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PETROGRAPHY AND RESERVOIR PROPERTIES OF CHESTERIAN (UPPER MISSISSIPPIAN) ARENITES, SOUTHERN ILLINOIS

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ABSTRACT

Petrographic and petrophysical studies of oil- and gas-producing Chesterian arenites show no statistically significant stratigraphic distribution of petrographic types. Observed secondary porosity types are: corroded grains, honeycombed grains, moldic pores, moldic enlarged pores, oversized pores, elongate pores, and inhomogeneity of packing. These porosity types mainly originate from burial dissolution of calcitized feldspars and interstitial calcite cement. Two to three porosity types were selected to characterize each of the Chesterian arenites leading to their division into four major groups which coincide with variations of sorting. Group I includes the Aux Vases-Bethel-Ridenhower; Group II the Cypress-Hardinsburg-Tar Springs; Group III the Waltersburg-Palestine, and Group IV the Degonia. The direct correlation between sorting and types of porosity indicates that increased sorting enhanced the circulation of burial dissolving solutions. The proposed groups reflect only reservoir potentials which are not necessarily related to oil productivity.

INTRODUCTION

The Chesterian Series (Upper Mississippian) is widespread throughout southern Illinois and is characterized by cyclic alternations of limestone-shale formations and sandstone-shale formations (fig. 1). Most of the sandstones are elongate bodies shaped as belts, dendroids, ribbons or pods, generally oriented NE-SW and cut into underlying formations. These bodies were produced by a deltaic distributary system of the ancient Michigan River (Potter et al., 1958; Potter, 1963; Swann, 1963; Willman et al., 1975). Today more than half of the oil in the Illinois Basin is produced from Chesterian sandstones, largely from the lower units, particularly the Cypress Sandstone (Swann and Bell, 1958).

These facts prompted this statistical investigation of the petrography, diagenetic evolution and generation of burial secondary porosity of these oil-producing sandstones. Previous fundamental studies by Siever (1953) and Potter (1963) established the relationships between petrology, sedimentary structures, and the environment of deposition of the Chesterian sandstones in the Illinois Basin.

MATERIALS AND METHODS

Samples were collected from the least weathered portions of outcrops in southern Illinois (fig. 2) due to the unavailability of sizeable subsurface cores for petrographic and porosity-permeability measurements. Comparison between the few available small cores and corresponding outcrop samples indicates that the sampling has avoided the major effects of weathering. Any error introduced by the effect of weathering in the porosity-permeability measurements would be 2%. Distribution (fig. 2) of the investigated 333 samples is as follows: Aux Vases: 30, Bethel: 36, Ridenhower: 5, Cypress: 34, Hardinsburg: 64, Tar Springs: 82, Waltersburg: 22, Palestine: 21, and Degonia: 39.

Thin sections of each sample were cut perpendicular to bedding and impregnated with blue low viscosity epoxy to reveal porosity. The petrographic investigation included: (1) determination of the maximum apparent grain size of quartz grains or clasticity index (Feiznia and Carozzi, 1987), (2) visual estimates of percentage of framework grains (quartz, feldspars and lithics), (3) of cement (quartz and feldspar overgrowths, calcite, dolomite, authigenic clay minerals, (4) of matrix (detrital clay minerals and hematite), and (5) of porosity.

A diameter ratio, which represents the inverse of sorting, can be estimated from the 16th and 84th percentiles of the grain size distribution, and 5 classes of sorting can be defined (Folk, 1974). In practice, a high degree of reliability of the estimation of the 16th and 84th percentiles is difficult to maintain and the average values of the estimates represent in reality the diameters in mm of the 10th and the 90th percentiles. These conditions allow to establish only 3 classes of sorting: well sorted (1.6-2.0 mm), moderately sorted (2.0-4.0 mm), and poorly sorted (4.0-16.0 mm).

Porosity and permeability were measured with Ruska equipment on plugs drilled as close as possible to each thin section. Porosity terminology is after Schmidt and McDonald (1979). Location of sampled sections, detailed descriptions of the thin sections, measurements of porosity and permeability, and description of the multivariate correlation program used to establish the possible relationships between measured petrographic and textural parameters and occurrence and types of secondary porosity are found in Ou (1984).

RESULTS

Petrographic Classification

Chesterian arenites belong, on the basis of framework grains, to four major petrographic groups using the classification of Williams et al. (1954). The following rock types have been identified: quartz feldspathic arenites, feldspathic arenites, subfeldspathic lithic arenites, and lithic arenites. The first three being by far the most common. No statistically significant distribution of these petrographic types among the nine Chesterian arenites was recognized.

