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Evolution of Porosity in "Deep" Sandstones of the Permian upper part of the Minnelusa Formation, Powder River Basin, Wyoming

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Abstract

Analysis of intergranular volume in deep (>15,000 feet) sandstones of the Permian upper part of the Minnelusa Formation has demonstrated that porosity loss in these sandstones is largely a function of cementation rather than mechanical compaction or pressure solution. Intergranular volume, defined as the sum of porosity and cements, averages 42% of the rock volume, which approximates the initial (depositional) porosity of eolian and related sands. Quartz cement averages 49% of the intergranular volume, dolomite averages 35%, and porosity averages 13%. Quartz and dolomite cementation are the main cause of porosity loss. The few relatively low values of intergranular volume indicate that compaction occurred locally, possibly due to a lack of early quartz cement.

Porosity averages 5% of the whole-rock volume, and ranges up to 23%. Secondary porosity is present locally, formed by the dissolution of anhydrite cement and potassium feldspar. Sandstones with porosities greater than 8% generally have a component of porosity formed by anhydrite or feldspar dissolution. Sandstones with porosities less than 8% are those with high percentages of quartz cement; the porosity is widely spaced and isolated by extensive quartz overgrowths.

Introduction

Exploration for hydrocarbons remains active in the eolian sandstones of the Permian upper part of the Minnelusa Formation in the Powder River Basin. Most of the production from the Permian upper part of the Minnelusa is from sandstones at depths ranging from 6000 to 10,000 feet. As the Upper Minnelusa play has matured, most drilling has focused on sandstones in this depth interval. However, some drilling has occurred, and a few fields have recently been discovered (Jorgenson and James, 1988), at depths greater than 10,000 feet. Several fields, such as Reno, Reno East, and Pheasant, were discovered at depths of approximately 15,000 feet in the 1960's (Wyoming Geological Association, 1981). Important questions facing the explorationist are 1) how much porosity is present at depths greater than 10,000 feet in the upper part of the Minnelusa, and 2) how is the porosity distributed. The purpose of this paper is to document the evolution of porosity in sandstones of the upper part of the Minnelusa Formation from depths greater than 15,000 feet, the deepest penetrated Minnelusa sandstones in the Powder River Basin. The amount, type, and distribution of porosity at depths greater than 15,000 feet constitute a "worst-case scenario" for porosity in the upper part of the Minnelusa between 10,000 and 15,000 feet.

This study documents a petrographic and scanning-electron microscope (SEM) examination of 37 samples from core of three wildcat wells drilled into the sandstones of the Permian upper part of the Minnelusa Formation at depths ranging from 15,000 to 15,400 feet (Figures 1,2). All samples were point-counted for 1) whole-rock composition (Table 1), 2) determination of sandstone type (Table 2), and 3) amounts of intergranular volume, porosity, and authigenic constituents (Table 3).

Facies of the upper part of the Minnelusa

The Permian upper part of the Minnelusa Formation consists of a series of transgressive-regressive depositional cycles, beginning with marine dolomites that grade into shoreline, sabkha, and eolian sandstones (Fryberger et al, 1983; Fryberger, 1984; George, 1984). These cycles are identified in cores of the deep wells sampled for this study. The samples were taken from shoreline, sabkha, and eolian sandstones, with most of the samples representing eolian ripple and avalanche strata.

Framework Composition of Sandstones

The framework compositions of the sandstones, calculated from point-count data (Tables 1, 2), indicate that the average composition is a subfeldspathic arenite. Quartz ranges from 70 to 99% of the framework, feldspar up to 28%, and lithics range up to 7% of the framework. Most sandstones are subfeldspathic arenites, but several sandstones are quartz arenites, using the classification of Pettijohn, Potter, and Siever (1973). Feldspar is dominantly potassium feldspar; plagioclase is rare (Table 1). Lithic grains are mainly dolomite clasts, followed by detrital chert.

Intergranular Volume

Intergranular volume is defined as the volume of a sandstone that is not occupied by framework grains, and is the sum of porosity and cements. Mechanical compaction and pressure solution decrease the amount of intergranular volume (hence porosity is lost). Cementation results in a reduction of porosity, but does not change the amount of intergranular volume. Most sandstones exhibit some combination of cementation, mechanical compaction, and pressure solution (Houseknecht, 1987; 1988).

Values of intergranular volume for the deep sandstones of the upper part of the Minnelusa average 42%, with a low of 27%, and a high of 64% (Figure 3). The average value of 42% indicates that, overall, little compaction has occurred in these sandstones as initial (depositional) values for intergranular volume are approximately 40% (Houseknecht, 1988). The low values, however, indicate that some sandstones have been partly compacted, and the highest values demonstrate peripheral replacement of framework grains by cements. The sandstones with intergranular space greater than 50% are those that have been pervasively cemented, and partially replaced, by dolomite. The values below 40% may represent those samples that had little early quartz cement. In contrast to samples with early cement such as quartz, the relatively uncemented sandstones would not have been as protected from compaction. This variability in intergranular space, in closely spaced samples, suggests that the early quartz cement had an irregular rather than a uniform distribution.

Diagenetic Alterations

Quartz Cement

Quartz, the first cement to form (Figure 4), forms 5 to 36 (averaging 20%) of the volume-percent of the whole-rock. With respect to intergranular volume, quartz cement occupies 13 to 88%, and averages 49%. Quartz forms syntaxial overgrowths that range from small, isolated overgrowths to interlocking mosaics that pervasively cement a local pore system (Figure 5A). The porosity remaining in sandstones in which the intergranular volume consists of more than 49% quartz cement is isolated in the centers of the pores, and widely separated (Figure 5B).

Quartz cementation began early as indicated by the overgrowths surrounding some quartz grains. The quartz cement may have produced a rigid framework that arrested compaction. The irregular distribution of quartz cement means that some sands were not as compacted relative to adjacent sands that were not as cemented.

Anhydrite Cement

Anhydrite cement was found in six samples (Table 1). The anhydrite post-dates, and partly replaces, quartz cement (Figure 6A). Like quartz, anhydrite cement may have had an irregular distribution, mainly cementing those sandstones with little to moderate quartz cementation.

Anhydrite is found as a poikilitic cement, where single crystals of anhydrite cement several adjacent pores. The anhydrite abuts previous quartz overgrowths, but in many cases replaces the overgrowths and parts of the detrital grains.

Anhydrite Dissolution

Anhydrite cement dissolved to produce secondary intergranular porosity. Evidence for dissolution included optically continuous, isolated remnants of anhydrite, and embayments along the edges of remnant anhydrite (Schenk and Richardson, 1985). Anhydrite dissolution was isolated, reflecting the initial distribiution of anhydrite cement (samples EA15285-6; EA15294-5; EA15364-5). In these samples the porosity is 8 to 23%, the highest values recorded from the deep sandstones. Thus, isolated areas of anhydrite may have dissolved to produce local porosity highs, whereas adjacent sandstone was cemented mainly by quartz or dolomite.

