A tertiary CO_2 flood pilot test was conducted by Chevron U.S.A., Inc. during 1974-1975 in a watered-out area of the SACROC Unit, Scurry County, Texas. Graue and Blevins[1] concluded that pressure fall-off and pulse test data provided evidence of CO_2 dissolution of reservoir rock, aggravation of reservoir heterogeneities and tendencies of CO_2 to channel through the reservoir. Graue and Blevins[1] interpretations were part of the reason for this study.

The core from the Denver Unit CO_2 pilot area provided an ideal data set to look for the enhanced porosity due to carbonate dissolution implied in the Chevron report. Recent literature on sandstone and carbonate diagenesis emphasizes the role of naturally occurring CO_2 in leaching processes. This study may also be relevant to assessing the role of such processes.

DATA BASE AND METHODS

This report is based on data obtained from the examination of: (1) 735 feet (224 m) of slabbed core; (2) 395 petrographic thin sections; (3) plug and whole core analyses; and (4) chemical analyses of pilot flood water.

All thin sections were examined with a conventional petrographic microscope under plane- and cross-polarized light. Due to pervasive dolomitization of the cored interval, the original depositional texture had been largely obliterated. However, insertion of a thin sheet of paper under the thin section to diffuse the light provided a greatly improved image of the original depositional texture.[2] All thin sections were examined with diffused light.

Thin sections of all samples were prepared using a blue-dyed impregnating resin to aid in the recognition of pore space. The modal composition of 112 samples (wells 3731-W and 3741) was determined by point counting a minimum of 500 points in each thin section. The probable error is ±1.9 percent for a constituent comprising 5 percent of the sample, at a 95.4 percent confidence level. The probable error is ±4.4 percent for a constituent comprising 50 percent of the sample.[3] Bulk mineralogy and visible porosity were counted in this manner.

The fluid observation well, 3733, was perforated in the same interval as 3731-W (pilot injector). Once a week, between August 1, 1977, and February 12, 1978, the fluid observation well was pumped until a total of 25 barrels (3.97 m^3) of water had been produced. Near the end of each test, a sample of water was collected for analysis. These water samples were used to monitor any changes in the chemistry of the pilot flood water.

RESERVOIR GEOLOGY OF THE WASSON SAN ANDRES FIELD

The Wasson San Andres field is located on the southeastern edge of the North Basin Platform in Gaines and Yoakum Counties, Texas. The SWEPI-operated Denver Unit covers about 45 percent of the productive area of the field.[4]

The Wasson San Andres field is a classic example of a carbonate reservoir located on a regressive carbonate shelf platform. The vertical sequence from open marine upward through intertidal and supratidal is a classic regressive or shoaling-upward sequence. The main portion of the oil reservoir is in dolomitized open marine packstones and wackestones, which occur in the position of the "Main Pay" interval (Fig. 4). This section is overlain by progressively poorer-quality, shallower-water restricted marine and intertidal rocks, generally correlative with the "First Porosity" interval. These rocks grade upward into the nonproductive dense mudstone and anhydrite of the overlying supratidal section, which forms the seal of the Wasson San Andres reservoir. The Wasson San Andres section has been subdivided into five "First Porosity" zones and six "Main Pay" zones. These zones can be recognized throughout the Denver Unit.

RESERVOIR GEOLOGY OF THE PILOT AREA

Examination of slabbed cores and thin sections from the "Main Pay" interval showed that three rock types are present: (1) a pelletal dolomite packstone with interparticle and intercrystal porosity (pelletal packstone); (2) a fossiliferous dolomite wackestone with moldic porosity (moldic wackestone); and (3) a fossiliferous dolomite packstone with moldic and interparticle porosity (moldic packstone). Both nodular and pore-filling anhydrite are present in various amounts in all three rock types.

Pelletal Packstone

This rock type occurs both as homogeneous units and in burrows and irregular patches in the wackestones. Due to the excellent interparticle porosity, permeability ranges up to 152 md. Porosity is as high as 24.3 percent.

Moldic Wackestone

Molds and vugs are dominant porosity types, ranging in size up to 6 mm. Many of the molds did not become filled with blue epoxy during sample impregnation. This suggests that they are isolated from other pores by a relatively "tight" matrix. Due to the isolated moldic porosity, this rock type has a permeability of less than 1 md, even though moldic porosity may range as high as 10 percent.

Moldic Packstone

This rock type cannot be distinguished from the pelletal packstone in slabbed cores, but appears as a sucrosic dolomite with more moldic than intercrystal porosity in thin section. Due to the connection of the moldic porosity through interparticle pores, higher permeabilities and lower residual oil saturations are found in these samples than the other rock types in the pilot area.

Environment of Deposition

Examination of the cores suggests that deposition occurred in a shallow marine shelf environment. Moldic wackestones represent the original sediment. Pelletal packstones are probably the remains of fecal pellets produced by organisms which burrowed through the muddy sediment. When this burrowing was very intense, a sediment consisting entirely of pellets was produced as organisms reworked sediment. When burrowing was less prevalent, pellets were restricted to well-defined burrows cutting through wackestone sediment.

