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A Study of Fluid Migration in Porous Media by Stereoscopic Radiographic Techniques*

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ABSTRACT.—Stereoscopic radiography provides an effective method of studying small-scale fluid migration in porous media in that it permits visual observation in three dimensions of the fluid front and its relation to sedimentary structures. The technique consists of imbibing or forcing an opaque radiographic solution into a rock specimen from a centralized point source while procuring a series of stereo paired radiographs. The thickness of sample in which this process can be adequately viewed by radiography is limited to about three centimeters.

Visually obscure "cryptostructures" commonly develop pronounced control on fluid movement. Thirty percent of all the homogeneous sandstones used in this study developed anisotropic flow patterns resulting from such structures. This represented, however, controlled flow patterns in 80 percent of the homogeneous samples in which cryptostructures had been detected by radiography. In contrast, little or no control was effected by cryptostructures in 22 percent of all the sandstone samples including both visibly stratified and homogeneous types. It is concluded that cryptostructures, like visible structures, affect fluid movement only to the extent that they represent aggregate differences in effective porosity. In seemingly homogeneous sandstones they may reduce or even prevent fluid transmission.

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*A thesis submitted to the faculty of the Department of Geology, Brigham Young University, in partial fulfillment of the requirements for the degree Master of Science, July 28, 1966.

INTRODUCTION

Purpose and Scope of Study

Fluid migration has been extensively studied and most physical properties of porous materials and percolating fluids have been analysed or mathematically predicted. Although the nature of the fluid fronts has been studied in various ways, it is difficult to visually analyze this phenomena in three dimensions especially in naturally lithified sediments. Most of our present knowledge is the result of indirect observations on artificial materials. Flow patterns in lithified sediments, however, commonly defy theoretical predictions because of incidental irregularities in sorting, cementing, fabric, and sedimentary structures. Hamblin (1965) recently demonstrated that structures commonly exist in the majority of seemingly homogeneous sandstones. Such features provide a possible explanation to anisotropic fluid migration and unexpected configuration of fluid interfaces especially in the homogeneous type sandstones. The purpose of this study is to evaluate such possibilities. The first consideration was to explore the use of stereoscopic radiography as a means of visually analyzing the configuration of an advancing fluid front in three dimensions. Inasmuch as sedimentary structures, whether hidden or visible, are readily detected with radiography, both the location of such features and the development of the fluid front can be related. A preliminary evaluation of the effect of cryptostructures on fluid flow was therefore a second consideration in this study.

Previous Work

Basic principles governing fluid flow conditions and rates were notably advanced by the early work of King (1899) and Slichter (1899). The analytical and mathematical treatments of fluid motion and reservoir properties were extensively added to by Muskat (1937). Hubbert (1940) developed an advanced theory of fluid flow which related thermodynamic principles for the first time. Meinzer and Wenzel (1942) extended knowledge of the relationships between permeability, hydraulic pressures and reservoir storage. Most of these contributions were advanced in the areas of hydrology. Subsequent contributions resulting from an explosive interest in this area by the petroleum, hydrology, and engineering industries are too numerous to mention. Scheidegger (1960) produced an important compilation of the dynamic, chemical, and mathematical relationships which have been established and has also made frequent contributions in the same fields.

Studies relating porosity and permeability to the structural framework of porous media are comparatively few. Newell (cited by King, 1899, p. 126) and Fettke (1938) noted the anisotropic character of permeability in sandstones. Correlations between grain packing, porosity and permeability were studied by Fraser (1935) and Gatton and Fraser (1935). Griffiths (1949) and Griffiths and Rosenfeld (1953) investigated the relation between fabric and vectorial permeability. Others who explored fabric and permeability relationships include Hutta (1956) and Potter and Mast (1963). They were unable to establish any strong relationships between the orientation of dimensional fabric and maximum permeability. Lehr (1961) conducted one of the few experiments utilizing consolidated materials to compare flow patterns with grain-size distribution. The microscopic study of fluid phenomena in an artificial system by Chatenever

(1951) provided a demonstration of basic fluid front patterns produced when an immiscible fluid invades a prewetted system.

X-ray techniques utilized by Laird and Putnam (1951) enabled them to instrumentally deduce the extent of fluid saturation in a porous sample. Hamblin (1962, 1965) extended the use of radiography to study the internal nature of sandstones and also demonstrated the extensive occurrences of structures in seemingly homogeneous units.