Dolomite Cement

Dolomite cement comprises an average of 15% of the whole rock in the deep sandstones of the upper part of the Minnelusa and ranges up to 54% (Table 3). Dolomite occupies up to 84% of the intergranular volume in the sandstones; it averages 35%. Dolomite and quartz together account for an average of 85% of the intergranular volume.

Dolomite occurs as isolated rhombs or as subhedral to anhedral masses of crystals that pervasively cement some sandstones (Figure 6B). Dolomite replacement of framework quartz grains is common, and in one sample a sandstone was diagenetically converted to a "dolomite" by replacement (Sample 3-34A-15339). Where dolomite cementation and replacement is pervasive, the differentiation of dolomite cement from dolomite lithic clasts is difficult.

Dolomite cement post-dates both quartz and anhydrite cement, as it is found both on and replacing these phases. Dolomite replaces both the quartz framework and overgrowth cement (Figure 6B). Dolomite automorphically replaces anhydrite cement, manifested as small rhombs in the anhydrite cement (Figure 6A).

Feldspar Dissolution

Potassium feldspar averages 8% in the deep Minnelusa sandstones, and ranges from 1 to 28%. In several samples the feldspars are partially dissolved (Figure 7A), forming a small percentage of intragranular porosity (Table 1).

Sandstones that exhibit feldspar dissolution have total porosities greater than 8%; if little or no feldspar dissolution was observed, porosity is generally less than 8%. Thus, a relationship is suggested between total porosity and feldspar dissolution. Samples with pervasive quartz cementation do not exhibit feldspar dissolution.

Dolomite rhombs and several detrital chert grains also exhibit some dissolution, possibly related to migrating fluids that partially removed the feldspars. However, dissolution of dolomite and chert is rare, producing only a trace component of porosity.

Hydrocarbon Migration

Hydrocarbons migrated into the sandstones relatively late in the burial history of the upper part of the Minnelusa. Dead oil lines pores in several samples (Figure 7B). Many of the thin sandstones in the Energenetics Inc. 12-34 Ackerman core are stained with oil.

Other Diagenetic Phases

Other diagenetic phases observed in trace amounts in the sandstones included illite, chert cement, and pyrite (listed as "others" in Table 3).

Illite occurs as lath-like crystals on dolomite and quartz overgrowths, and as thin coatings on detrital grains in one sample (7m-15048). Chert occurred as a cement in the centers of a few pores and as a replacement after dolomite. Pyrite was observed replacing quartz and dolomite, and may have formed as iron in the migrating oil combined with sulfur liberated during anhydrite dissolution. Illite, chert, and pyrite are rare, and contribute little to the evolution of porosity in the sandstones.

Evolution of Porosity

From initial values of approximately 40%, porosity in the deep sandstones of the upper part of the Minnelusa now averages 5% (Table 3), and ranges up to 23% (Figure 8). Porosity averages 13% of the intergranular volume, and ranges up to 45% (Table 3). The average value of 42% for intergranular volume demonstrates that cementation was more important in the evolution of porosity than the processes of mechanical compaction and pressure solution.

Quartz was the earliest cement, and probably continued to be deposited throughout much of the burial history of the sandstones as rising basinal fluids cooled, precipitating quartz (Wood and Hewett, 1984). Pervasive quartz cementation was irregular in distribution. Anhydrite cement and dolomite cement formed later, mainly in areas not cemented heavily by quartz. Dissolution of relatively soluble anhydrite increased porosity (Figure 9), but the irregular distribution of anhydrite produced a similar distribution of dissolution porosity. Potassium feldspar dissolution occurred in sandstones that had higher porosities (Table 1), as fluids were able to pass through the more porous sandstone.

Discussion

The amount of intergranular volume initially present in a sandstone is a function of grain size and sorting (Houseknecht, 1987), but is also related to depositional process. For example, eolian sands exhibit initial porosities (intergranular volumes) ranging from an average of 39% in ripple strata to 47% in avalanche strata (Schenk, 1983). The relatively high value for avalanche strata is due to the loose packing of grains produced during avalanche processes. This variability in initial value of intergranular volume demonstrates that caution is necessary when estimating the amount of compaction in a sandstone from the amount of intergranular volume. This caution applies to the sandstones of the upper part of the Minnelusa, as many of the samples were eolian ripple and avalanche strata.

As a sandstone is progressively cemented, porosity decreases, and intergranular volume is conserved if compaction is not a factor. In the ideal case, pervasive cementation would, in the absence of mechanical and chemical compaction, conserve initial intergranular volume. However, some cements partially replace framework grains, leading to values of intergranular volume that are as high as 55 to 60%. Peripheral replacement of framework grains is difficult to differentiate from intergranular cementation during point-counting. Thus, replacement serves to increase the values of intergranular volume, although such replacements of framework constituents should strictly be condsidered as part of the intragranular volume. Dolomite is both a cement and a replacement phase in the upper part of the Minnelusa, and sandstones heavily cemented with dolomite exhibit anomalously high values of intergranular volume, indicative of peripheral framework replacement. Dissolution of framework grains leads to the the designation of the porosity as intragranular volume.

The high values of intergranular volume, and the presence of soluble cements such as anhydrite and dolomite, recorded from the deep sandstones of the upper part of the Minnelusa suggest the possibility that porosity greater than 8 to 10% could be present at depth. Anhydrite and dolomite dissolution were noted on a small scale in the sandstones; the possibility exists that these minerals were more pervasive elsewhere. If removed, significant porosity could occur at depth.

Sandstones pervasively cemented with quartz are subject to fracturing, particularly in areas where the sandstones have been structurally modified. The few fields discovered in the deep sandstones, such as Reno, Reno East, and Pheasant, have been associated with anticlinal structures (Wyoming Geological Association, 1981). The possibility of fracture porosity in deep sandstones cemented by quartz should be considered.

Summary

The loss of porosity in the deep sandstones of the upper part of the Minnelusa Formation is largely a function of quartz and dolomite cementation. The dissolution of anhyhdrite and feldspar may be important locally for porosity that is higher than 8 to 10%. Mechanical compaction and pressure solution played a minimal role in the loss of porosity in these sandstones, as indicated by the values of intergranular volume.