Both dolomitizing and anhydrite precipitating fluids were probably derived from overlying, supratidal sediments deposited after the open marine reservoir rocks. The original sediment was composed entirely of calcite and aragonite with no associated dolomite or gypsum.

RESERVOIR MODEL

We used the core from 3731-W, 3734 and 3735 to define correlative layers based on lithology changes. Although bedding is not readily evident in the cores, the excellent log correlation indicates that the rock types change uniformly with depth in all of the pilot area wells. By lining all three cores side by side, and adjusting the depths, it was possible to see cyclic changes in the rock which can be correlated to porosity changes recorded by the neutron logs.

Figure 5 was constructed by determining the average rock type present in all three cores at a given depth. In this manner, local variations could be ignored. Specifically, the rock was divided into four classes: (1) 100 percent packstone; (2) packstone with isolated patches of wackestone; (3) wackestone with isolated patches of packstone, and (4) 100 percent wackestone. The above rock types are listed in order of decreasing porosity and permeability.

Figure 5 shows that a total of 31 layers could be observed in the interval covered by core material from all three of the wells. The thickest and most frequently occurring layers consist of predominantly packstone with isolated patches of wackestone. There are three layers of 100 percent packstone and only one layer which is represented completely by wackestone.

The neutron porosity is plotted for all three of the wells after adjusting log depths to correspond with core depths (Fig. 5). In all three wells, changes in porosity correspond to changes in rock type. The reason for the excellent correlation with porosity logs is related to cyclic changes from a predominantly packstone to a predominantly wackestone rock.

Evidently, burrowing organisms which produced the pelletal packstone did not usually reach an abundance sufficient to create a sediment consisting entirely of fecal pellets. Nor did they usually disappear entirely to allow a sediment which was entirely wackestone to be deposited. Instead, the most common occurrence seems to have been an alternation in the intensity of burrowing accompanying deposition of the wackestone. When the burrows comprise a large percentage of the rock, they form a connected, permeable packstone. However, a small amount of the unburrowed wackestone may still be present. Conditions of temperature, nutrients, water depth and salinity probably alternated between being more or less favorable to the development of the burrowing, pellet-producing organisms. These cyclic changes produced the layered porosity distribution observed today. Performance of the CO_2 pilot has demonstrated that indeed these packstone units do exhibit better fluid flow properties than the adjacent layers.

POROSITY AND PERMEABILITY

Thin sections from wells 3731-W and 3741 were point counted to determine the relative amounts of individual pore types. Six different kinds of porosity are identified in the CO_2 pilot area. All six pore types are represented in both wells and include the following: (1) intercrystal, (2) vug, (3) moldic, (4) intracrystal, (5) fracture, and (6) intraparticle (Fig. 6).

Intercrystal Porosity

Intercrystal pores are those that form between the crystals in the rock. Intercrystal porosity is most common in the packstones throughout the cored sequence. The reason for this particular relationship is that the original rock fabric was grain-supported (either packstone or grainstone). The original rock had abundant interparticle porosity, and hence, after dolomitization and recrystallization the final product is apt to have abundant intercrystal porosity provided an authigenic mineral does not occlude the remaining pore space. Samples with abundant intercrystal porosity provide the highest permeability values.

Vug Porosity

Vugs are irregular-shaped pores that form without regard to original depositional texture. It is interesting to note here that vug porosity is being formed at the expense of anhydrite.

Moldic Porosity

Moldic porosity is most common in the wackestone lithologies; however, this kind of porosity is present in some of the packstones. The molds represent dissolved fossil debris. Some molds are tubular-shaped and represent the molds of foraminifera which are abundant in Permian carbonates. Molds may be touching each other or interconnected by another pore type.

Intracrystal Porosity

All the intracrystal porosity observed occurs within dolomite rhombohedra and can be termed hollow rhombs. It apparently has no particular affinity for any specific lithology. This kind of porosity formed due to the dissolution of anhydrite at some point after anhydrite had replaced the center of the rhombs. The origin of this pore type was discussed by Folk and Siedlecka.[5]

Fracture Porosity

Fractures are not as abundant as some of the other pore types, yet they do contribute to the total porosity. The most striking feature of the fractures is their smooth walls. Apparently a fair amount of fluids have moved along these pathways. Some fractures are partially occluded by anhydrite whereas others are completely anhydrite-free. This pore type is not fabric selective and therefore occurs in all kinds of lithologies.

Intraparticle Porosity

This kind of porosity is volumetrically insignificant in the rocks examined in this investigation. It consists of pores developed within a particular particle type such as a fossil.

Discussion

As noted earlier, rocks in the CO_2 pilot area are mostly mixtures of two end-member rock types. These are moldic wackestone and pelletal packstone. A well-defined boundary can usually be drawn between these rock types even on a microscopic scale. Fluid flow properties accordingly reflect relative proportions of these two rock types.

Figure 7 is a porosity versus permeability plot of data from plugs taken from the 3731-W and 3734 cores. The lithology data are based on the thin sections cut from the end of each plug. The plot shows a group of moldic wackestones at the low end of the porosity and permeability scales. At the high end of both scales there is a group of pelletal packstones. The remainder of the samples show an increase in the amount of packstone present from the lower porosities and permeabilities to the highest values of these parameters. A similar relationship to that shown on Figure 7 was found in the samples from the 3735 core.