Petrographic Components

Quartz is the dominant framework grain in all the types of arenites except the rare lithic arenites. It commonly displays undulose extinction, syntaxial overgrowth, and marginal replacement of original grains and overgrowths by calcite cement. Feldspar is the second abundant framework grain represented in decreasing order of importance by orthoclase, microcline and albite, all of which may display syntaxial overgrowth. Sericitization of potassic feldspar and plagioclase ranges from sericite flakes scattered randomly or concentrated along cleavage planes to complete replacement by sericite aggregates. Kaolinitization of potassic feldspar although not so common as sericitization, completely destroys individual grains converting them into vermicular aggregates. Calcite replacement of all feldspar types is common, ranging from marginal replacement to skeletal grains, and upon completion to euhedral patches of microgranular calcite cement. Accessory components are zircon, tourmaline, and muscovite flakes often distorted and split between more rigid framework grains.

Lithic grains in order of decreasing importance are: microcrystalline quartz ("chert"), metaquartzite, calcareous siltstone, hematitic siltstone, shale-claystone, micaschist, and dolomite. X-ray diffraction shows that the matrix consists of hematite-stained illite and mixed layer illite-smectite.

This study indicates that the mesogenetic sequence of cementation is the following. In a first phase, pressure solution of quartz and feldspar grains preceded interlocking quartz and feldspar overgrowths leading locally to quartzitic texture. In a second phase, carbonatization by precipitation of interstitial calcite cement with mosaic to poikilotopic texture and extensive calcitization of feldspars was followed by illite-smectite and illite-sericite precipitation as films with fibrous structure perpendicular to surfaces of growth. In a third and last phase, decarbonatization took place by dissolution of calcite cement and calcitized feldspars associated with direct dissolution of feldspars.

Porosity Types

With the exception of rare instances of primary interparticle porosity reduced by incomplete overgrowth on quartz and feldspar, most of the visible porosity is secondary, generated by burial processes, and consists of the following types: corroded grains, honeycombed grains, moldic pores, moldic enlarged pores, oversized pores, elongate pores and inhomogeneity of packing.

Corroded grains (fig. 3, A,B) result from marginal dissolution of original boundaries or overgrowths on both quartz and feldspar grains, directly or after partial replacement by calcite. Honeycombed grains (fig. 3, A,B,C) result from the partial selective dissolution mainly along microperthitic intergrowths of potassic feldspars either fresh or previously altered to kaolinite or sericite, generating a typical skeletal aspect. Lithic grains are rarely affected by this process.

Moldic pores correspond to feldspar grains which have been completely dissolved, directly or after calcitization, leaving a peripheral film of clay minerals or hematite (fig. 3, C,D,F). In feldspathic arenites, quartz overgrowth is a predominant process of cementation which develops euhedral faces often penetrating adjacent softer feldspar and lithic grains. Consequently moldic pores display either the euhedral subrectangular shape of feldspar grains or its combination with other straight margins corresponding to penetrating quartz overgrowth faces. Complex polygonal pores are thus generated. Moldic enlarged pores (fig. 3, E,F) derive from moldic pores which were further enlarged so that the dissolution of feldspar grains also involved overgrowths or detrital cores of adjacent quartz grains. Therefore the shape of these pores becomes more irregular associating straight and random margins. Oversized pores originate mainly from the dissolution of two or more adjacent feldspar grains directly or after calcitization with possible extension into the overgrowths or detrital cores of surrounding quartz grains (fig. 3, G). A second possibility is by dissolution of adjacent feldspar grains and surrounding patches of calcite cement (fig. 3, H). The shape of these pores becomes extremely variable, ranging from rectangular when a row of grains are dissolved to a combination of random margins and straight faces. Elongate pores (fig. 3, I), in places quite abundant, result from the uniform marginal replacement of quartz and feldspar grains with or without overgrowths, by calcite cement along irreducible lamellar pores, followed by dissolution of the carbonate.

Inhomogeneity of packing (fig. 3, J) results from tightly-packed grains of quartz and feldspar cemented by pressure solution and overgrowth and other patches where no overgrowth or an incipient one have left interstitial spaces filled by calcite cement. This peculiar texture is often related to bioturbation processes. Subsequent dissolution of the carbonate generates irregularly distributed pores with straight to curved margins depending on the amount of overgrowth on adjacent grains.