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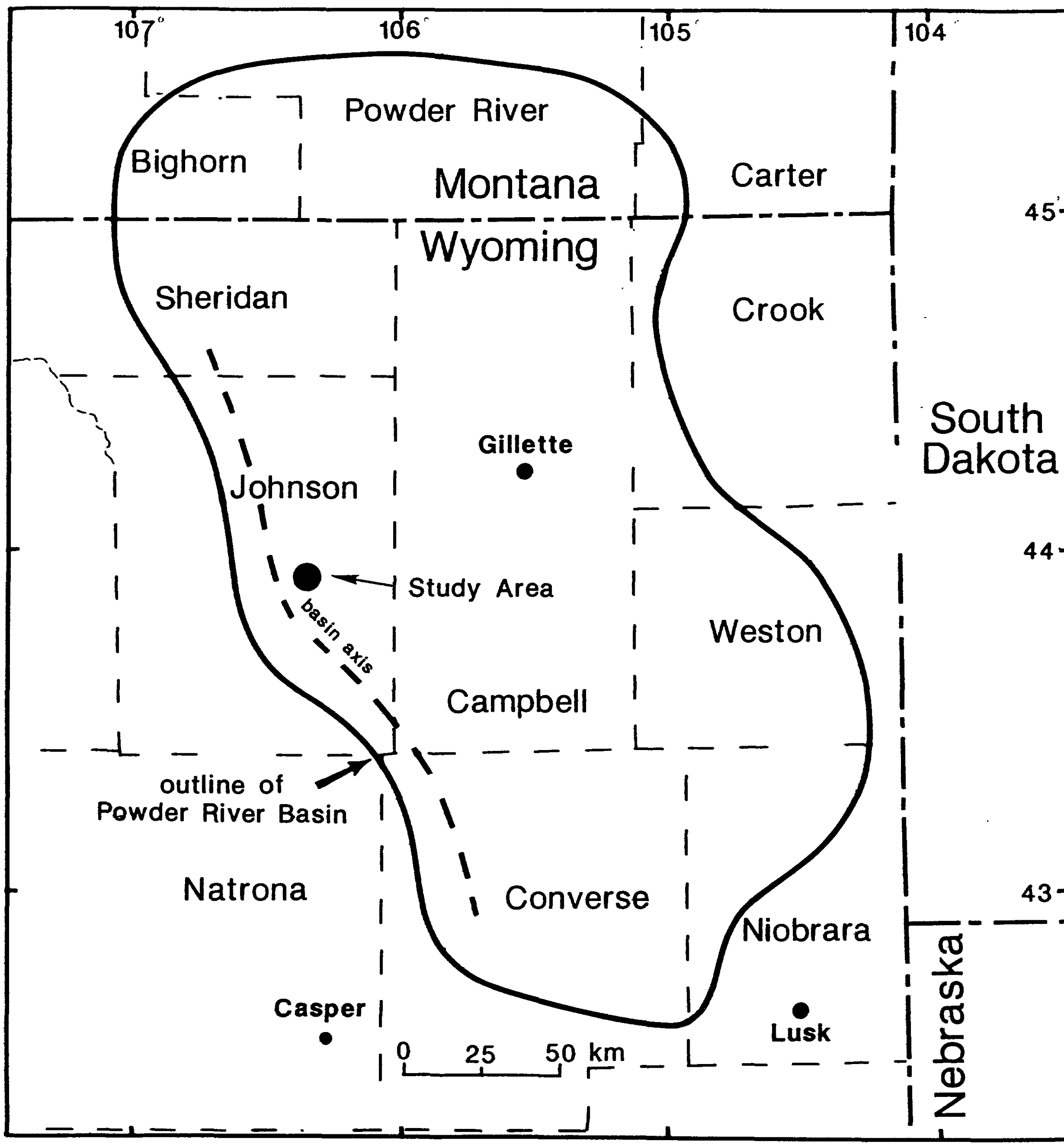

Figure 1. Location map outlining the Powder River Basin and the study area in northeastern Wyoming and southeastern Montana. The three wells sampled for this study are located along the basin axis in Johnson County, Wyoming. The Permian upper part of the Minnelusa Formation is buried to greater than 15,000 feet in this area.

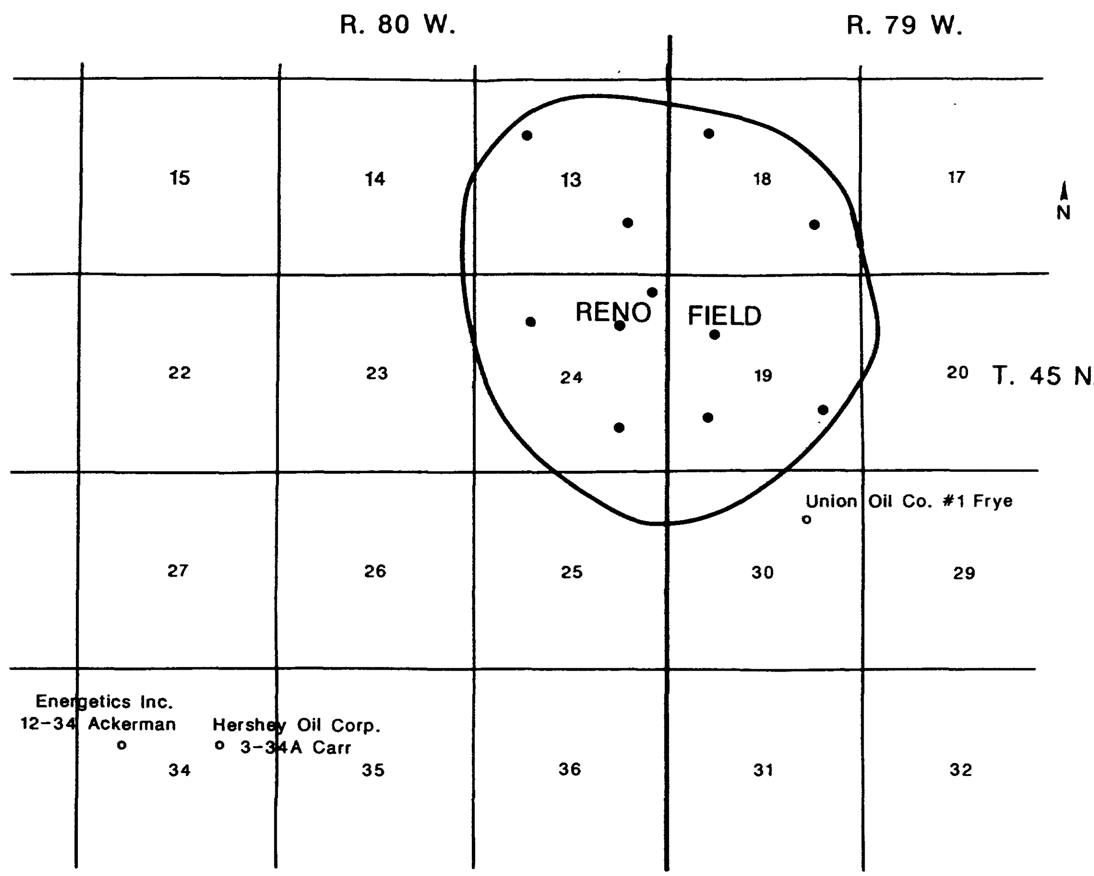

Figure 2. Location map of the three wells studied in Johnson County, Wyoming. The wells are 1) Energetics Inc. 12-34 Ackerman, SW NW sec. 34, T. 45 N., R. 80 W., 2) Hershey Oil Corp. 3-34A Carr, Sw NE sec. 34, T. 45 N., R. 80 W., and 3) Union Oil Co. 1 Frye, NW NE sec. 30, T. 45 N., R. 79 W. Sample numbers in Tables 1-3 correspond to sampled footages in these wells. Reno Field produces from the Permian upper part of the Minnelusa Formation; black dots are producing wells.