Four samples represented by moldic packstone lie above the general porosity/permeability trend. The touching moldic porosity observed in these samples evidently gives them a higher permeability/porosity ratio than the pelletal packstone and moldic wackestone rocks.

It is important to note here that only one thin section was made from each plug, and that the plugs are too heterogeneous to accurately determine the lithology of the entire plug. However, the general trend evident on Figure 7 reflects the changes in rock types as a function of porosity and permeability.

RESERVOIR ROCK DISSOLUTION

Statistical Comparison

Examination and comparison of the pre- and postpilot cores (whole and slabbed) did not show significant evidence of reservoir rock dissolution. However, a statistical comparison of the pre- and postpilot cores was undertaken to document any minor changes in reservoir rock characteristics as a result of brine and CO_2 injection.

Any statistical comparison must first consider the types of data being compared. Data used to statistically compare the prepilot core (3731-W) with the postpilot core (3741) came strictly from point counting. These data were obtained by the same technique in both wells and are comparable.

Prior to making a statistical comparison of the available data, two restrictions had to be imposed on the set so that, as nearly as possible, the same things were being compared. These are: (1) a comparison had to involve the same type of lithology, and (2) no sample could contain more than 10 percent anhydrite.

Comparison of samples composed of the same lithology is important because different combinations of pore types are present in different rock types. A comparison involved thin sections composed of 100 percent packstone or mixed (packstone/wackestone) thin sections where there was not more than 25 percent wackestone. The percent anhydrite restriction was imposed on the data set to avoid large patches or nodules of anhydrite in the rock. The 10 percent cutoff is not only a natural break in percent anhydrite, but accounts for most of the pore-filling anhydrite observed in thin section. Thin section examination shows that the pore-filling anhydrite has undergone preferential dissolution in comparison to the nodular anhydrite.

Student's t test is one of the most common statistical tests of significance.[6,7] The t test is used to test whether two sample sets are from the same population by comparison of the two means. A confidence level can be applied during the test to give an indication of the level of significance.

Statistical facts about the computer data files were calculated (mean, standard deviation, etc.) and the t test was used to determine whether there was a significant change in the various pore and mineral types between 3731-W and 3741. The results of the statistical comparison of pre- and postpilot core are outlined in Table 1. A total of 28 packstone samples and 26 mixed samples from both wells were used in the statistical comparison of pre- and postpilot core.

From a comparison of the packstones one can note that there has been a 1.5 percent increase in total point-counted porosity in the 3741 well but this increase is not significant at the 95 percent confidence level. However, vug porosity increased 1.8 percent and is significant at the 95 percent confidence level. At least some of the vug porosity in the packstones formed at the expense of anhydrite.

When comparing the mixed lithologies, one finds that total point-counted porosity increased less than one percent in the 3741 well and is not significant at the 95 percent confidence level. However, both moldic and vug porosity increased significantly in the 3741 well. These pore types also formed at the expense of anhydrite. The fact that moldic and vug pores increased significantly in the 3741 well is due to lithology in this case. Molds are a common pore type in the wackestones and anhydrite-filled molds are also common. Thus, if anhydrite was being dissolved during fluid injection in the pilot area, then moldic pores would have a good chance of being formed by the dissolution process.

Petrographic and Chemical Evidence

Thin section examination of postpilot core (3741) did not show evidence of dolomite dissolution. Large vugs, channels or other evidence of high permeability thief zones created by carbonic acid dissolution of the dolomite were not observed in the postpilot core located 25 feet (7.6 m) from the pilot injection well. However, minor anhydrite dissolution is documented from thin section examination and chemical analyses of the pilot flood water. These results are significant when one considers the large brine and CO_2 injection volumes (approximately 90 pore volumes of brine and 30 pore volumes of CO_2) that contacted the postpilot core.

Anhydrite dissolution is a common process that affected the reservoir rock and produced several features which were observed in thin section. The dissolution features are more prevalent in the postpilot core (3741) and includes: (1) etching and embayment of anhydrite crystal margins, (2) solution of anhydrite parallel to cleavage, producing rectangular pores within anhydrite crystals, (3) solution of anhydrite at boundaries between dolomite crystals and anhydrite, (4) optically continuous anhydrite crystals separated by void space in the rock, and (5) partial dissolution of anhydrite in the centers of molds and vugs. The result of anhydrite dissolution is porosity enhancement.

Figure 8 shows that anhydrite dissolution has taken place in a void that was originally a moldic pore prior to porosity occlusion by anhydrite. The smooth, curved surfaces of the anhydrite suggest that moving liquids were responsible for this feature. All anhydrite in the photograph is in optical continuity.

Figure 9 shows an unusual anhydrite dissolution feature. All the anhydrite in this photograph is in optical continuity; however, the anhydrite was preferentially dissolved along some cleavage planes and not others.