ACKNOWLEDGMENTS

This investigation is part of a more extensive project exploring the use of radiographic techniques for geologic studies. It was largely supported by the National Science Foundation through grant GP-1980, to Dr. William Kenneth Hamblin.

The author wishes to express grateful appreciation to Dr. Wm. Kenneth Hamblin who suggested this problem, provided constant suggestions and supervision, and offered constructive criticism of the manuscript. Dr. Harold J. Bissell collected and identified many sandstones used in this study and offered many important suggestions. The assistance and encouragement of my wife, Kaye, is also sincerely appreciated.

PROCEDURES AND TECHNIQUES

Stereoradiography utilizes the same basic principle of procuring a stereoscopic image as stereo photography. The major difference, however, is that radiography utilizes the absorbent contrasts of different chemical and mineral compositions to produce a relatable, internal image on the film. Such a method enables one to look into a rock as if it were transparent, viewing in effect the positions and structural relationships of the various constituents in three dimensions. If fluids, which are opaque to x-rays, are injected or imbibed into a specimen the configuration of the fluid front inside the rock will also be seen. By making a series of stereoscopic x-ray pictures a progressive record of fluid emplacement and advance can be preserved and studied. The radiographic fluids, as well as the highly absorbent minerals like magnetite, hematite, biotite, zircon, and calcite, will appear as dark images on the positive prints taken from the radiographs.

Experimental Equipment

Equipment used in experimental work consisted of an x-ray unit, an exposure box, and a fluid pressure system as illustrated in text-figure 1. The x-ray unit was of a medical type rated with a 150 kilovoltage (KvP), 200 milliamp (Ma) potential. Rapid exposures used in procuring time-lapse sequences commonly necessitated the use of the "hard" type x-ray exposures. When much softer radiation was desirable, a smaller industrial unit with a beryllium window was employed. Kodak industrial film types "M" and "R" were utilized because of their high contrast and fine grained qualities. To economically facilitate rapid time-lapse exposures of injection and imbibition patterns in vertically positioned samples, a lead-lined exposure box was constructed to permit approximately one-eighth of an 8X10 film sheet to be exposed at a time while the other part was protected from exposure.

Pressurized fluid injections were conducted with the use of a modified hydraulic brake-bleeder tank marketed by K-D Tool Company. A 2-60 psi.

pressure gauge and a modified rapid-coupling hose system were added to the basic unit. The hose system of the fluid tank was secured by a screw type clamp to the bases of standard medical hypodermic needles used to conduct the fluid to the center of the sample. Needles with interior diameters of 0.7 to 0.9 mm. (sizes 14 to 18) provided desirable results.

Fluids

Several highly absorbent or opaque radiographic fluids were found to be useful in delimiting interconnected pore systems during injection and gravity flow procedures. They included:

(a) "Ditriokon"—an angiocardiographic solution formed from sodium diprotirizoate and ditrizoate and produced by Mallinckrodt Inc. This medium is extremely opaque to x-rays and produces an excellent contrast on radiographs. Its low viscosity (45ssu at 76 F.) and high contrast made it the most useful of the fluids for this study.

(b) "Baridol"—a commercially prepared opaque medium containing colloidally stabilized barium sulphate. This product is marketed by Pacific Chemicals. Because of its high viscosity (621ssu at 76 F.), moderately high contrast and low cost it was found to be most useful for imbibition tests on poorly indurated sandstones.

(c) Sodium Iodide solution—a mixture of 40 gms. of sodium iodide (U.B.P.) to 100 ml. water was found to produce contrasts sufficient to be used in moderately indurated sandstones. This concentration provided only fair contrasts, a near maximum for the solution, and a very low viscosity (28ssu at 78.6 F.).