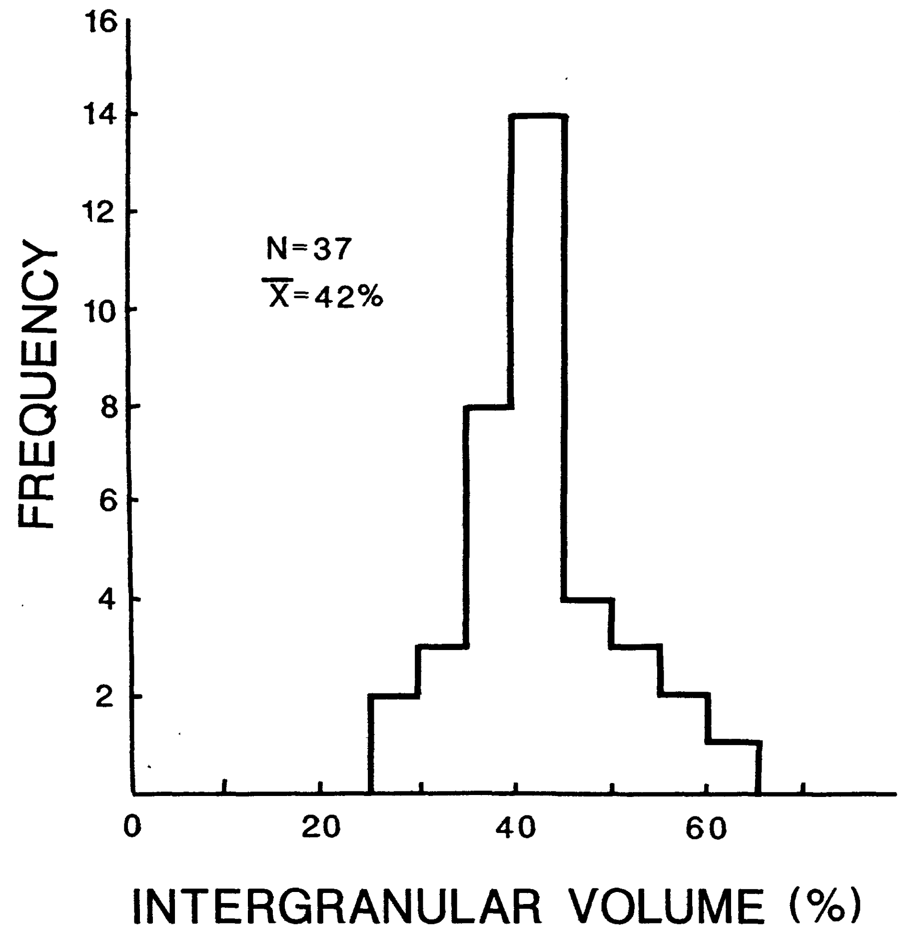

Figure 3. Histogram of intergranular volume in deep sandstones of the Permian upper part of the Minnelusa Formation. Intergranular volume is the sum of porosity and cements, and averages 42%. This value indicates that, in general, little compaction and pressure solution has occurred in these sandstones. Values of intergranular volume greater than 50% indicate that cements have partially replaced framework grains.

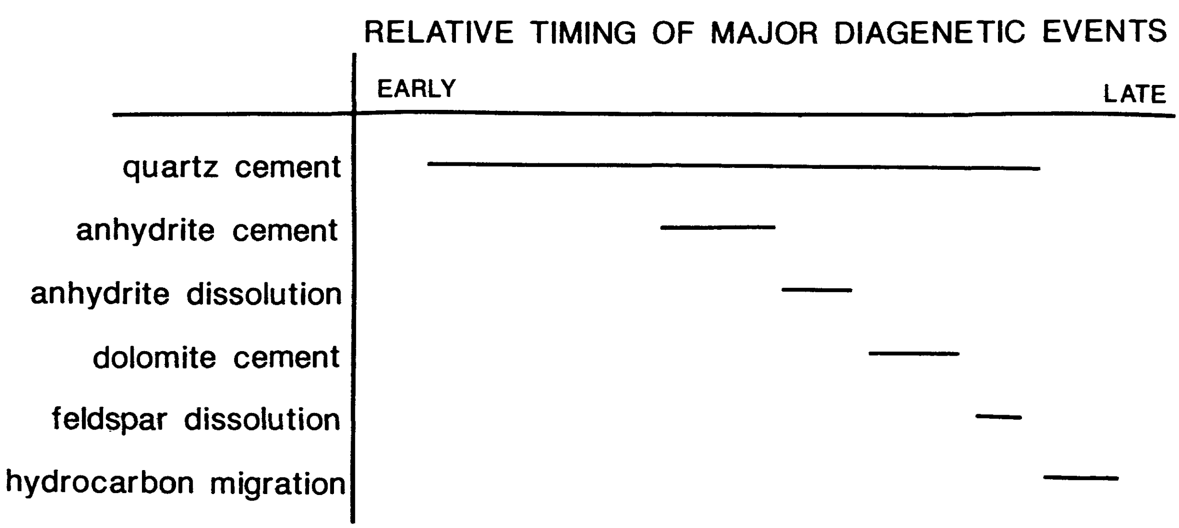

Figure 4. Relative timing of major diagenetic events in the deep sandstones of the upper part of the Minnelusa Formation. Quartz and dolomite cementation is the major cause of porosity loss in the sandstones.