Chemical analyses of brine preflood water from the fluid observation well (3733) provided additional evidence of anhydrite dissolution. The purpose of this brine (65 000 mg/L Cl^-) injection was to precondition the pilot area with a low resistivity water. The brine preflood was designed to establish a more uniform, known distribution of water salinity and provide significant resistivity contrast between brine and hydrocarbon phases for increased accuracy in quantitative log analysis. The Cl^- concentration increased steadily in the fluid observation well from 11 000 to 65 000 mg/L, indicating that floodout of the reservoir had occurred. Anhydrite dissolution was evidenced by an increase in calcium and sulfate ions above the level normally associated with the increase in sodium chloride (Fig. 10). In fact, the measured calcium and sulfate concentrations were in line with the theoretical equilibrium value calculated from textbook equilibrium constants. The calculated rock volume dissolved is 1880 ft^3 (53 m^3) or 0.04 percent of the total bulk volume of a cylinder with radius of 122 feet (37 m) and length of 92 feet (28 m).

CONCLUSIONS

Core studies in the CO_2 pilot area revealed two basic end-member rock types: pelletal packstones, which exhibit high porosity and permeability due to the effective inter-pellet pore fabric; and moldic wackestones, which have lower porosity and significantly lower permeability, due to the disconnected fabric of the moldic pores. The majority of the rock section consists of a mixture of these end-member rock types due to cyclical variations in the degree of organic burrowing, which created the pellet packstones, by reworking of the original wackestone lithology. The geologic model of the pilot area thus consists of numerous correlative porosity zones composed dominantly of packstones, interbedded with poorer quality moldic wackestones.

Thin section examination of postpilot core did not show evidence of dolomite dissolution. However, minor anhydrite dissolution (probably due to large brine injection volumes) is documented from thin section examination and chemical analyses of the pilot flood water. As a result of anhydrite dissolution, total point-counted porosity is slightly higher in the postpilot core but not statistically significant. Large vugs, channels or other evidence of high permeability thief zones created by carbonic acid dissolution of the dolomite were not observed.

Since carbonic acid is an effective agent for increasing the solubility of dolomite, the lack of a substantial porosity increase in the postpilot core must be explained. We believe that a substantial portion of the pore volume during the CO_2 flood contains CO_2 rather than carbonic acid. Some undisplaced water will be trapped in the smaller pores as the wetting phase and CO_2 will dissolve in this water forming carbonic acid. This carbonic acid will in turn dissolve dolomite until dolomite saturation is reached. However, since the water will not be a mobile phase to any great extent during the CO_2 flood, no transport mechanism exists to remove the Ca^{2+}, Mg^{2+}, and HCO_3 ions from the small pores. The introduction of large amounts of CO_2 into the reservoir increases the solubility of dolomite but inhibits the removal mechanism for the dissolved products. In contrast, the anhydrite was dissolved during the brine preflood. The introduction of brine undersaturated with $CaSO_4$ during this preflood both enhanced solubility and provided a transport mechanism, resulting in small but statistically significant increases in porosity. Minor amounts of dolomite dissolution may have contributed to this porosity increase. A brine postflood was carried out after the CO_2 flood and should have formed carbonic acid from trapped CO_2 and provided a transport mechanism to remove dissolved dolomite from the reservoir. There is ample evidence that this occurred. However, sufficient pore volumes of brine were not available to significantly increase total porosity in our samples.

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Table 1

		PRE PILOT DU 3731-W		POST PILOT DU 3741		Δ AVG.% 3731→3741	STATISTICALLY SIGNIFICANT @ 95% C.L.?
		AVG.%	RANGE%	AVG.%	RANGE%		
PACKSTONES n=28	POINT-COUNT POROSITY	13.9	9.6-21.4	15.4	8.8-19.2	+1.5	NO
	INTERCRYSTAL POROSITY	11.9	7.8-21.2	11.0	3.0-16.8	-0.9	NO
	VUG POROSITY	0.9	0.0-3.0	2.7	0.6-6.4	+1.8	YES
	MOLDIC POROSITY	0.8	0.0-2.6	0.9	0.0-3.8	+0.1	NO
	INTRACRYSTAL POROSITY	0.3	0.0-2.8	0.5	0.0-3.0	+0.2	NO
	FRACTURE POROSITY	0.1	0.0-0.6	0.3	0.0-1.4	+0.2	NO
	ANHYDRITE	3.0	0.4-7.1	3.3	0.0-9.2	+0.3	NO
MIXED n=26	POINT-COUNT POROSITY	12.5	6.8-25.0	13.3	7.9-20.6	+0.8	NO
	INTERCRYSTAL POROSITY	10.8	4.4-23.4	8.9	3.2-17.2	-1.9	NO
	VUG POROSITY	0.9	0.0-2.3	2.0	0.4-4.4	+1.1	YES
	MOLDIC POROSITY	0.4	0.0-0.8	1.6	0.0-6.4	+1.2	YES
	INTRACRYSTAL POROSITY	0.3	0.0-1.0	0.5	0.0-2.8	+0.2	NO
	FRACTURE POROSITY	0.1	0.0-0.8	0.2	0.0-1.0	+0.1	NO
	ANHYDRITE	5.4	1.4-9.0	4.2	0.6-9.4	-1.2	NO