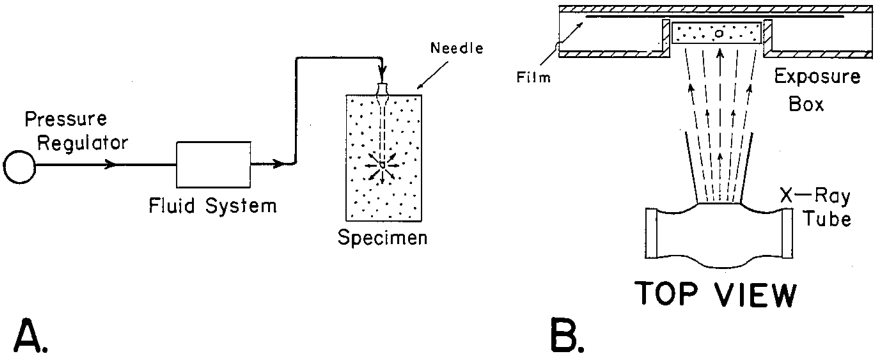
(d) Mixtures—mixtures of Baridol and NaI solution (as above) enhanced the desirable properties of each—low viscosity and moderate to high contrasts. Three mixtures were used: (1) 15% Baridol, 85% NaI; (2) 30% Baridol, 70% NaI; and (3) 50% Baridol, 50% NaI.

(e) Potassium Iodide solution—a mixed solution with similar properties as NaI solution.

There are many other good radiocardiographic solutions on the market which could have been used but generally their costs were prohibitive to this type of study.

Sample Preparation

Rock samples were sliced into rectangular specimens which would fit into the window of the exposure box. The thickness of each specimen type varied according to its apparent degree of induration and permeability; the more poorly indurated, highly porous sandstones being cut thickest. The most useful range of thickness varied between one and three centimeters. Specimens were generally sliced perpendicular to the apparent stratification planes and oriented so that these planes would be situated in a horizontal position during injections or gravity flow. Each sample was also dried in an attempt to remove interstitial fluids. The main requirement, aside from limiting thicknesses, was the necessity of having samples void of open fissures.



TEXT-FIGURE 1.—Experimental Apparatus
(A) Injection System
(B) Exposure System

Samples were then prepared for various fluid flow experiments which included both imbibition, and injection of dry and prewetted systems. The more friable sandstone types were prepared for imbibition tests by simply drilling an open hole or "well" about half way through the cut specimens with a one centimeter diameter masonry bit. The remaining sandstone types had much smaller holes drilled into them to accommodate the hypodermic needles used for injections. Hot Canadian balsam was then used to seal the needles in place. Special efforts were made to prevent clogging of the pore openings in the immediate vicinity of the needle tip and to seal all other areas of the drilled hole. The desired effect was to provide a centralized point-source for the injected fluids. Prewetted systems were additionally prepared either by soaking the specimens in kerosene for several days prior to being injected or by pre-injecting the specimen with a light-contrast medium, then conducting the experiment with a high-contrast medium. Occasionally flow conditions of both systems were controlled by sealing certain sides of the specimens with wax.

Selected samples, which had previously been injected and which had developed patterns seemingly little affected by their inherent structural features, were cut into four or five wafer-thin slices and x-rayed with the soft rays of the industrial unit in an effort to detect grain fabric and to determine its relation with the emplaced opaque media.

Imbibition and Injection Procedures

Both continuous and periodic imbibition and injection procedures were used depending on the type of radiographic record desired. True time-lapse sequences were possible only when single radiographs were taken but when stereo paired radiographs (stereoradiographs) were desired a staggered series of exposures were made. This involved releasing fluid pressures for periods of one to four minutes in order to prevent volume changes in the fluid front between exposures of the stereo pairs and to allow the x-ray cathode to cool. Comparisons made between patterns developed under continuous and periodic injections in the same sandstone had so little variance that the methods were considered comparable for this study. The Frontier Sandstone provided a partial exception to the normal. Both pressures and the types of fluids used depended upon the compactness of the sandstone samples. Generally, pressures had to be increased in steps as the fluid front expanded farther from the point source. These increases were initiated when it became apparent that the fluid front had stabilized as a result of surface attraction and other fluid interactions. Occasionally a single pressure plateau was all that was necessary during a complete injection.

The more viscous fluids used in imbibition runs were conducted into the well from a separation funnel with a regulatory stopcock. Imbibitions were likewise continuous when single radiographs were taken and periodic when stereoradiographs were desired. Longer time intervals were needed to prevent movment between exposures as a result of increased capillary action.