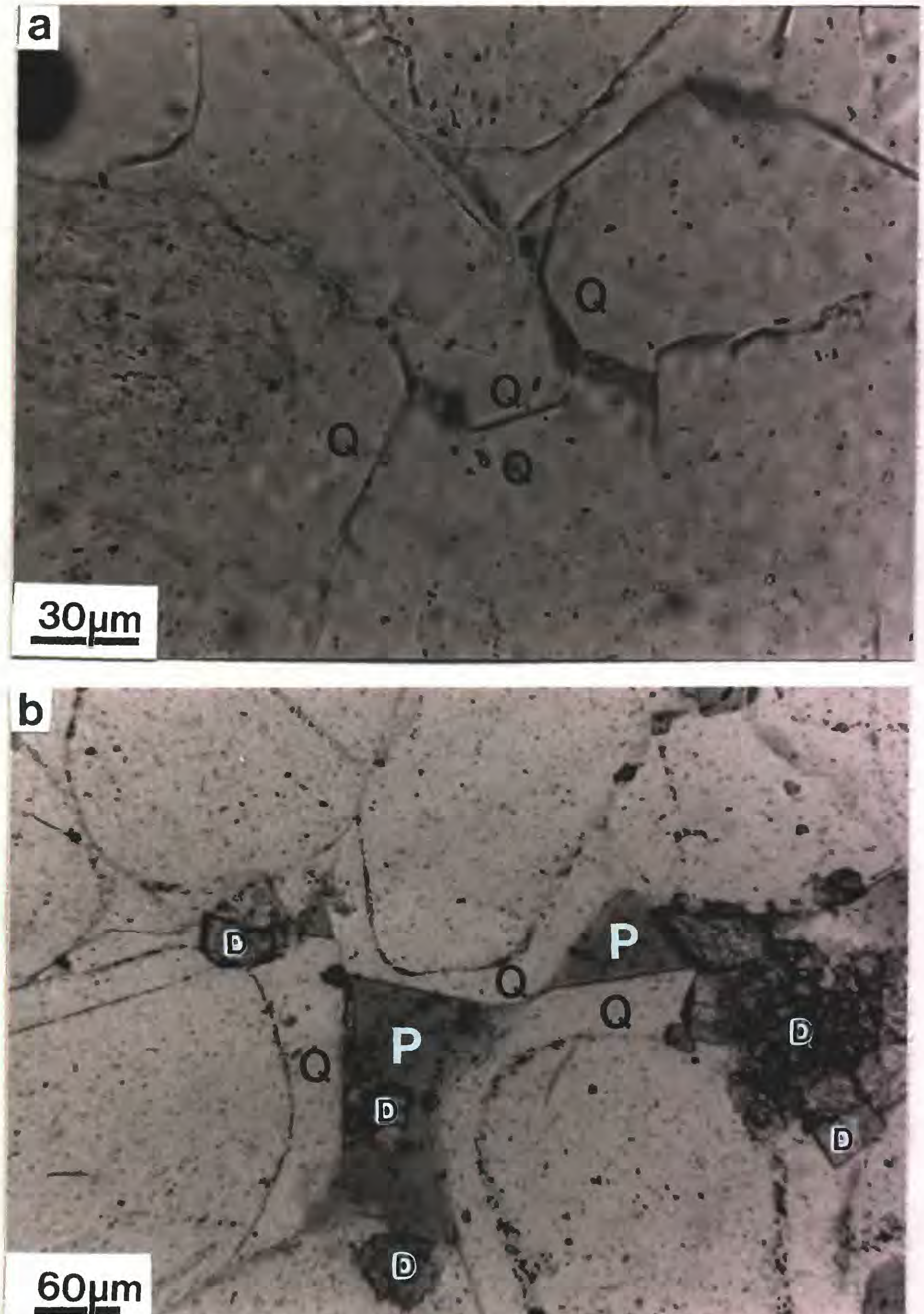

Figure 5. (A) Pervasive cementation by quartz results in interlocking quartz overgrowths (Q) and no porosity; Sample EA15266. (B) Less pervasive quartz cementation (Q) results in isolated and widely spaced porosity (P). Dolomite (D) cement partially fills pores. Sample EA15364-5.

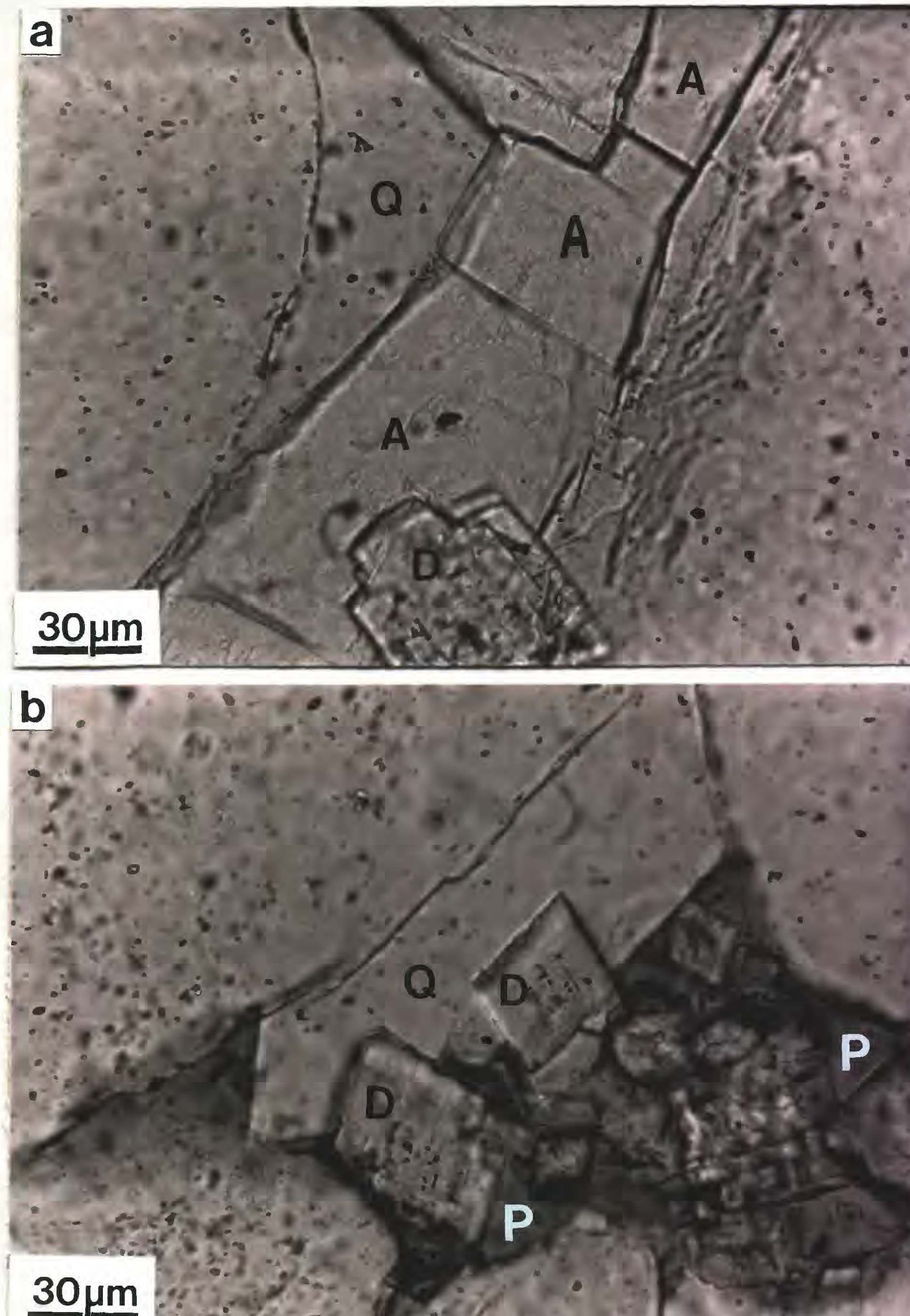

Figure 6. (A) Anhydrite cement (A) locally fills pores, and abuts quartz overgrowths (Q). Anhydrite also replaces quartz grains and overgrowths. Dolomite (D) automorphically replaces anhydrite. Sample EA15364-5. (B) Dolomite cement (D) replaces quartz, as demonstrated by automorphic penetration of dolomite into quartz. Note porosity (P) between dolomite rhombs. Sample EA15285-6.