DEPOSITIONAL AND DIAGENETIC INTERPRETATION

Two to three porosity types where chosen to characterize each of the nine investigated arenites leading to their division into four major types (table 1). Mean figures are also given for the major compositional and textural parameters such as: clasticity index, feldspar content, quartz and feldspar overgrowth, lithic grains content, matrix content, and diameter ratio (inverse of sorting). The relative uniformity of composition of all investigated Chesterian arenites previously shown by the absence of statistically significant distribution of petrographic types is also confirmed by the multivariate correlation program (see Ou, 1984). The program indicates no significant correlation between petrographic parameters and occurrence and types of secondary porosity, but a significant correlation with a textural parameter, namely the diameter ratio expressing sorting. The four variations of sorting correspond to the four major types based on porosity. Given the uniformity of all other parameters there is a direct correlation between sorting and types of porosity. This correlation indicates that increased sorting enhanced the circulation of the burial solutions which dissolved feldspars and calcite cement.

This study leads to a final interpretation (table 1) which divides the formations into four groups. Group I includes the Aux Vases, Bethel and Ridenhower Formations which have the following features: poor sorting, predominant honeycombed porosity with some corroded grains and oversized pores, average measured porosity of 8.55 to 10.00%, average measured permeability of 0 to 24.51 md. The Bethel Sandstone is the coarsest Chesterian arenite (Willman et al., 1975).

Group II includes the Cypress, Hardinsburg and Tar Springs Formations which have the following features: moderate sorting, honeycombed porosity enhanced by oversized and moldic porosity, average measured porosity of 14.78 to 15.12%, average measured permeability of 6.71 to 38.98 md. Within this group the association of three types of porosity characterizes the Cypress which has a corresponding good permeability.

Group III includes the Waltersburg and Palestine Formations which have the following features: good sorting, predominant oversized porosity enhanced by moldic and honeycombed porosity, average measured porosity of 12.77 to 17.67%, average measured permeability of 11.13 to 88.38 md. Within this group the Palestine Sandstone has the highest values of measured porosity and permeability of all Chesterian arenites. It displays the best pattern of prograding deltaic deposits (Potter, 1963).

Group IV consists of the Degonia Formation which has the following features: moderate sorting, predominant moldic porosity enhanced by honeycombed and oversized porosity, average measured porosity of 14.58%, average measured permeability of 54.58 md.

CONCLUSIONS

The proposed division of Chesterian arenites in four major groups based on the association of their types of secondary porosity and sorting reflects only their reservoir potential which does not necessarily coincide with their oil productivity. Indeed, the latter is a function of numerous other geological criteria such as migration paths, extent and shape of the arenite bodies, stratigraphic or structural traps and thickness of pay zones, which are beyond the scope of this study. This study confirms that the Cypress Sandstone could be a prolific producer, and it is indeed the most important producing sandstone over its entire extent (Swann and Bell, 1958). The Tar Springs Sandstone and the Waltersburg Sandstone appear as potential moderate producers. This is generally true, although they can be very good locally in small fields where productive thicknesses may reach 18 to 21 m, the greatest of any of the Basin's sandstones (Swann and Bell, 1958). Finally, oil production from the Palestine Sandstone and the Degonia Sandstone, which would appear to be potentially excellent producers, is minor, almost entirely confined to the immediate vicinity of faults, and has little correlation with their distribution (Swann and Bell, 1958).

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Table 1. Petrographic parameters, major porosity types, and porosity-permeability values of Chesterian arenites.

	Formation	C	F	OG	L	M	DR	Major porosity types in decreasing importance			AVP	AMP	AMK
								1	2	3			
IV	Degonia	0.40	17.73	f-c	7.73	6.36	3.01	moldic	honeycombed	oversized	15.45	14.58	54.58
III	Palestine	0.41	17.62	f-c	5.71	6.43	1.8	oversized	moldic	honeycombed	19.05	17.67	88.38
	Waltersburg	0.41	10.23	f	6.59	7.27	2.02	oversized	moldic	honeycombed	12.50	12.77	11.13
II	Tar Springs	0.40	17.11	f-c	9.56	7.44	2.87	honeycombed	oversized	———	15.00	14.89	6.71
	Hardinsburg	0.36	15.26	f-c	8.73	6.02	2.51	honeycombed	oversized	———	15.00	15.12	29.07
	Cypress	0.40	16.21	f-c	8.10	5.86	3.58	oversized	honeycombed	moldic	14.66	14.78	38.98
I	Ridenhower	0.35	19.00	c	12.0	10.0	4.22	honeycombed	corroded	———	11.00	10.00	N.A.
	Bethel	0.63	13.19	c	7.36	6.39	4.50	honeycombed	corroded	———	9.44	9.81	24.51
	Aux Vases	0.40	17.86	f-c	8.81	6.67	4.09	honeycombed	oversized	———	10.71	8.55	1.47