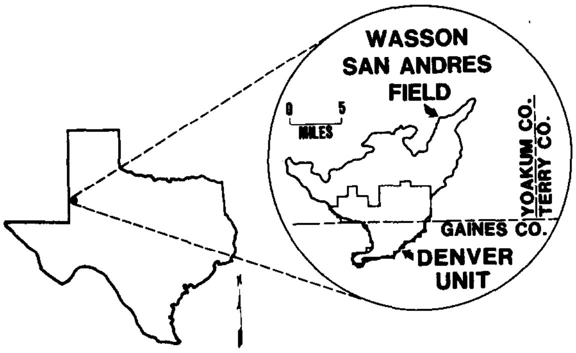


Figure 1 - Location map, Denver unit, Wasson San Andres Field

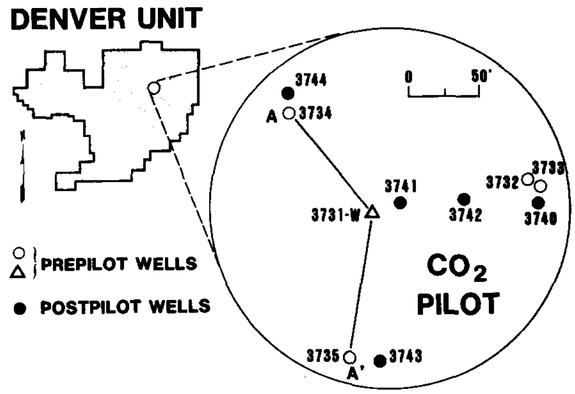


Figure 2 - Bottomhole well configuration, Denver unit, CO_2 pilot area

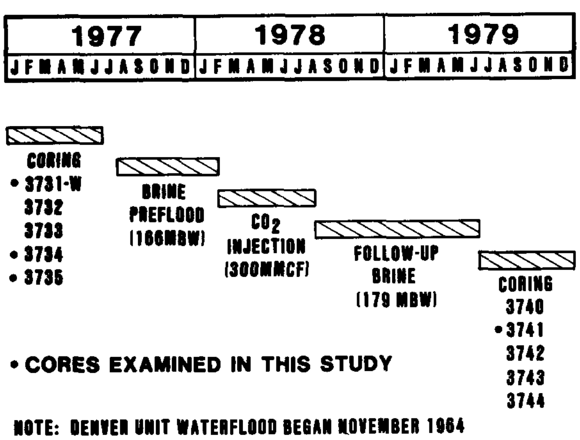


Figure 3 - Denver unit, CO_2 pilot timing