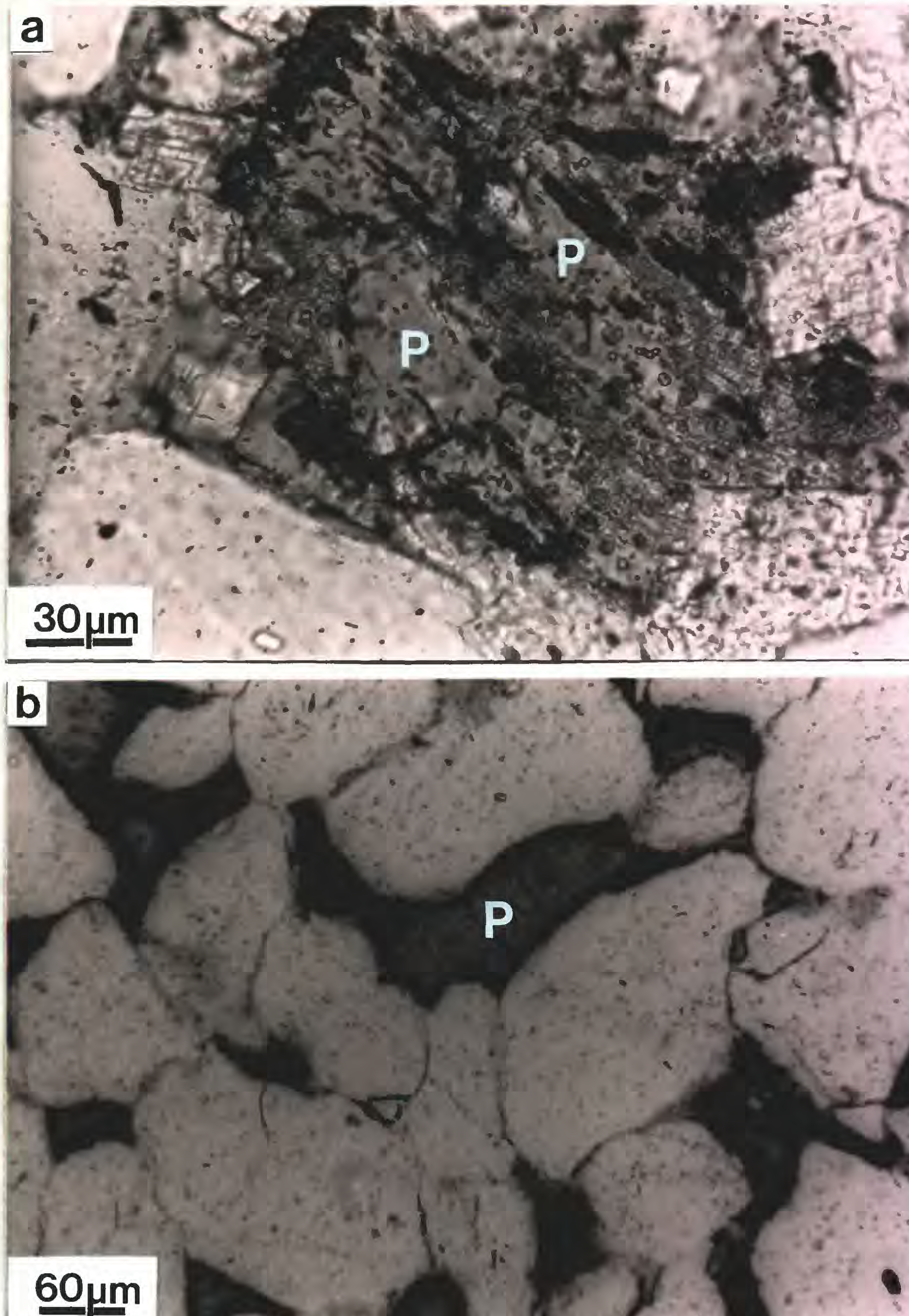

Figure 7. (A) Potassium feldspar was observed in all stages of dissolution. In this example only a skeletal outline of a feldspar remains, the remainder is intragranular porosity (P). Sample EA15148-9A. (B) Hydrocarbons (H) are present in some samples as a black oil that lines pores (P).

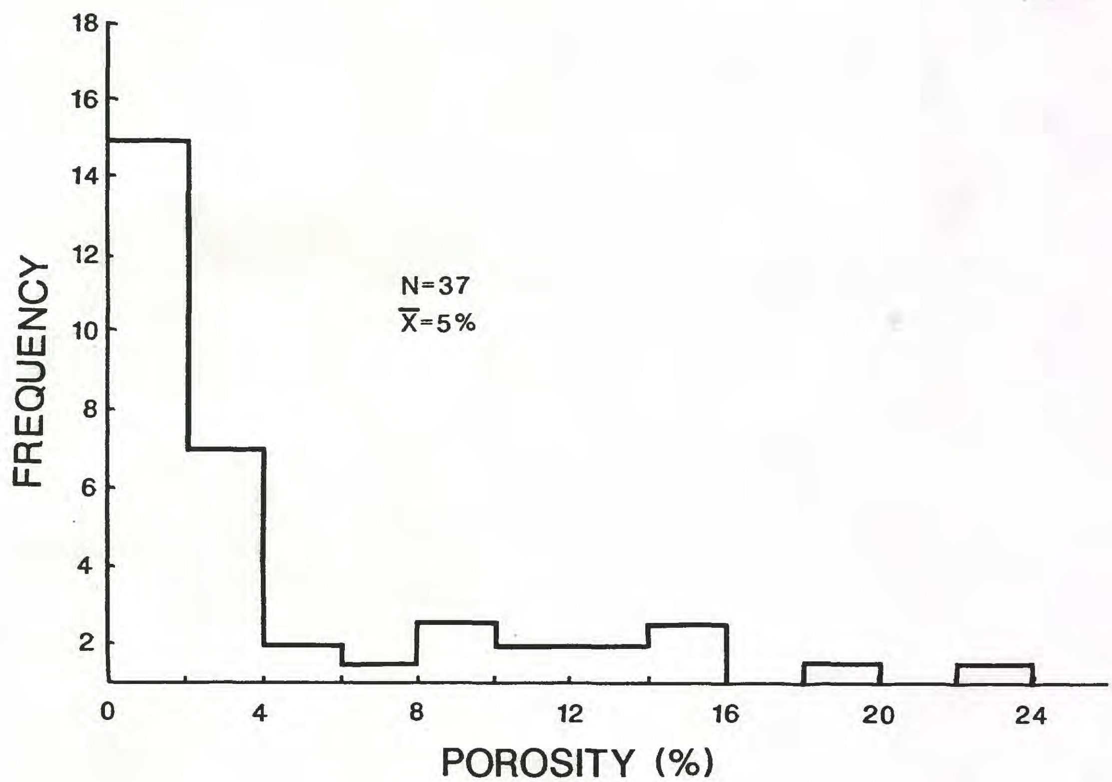

Figure 8. Histogram of porosity in the deep sandstones of the Permian upper part of the Minnelusa Formation. Porosity averages 5%, and ranges up to 23% locally. The higher porosities may be related to local dissolution of anhydrite; porosities greater than 8% have a component of intragranular porosity due to feldspar dissolution.