C: clasticity index (mm); F: feldspar content (%); OG: quartz and feldspar overgrowth, (f = frequent, c = common); L: content of lithic grains (%); M: matrix content (%); DR: diameter ratio (inverse of sorting); AVP: average visual porosity (%); AMP: average measured porosity (%); AMK: average measured permeability (md)

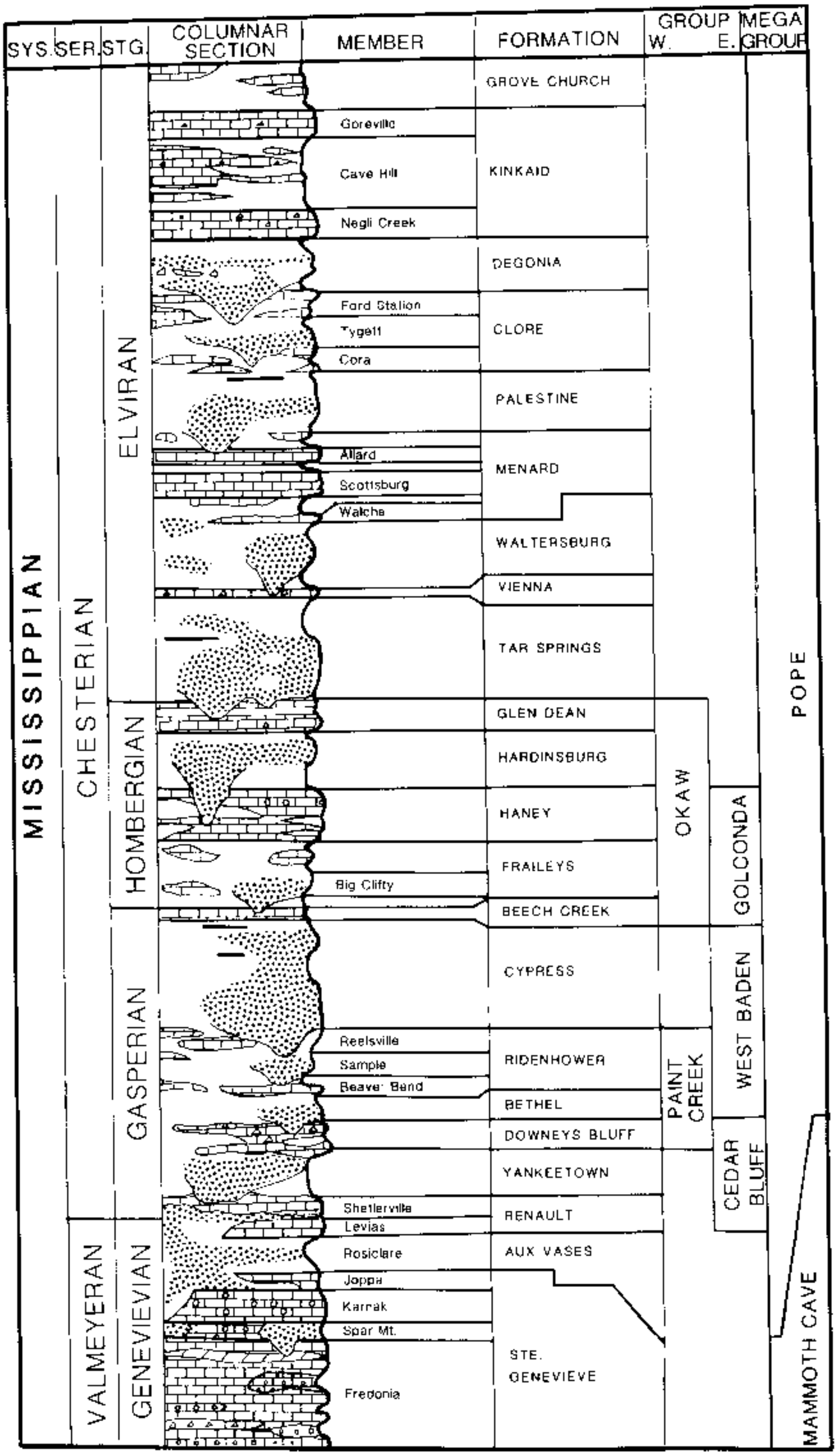

Fig. 1. Stratigraphic column of the Chesterian Series. Blank areas in columnar section are shales (modified from Willman et al., 1975).