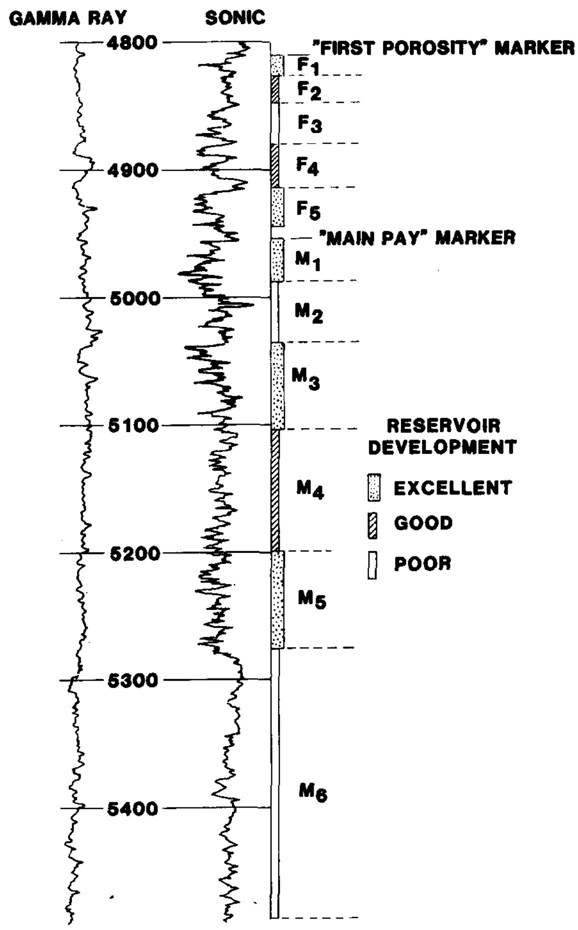


Figure 4 - Example log showing zonal subdivision of San Andres reservoir

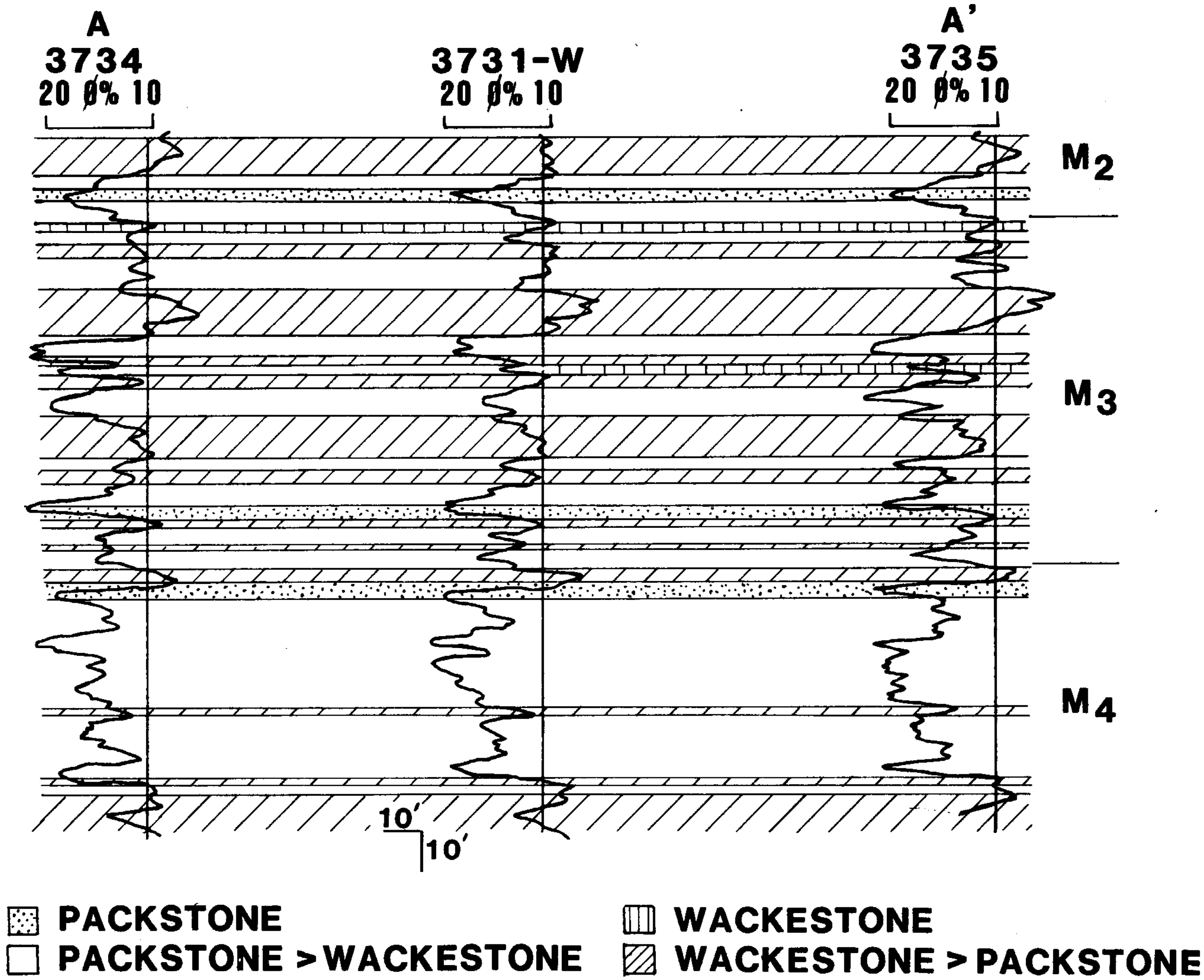


Figure 5 - Cross section of CO_2 pilot area showing correlation of rock types

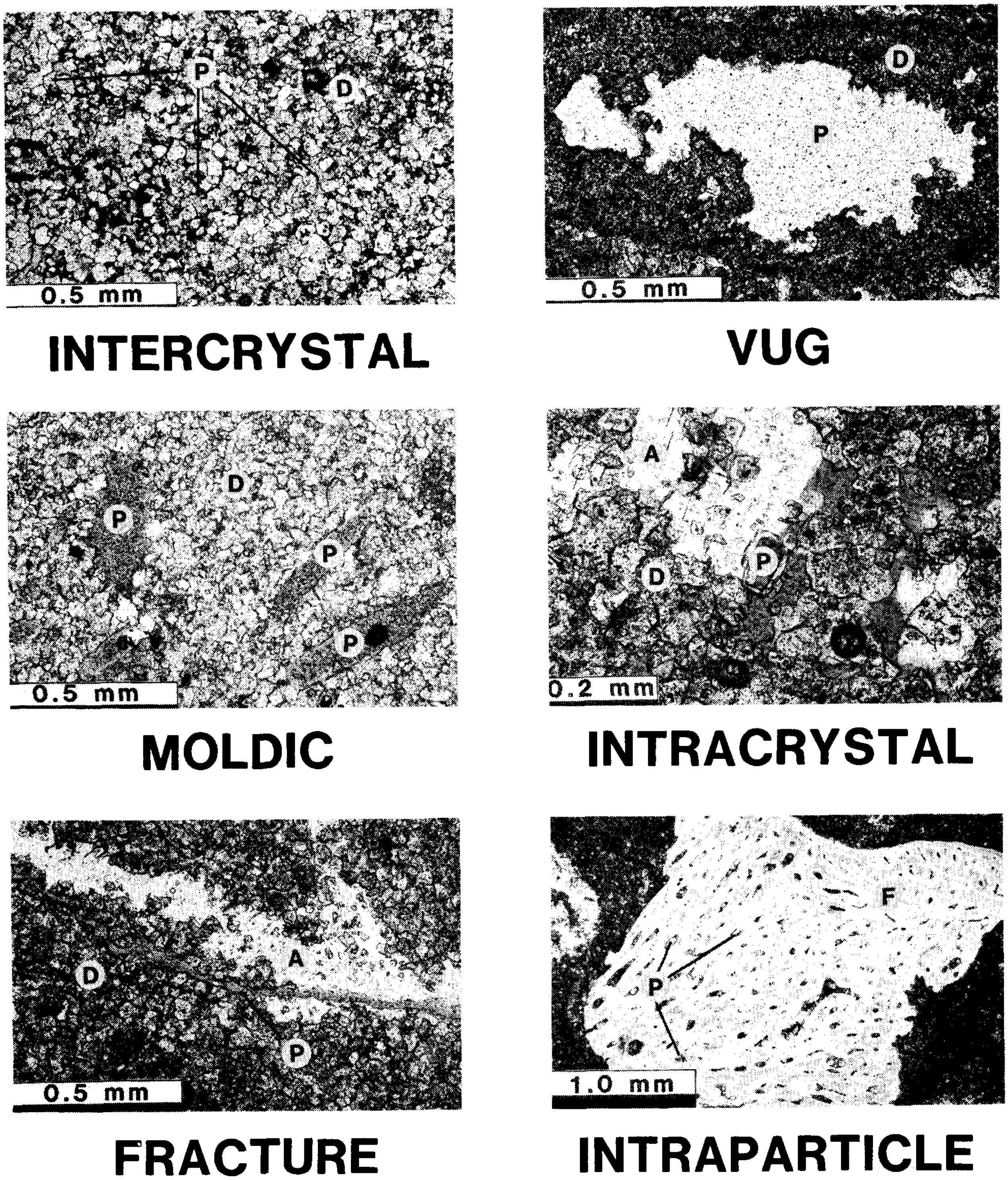


Figure 6 - Thin section photomicrographs of pore types from CO_2 