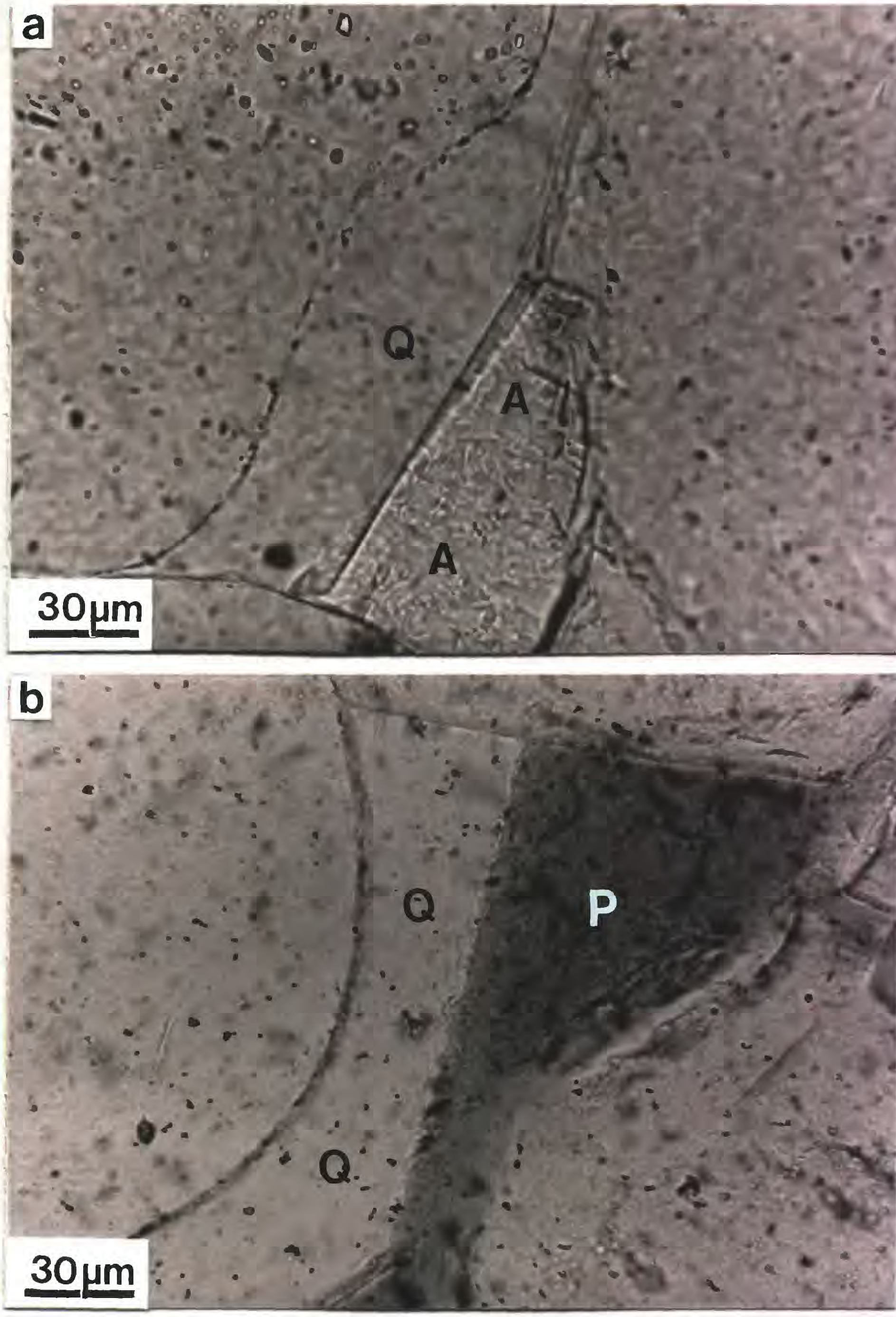

Figure 9. (A) Anhydrite cement (A) commonly abuts a quartz overgrowth (Q) possibly along a replacement boundary, with anhydrite partially replacing quartz. Sample EA15364-5. (B) Porosity (P) adjacent to a quartz overgrowth (Q). The straight boundary of the overgrowth may be a former anhydrite replacement boundary, although the interpretation of anhydrite dissolution is difficult without the presence of remnant anhydrite. Sample EA15364-5.

Table 1. Petrographic data—"Deep" Minnelusa Sandstones
[— indicates no counts]

Sample No.	Total counts	FRAMEWORK COMPOSITION Quartz	K-Feldspar	Plagio-clase	Lithics Chert	Lithics Carbonate	CEMENT COMPOSITION Quartz	Dolomite	Anhy-drite	Chert	Clays	POROSITY Inter-granular	Intra-granular
ENERGETICS INC.		12-34 ACKERMAN											
EA15091	567	367	29	2	4	3	37	49	—	—	—	70	5
EA15136-7A	585	329	43	1	2	3	28	167	—	—	—	11	—
EA15148-9A	524	292	7	—	—	4	88	14	—	—	—	51	—
EA15164	540	330	8	1	—	8	100	16	—	—	—	67	10
EA15173-4	522	312	13	—	—	3	109	9	—	—	—	63	12
EA15205-6	591	352	5	—	—	—	191	35	—	—	—	3	—
EA 15218	520	300	8	—	—	—	152	16	—	—	—	6	—
EA15228	542	260	63	—	—	9	130	50	—	15	15	—	—
EA15255-6	558	294	52	—	—	2	186	20	1	—	—	3	—
EA15265	525	309	63	3	1	5	89	35	—	—	2	17	—
EA15267-8	562	308	65	—	2	4	143	33	1	—	2	3	—
EA15270	561	312	63	1	1	3	143	24	1	—	—	12	—
EA15285-6	600	270	25	—	3	12	51	72	54	—	—	100	13
EA15294-5	569	181	71	—	1	5	108	73	—	—	—	113	17
EA15326-7	542	321	19	—	—	7	89	46	—	—	—	13	—
EA15334-5	573	268	52	3	—	13	82	127	—	—	—	23	—
EA15346-7	571	359	16	—	—	3	97	46	—	—	—	45	5
EA15364-5	523	292	2	—	9	14	105	42	24	—	—	33	—
EA15374-5	559	296	23	—	—	3	99	94	—	—	—	44	—
EA15380-1	581	323	28	—	—	2	29	167	—	—	—	22	—
HERSHEY OIL CORP.		3-34A CARR											
3-34A-15337	561	221	17	—	—	—	89	199	—	—	—	35	—
3-34A-15339	548	191	12	—	1	—	47	294	—	—	—	3	—
3-34A-15340	605	318	37	—	3	—	215	2	—	—	10	20	—
3-34A-15346	573	258	6	—	3	4	127	166	—	2	—	8	—
3-34A-15369	556	259	15	—	—	3	140	125	—	—	3	13	—
3-34A-15370	579	290	7	—	1	—	159	108	—	—	—	15	—
3-34A-15373	595	327	6	—	—	6	114	80	—	—	—	57	7
UNION OIL CO #1 FRYE													
7m-15012	574	242	46	—	2	4	111	168	—	—	—	1	—
7m-15034	586	266	48	—	9	10	52	199	—	—	2	—	—
7m-15048	551	315	27	—	5	—	133	55	—	10	8	—	—
7m-15054	588	323	12	—	—	—	152	25	—	—	—	64	12
7m-15065	586	309	12	—	3	—	138	38	—	—	1	73	12
7m-15076	561	252	14	—	—	12	100	182	—	—	1	—	—
7m-15093	561	293	17	1	10	—	194	43	—	—	—	1	—
7m-15106	567	288	33	—	2	—	54	189	—	—	—	—	—
7m-15132	570	278	33	—	8	15	124	101	2	8	2	—	—
7m-15191	596	339	5	—	3	5	164	83	—	—	—	1	—