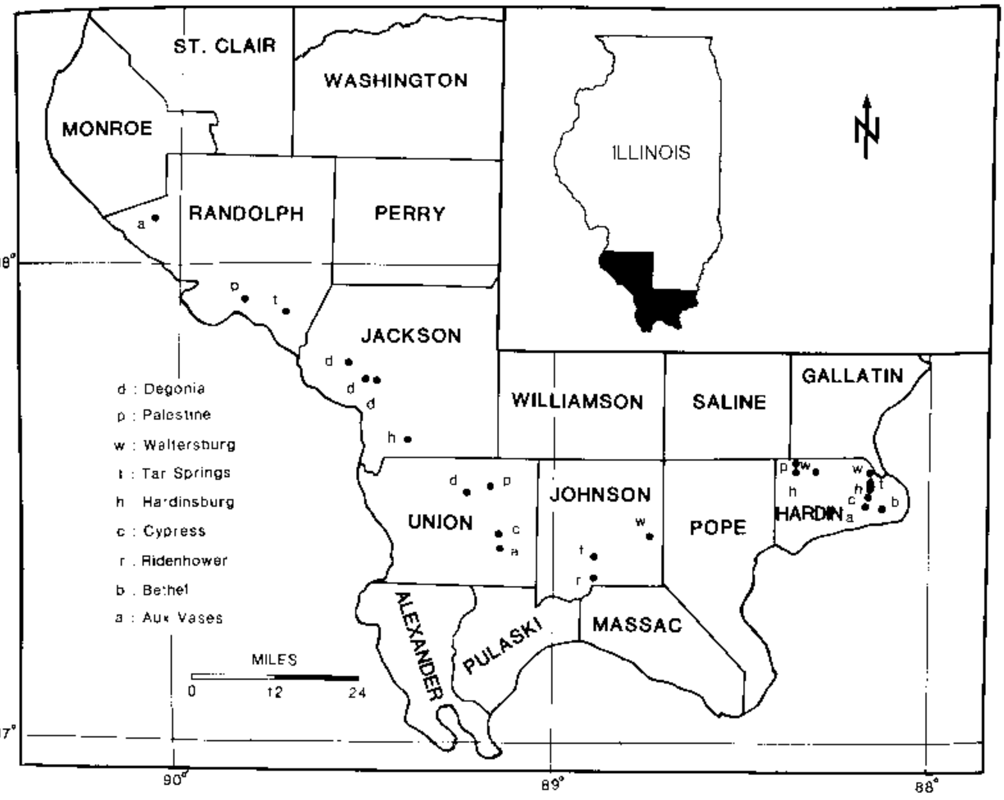

Fig. 2. Location map of sampled sections.