pilot area — (A) anhydrite, (D) dolomite, (P) porosity, (F) fossil

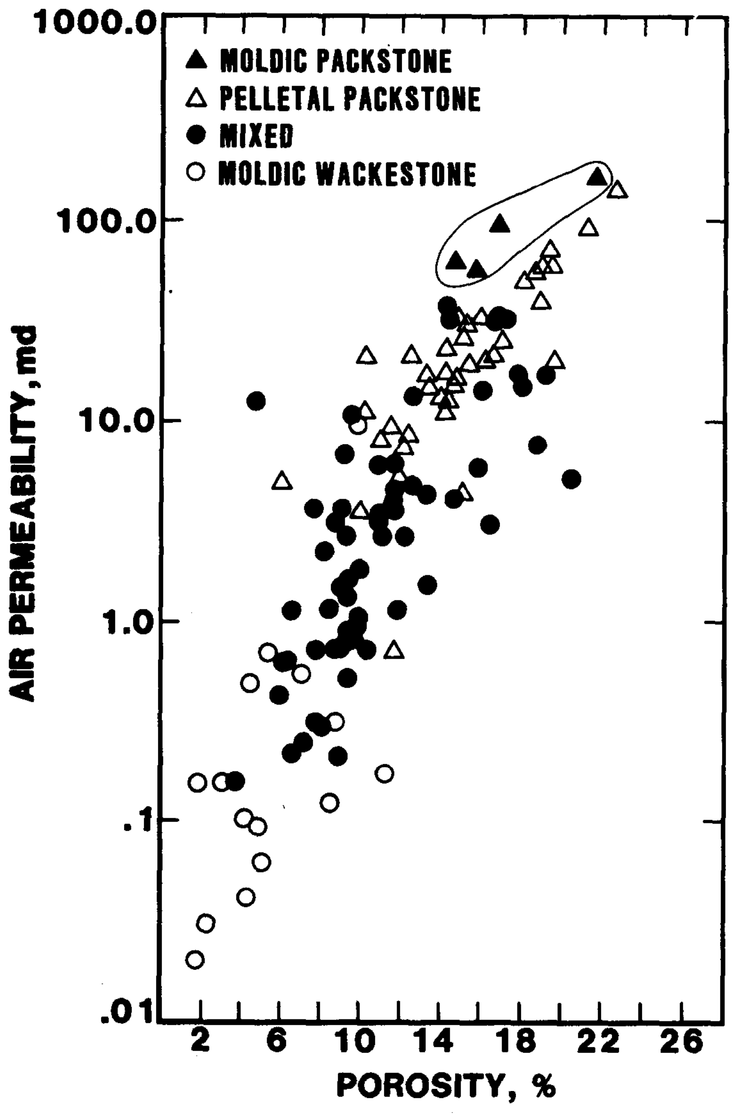


Figure 7 - Relationship between porosity, permeability and rock types

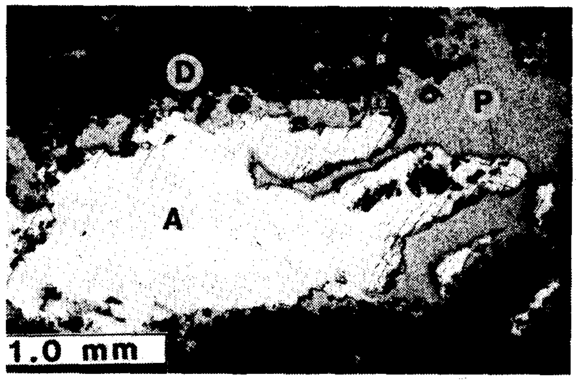


Figure 8 - Example of anhydrite (A) dissolution, (D) dolomite, (P) porosity, 3741. Plane-polarized light