Table 2. Framework Composition--"Deep" Minnelusa Sandstones

Sample No.	Quartz (%)	Feldspar (%)	Lithics (%)	Sandstone Classification
ENERGETICS INC. 12-34 ACKERMAN				
EA15091	91	7	2	subfeldspathic arenite
EA15136-7A	87	11	2	subfeldspathic arenite
EA15148-9A	96	3	1	quartz arenite
EA15164	95	3	2	quartz arenite
EA15173-4	95	4	1	quartz arenite
EA15205-6	99	1	--	quartz arenite
EA15218	97	3	--	quartz arenite
EA15228	78	19	3	subfeldspathic arenite
EA15255-6	84	15	1	subfeldspathic arenite
EA15265	81	17	2	subfeldspathic arenite
EA15267-8	81	17	2	subfeldspathic arenite
EA15270	82	17	1	subfeldspathic arenite
EA15285-6	87	8	5	subfeldspathic arenite
EA15294-5	70	28	2	subfeldspathic arenite
EA15326-7	93	5	2	subfeldspathic arenite
EA15334-5	79	16	5	subfeldspathic arenite
EA15346-7	95	4	1	quartz arenite
EA15364-5	94	1	5	sublithic arenite
EA15374-5	92	7	1	subfeldspathic arenite
EA15380-1	92	8	--	subfeldspathic arenite
HERSHEY OIL CORP. 3-34A-CARR				
3-34A-15337		1	3	quartz arenite
3-34A-15339	93	7	--	subfeldspathic arenite
3-34A-15340	94	6	--	subfeldspathic arenite
3-34A-15346	89	10	1	subfeldspathic arenite
3-34A-15370	95	2	3	quartz arenite
3-34A-15373	94	5	1	subfeldspathic arenite
UNION OIL CO. #1 FRYE				
7m-15012	82	16	2	subfeldspathic arenite
7m-15034	80	14	6	subfeldspathic arenite
7m-15048	91	8	1	subfeldspathic arenite
7m-15054	96	4	--	quartz arenite
7m-15065	95	4	1	quartz arenite
7m-15076	91	5	4	subfeldspathic arenite
7m-15093	91	6	3	subfeldspathic arenite
7m-15106	89	10	1	subfeldspathic arenite
7m-15132	83	10	7	subfeldspathic arenite
7m-15191				

Table 3. Components of Intergranular Space—"Deep" Minnelusa Sandstones

Sample No.	Intergranular Space (% of whole rock)	Components of Intergranular Space (% of whole rock) Quartz	Dolomite	Porosity	Anhy-drite	Others	Components of Intergranular Space (% of intergranular space) Quartz	Dolomite	Porosity
ENERGETICS INC. 12-34 ACKERMAN									
EA15091	29	7	9	13	—	—	24	31	45
EA15136-7A	36	5	29	2	—	—	14	81	6
EA15148-9A	43	17	3	10	—	13	40	7	23
EA15164	36	19	3	14	—	—	53	8	39
EA15173-4	36	20	2	14	—	—	56	6	39
EA15205-6	40	32	6	1	—	1	80	15	3
EA15218	40	29	3	1	—	7	73	8	3
EA15228	39	24	9	—	—	6	62	8	0
EA15255-6	38	33	4	1	—	—	87	10	3
EA15265	27	17	7	3	—	—	63	26	11
EA15267-8	32	25	6	1	—	—	78	19	3
EA15270	31	25	4	2	—	—	81	13	6
EA15285-6	49	9	12	19	9	—	18	24	39
EA15294-5	55	19	13	23	—	—	35	24	42
EA15326-7	35	16	17	2	—	—	46	49	6
EA15334-5	40	14	22	4	—	—	35	55	10
EA15346-7	34	17	8	9	—	—	50	24	26
EA15364-5	41	20	8	8	5	—	49	20	21
EA15374-5	43	18	17	8	—	—	42	40	18
EA15380-1	48	5	29	4	—	—	13	76	11
HERSHEY OIL CORP. 3-34A-CARR									
3-34A-15337	57	16	35	6	—	—	28	61	11
3-34A-15339	64	9	54	1	—	—	14	84	2
3-34A-15340	41	36	—	3	—	2	88	—	7
3-34A-15346	53	22	29	1	—	—	42	55	2
3-34A-15369	50	25	22	2	—	1	50	44	4
3-34A-15370	49	27	19	3	—	—	55	39	6
3-34A-15373	43	19	13	11	—	—	44	30	26
UNION OIL CO. #1 FRYE									
7m-15012	48	19	29	—	—	—	40	60	—
7m-15034	43	9	34	—	—	—	21	79	—
7m-15048	35	24	10	—	—	1	69	29	—
7m-15054	43	26	4	13	—	—	60	9	30
7m-15065	45	24	6	15	—	—	53	13	33
7m-15076	50	18	32	—	—	—	36	64	—
7m-15093	43	35	8	—	—	—	81	19	—
7m-15106	43	10	33	—	—	—	23	77	—
7m-15132	41	22	18	—	—	1	54	44	—
7m-15191	42	28	14	—	—	—	67	33	—
Averages:	$\bar{X}$=42%	$\bar{X}$=20%	$\bar{X}$=15%	$\bar{X}$=5%			$\bar{X}$=49%	$\bar{X}$=35%	$\bar{X}$=13%