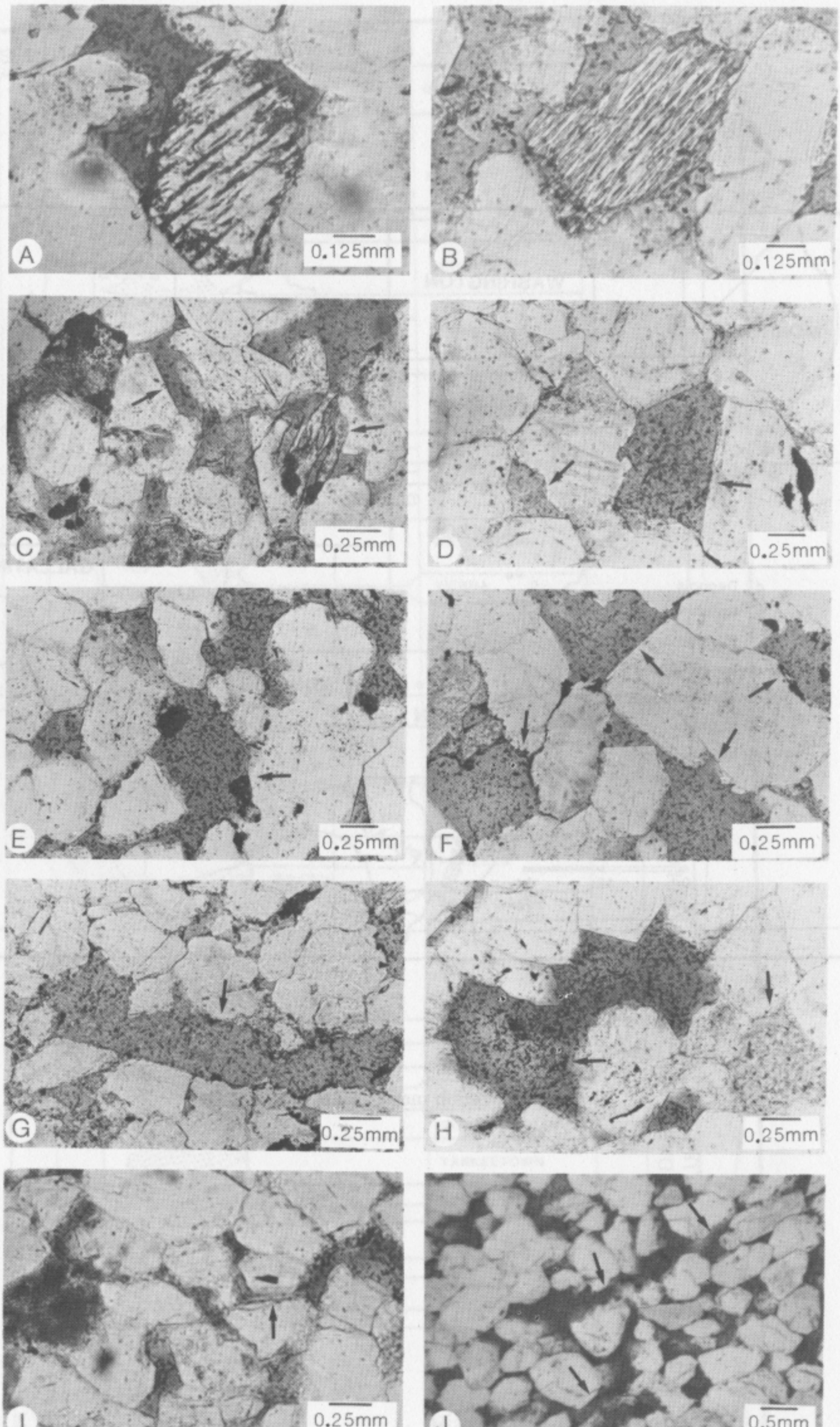
A
0.125mm
B
0.125mm
C
0.25mm
D
0.25mm
E
0.25mm
F
0.25mm
G
0.25mm
H
0.25mm
I
0.25mm
J
0.5mm

Fig. 3. Porosity types. All photomicrographs in plane polarized light, porosity appears dark.

A. Honeycombed porosity from differential dissolution of microperthitic orthoclase grain. Upper left quartz grain (arrow) shows deeply corroded margins. Hardinsburg Sandstone.

B. Honeycombed porosity from differential dissolution of microperthitic orthoclase grain. All the surrounding quartz grains display corroded margins at the expense of their nuclei or overgrowths. Hardinsburg Sandstone.

C. Honeycombed orthoclase grain (right arrow) and small moldic pore with straight margin due to adjacent quartz overgrowth (upper left arrow). Degonia Sandstone.

D. Moldic pores from dissolved feldspar grain (right arrow) and from lithic grain (left arrow), both with partial straight margins from adjacent quartz overgrowths. Tar Springs Sandstone.

E. Moldic enlarged pore (arrow) with random margins predominant over straight ones. Hardinsburg Sandstone.

F. Moldic pore (lower left arrow) and three moldic enlarged pores (upper center and right arrows) from dissolved feldspar grains. Waltersburg Sandstone.

G. Oversized pore (arrow) from dissolution of three adjacent feldspar grains. Cypress Sandstone.

H. Oversized pore with feldspar residue (center arrow) from dissolution of three feldspar grains and calcite cement. The complex shape of the pore combines straight margins of feldspar grains with pyramid of quartz overgrowth and rounded outline of detrital quartz grain. Hardinsburg Sandstone.

I. Elongate pore (arrow) outlined by partially dissolved quartz overgrowths. Tar Springs Sandstone.

J. Inhomogeneity of packing with very irregular pores by dissolution of calcite cement (arrows). Hardinsburg Sandstone.