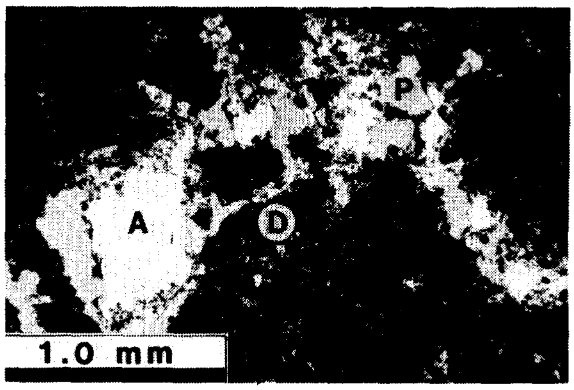
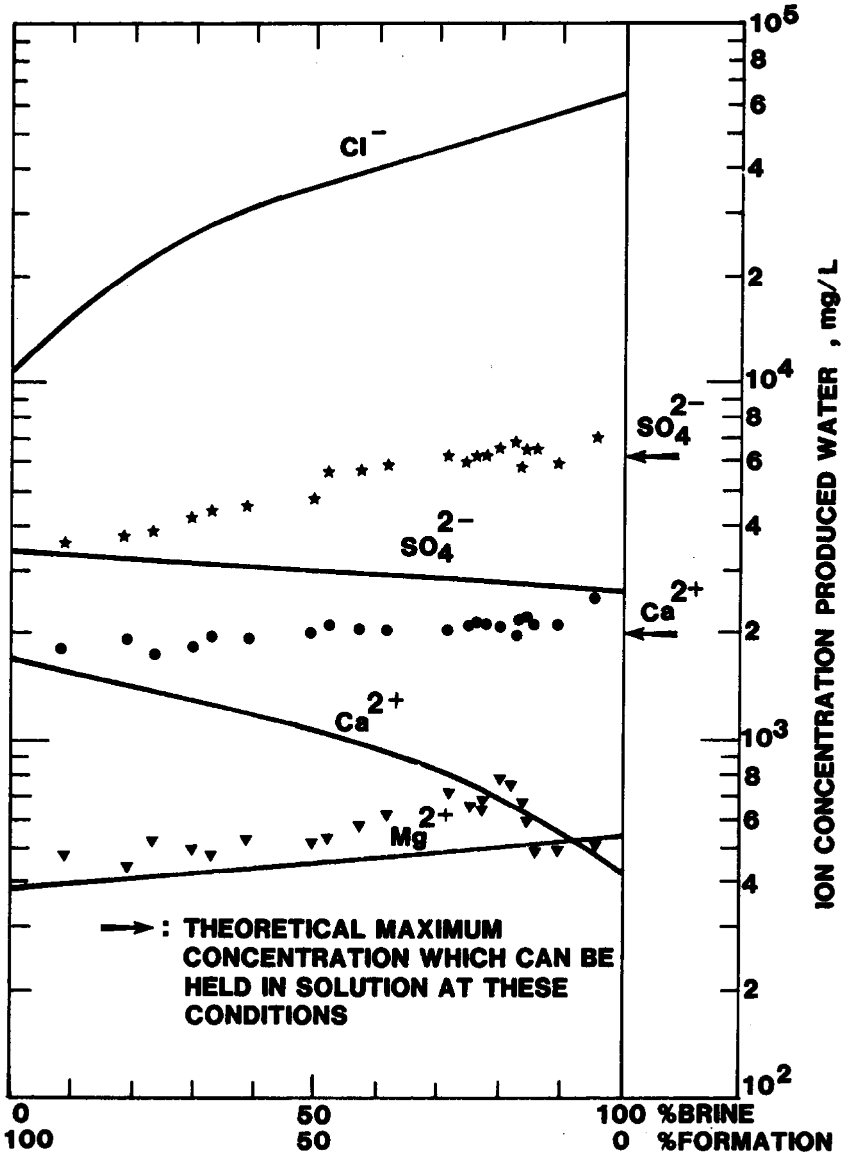


Figure 9 - Example of anhydrite (A) dissolution, (D) dolomite, (P) porosity, 3741. Plane-polarized light



SOLID LINES: COMPOSITION OF SAMPLED FLUID BASED ON INJECTED BRINE MIXING WITHOUT DISSOLVING FORMATION ROCK

★ $[SO_4^{2-}]$ • $[Ca^{2+}]$ ▼ $[Mg^{2+}]$

Figure 10 - Brine preflood data, CO_2 pilot area