Radiographic Techniques

Radiographs were taken on the medical unit from a 26 inch focal-film distance. Exposures on this unit were commonly made using the small 1.0 mm. focal spot at 60 KvP and 100 Ma. Stereoradiographs were produced by shifting the x-ray tube vertically a total of 7.6 cm. and inclining it toward the specimen about four degrees from the horizontal in both top and bottom positions. The stereoshift was made perpendicular to the stratification planes so as to increase the possibilities of aligning the emitted x-rays parallel to internal structural planes thereby increasing possible density contrasts on the x-ray film denoted by such structures. Tilting the x-ray tube is reported to enhance the stereo image. Films were processed in Kodak developer and fixer. For a more concise treatment of various radiographic techniques and principles one should refer to publications by Clauser, 1952, p. 65-105; Eastman-Kodak, 1957; or Hamblin and Salotti, 1964, p. 19-21.

NATURE AND DISTRIBUTION OF SAMPLES

The 44 sandstone samples utilized in this study were obtained from 35 formations representing a wide variety of sedimentary types and environments, ages and post-depositional conditions. They include samples from nine states located chiefly in the Midcontinent, Colorado Plateau and Great Basin areas. As both the presence and the apparent absence of visually detectable internal structures were important considerations in this study, equally representative groups of such types were included in the sandstones selected. Radiographs revealed the true extent to which the apparently homogeneous sandstones were void of structures and commonly enhanced details of visible structures. A comparison of the resulting differences is included in Table 1.

It should be noted that the term "sandstone" is herein used only with a grain size connotation concurrent with the Wentworth scale. Also the sandstones used in this study represent both selective and random choices and any inferred results extending outside the area of this study have limited merit.

CRYPTOSTRUCTURES REVEALED BY RADIOGRAPHY

Visual examination of the sandstone surfaces revealed that one-half were void of any evidences of stratification. Very thin bedded units (1 to 5 cm.) and laminations (less than 1 cm.) were prominently or vaguely suggested in about two-thirds of the other samples and cross-laminations and cross-bedding,

TABLE 1

Visual and radiographic comparisons of samples

Internal features	Visual appearance No. samples	Visual appearance % samples	Radiograph appearance No. samples	Radiograph appearance % samples
Homogeneous*	22	50.0	14	31.8
Laminated or bedded	16	36.3	19	43.2
Cross-laminated or cross-bedded	4	9.1	8	18.2
Both laminated and cross-laminated	0	0.0	2	4.5
Graded bedding	1	2.3	1	2.3
Disturbed bedding	1	2.3	3**	6.8

*Complete absence of any distinct or obscure stratification
**All samples contained other stratification

graded bedding and disturbed or reworked features were evident in the remainder. A concise breakdown of these figures can be noted in Table 1.

Radiographs exposed hidden internal structures, referred to as cryptostructures, in 37 percent of the seemingly homogeneous units and considerably enhanced the vague details of visual structures in many other samples. In most cases these structures consisted of such basic primary features as delicate cross-laminae and horizontal laminae occurring alone or in various combinations. The structural framework of visually stratified units was sometimes strikingly different than expressed to the naked eye. Freshly cut surfaces of a cored sample of the Berea Sandstone from central Illinois, for example, displayed prominent

EXPLANATION OF PLATE 1

RADIOGRAPHS OF FLUID FRONT PATTERNS IN A VARIETY OF SANDSTONES

FIG. 1.—Smooth, isotropic front in seemingly homogeneous Weber Sandstone from locality (10). Specimen thickness 1.7 cm.; cumulative injection 7 min. at 10 psi.; fluid Ditriokon. Exposure at 60 Kv, 100 Ma for 10 secs. x1.

FIG. 2.—Fingering or dendritic front in seemingly homogeneous Englevale Sandstone Member from locality (3). Specimen thickness 1.5 cm.; cumulative injection 16 min. at 5 psi.; fluid Ditriokon. Sample prewetted with Kerosene. Exposure at 60 Kv, 100 Ma for 9.5 sec. x1.

FIG. 3.—Lobate front in well laminated Tonganoxie Sandstone from locality (7). Specimen thickness 1.3 cm.; cumulative injection 5 min. at 4 psi.; fluid Ditriokon. Sample waxed. Exposure 50 Kv, 100 Ma for 12 sec. x1.

FIG. 4.—Tongued front in cross-bedded Dakota Sandstone from locality (4). Specimen thickness 2.8 cm.; cumulative imbibition 6 min.; fluid 50% Baridol, 50% NaI solution. Exposure at 60 Kv, 100 Ma for 12.5 sec. x1.

FIG. 5.—Lateral front in highly laminated Cretaceous sandstone from locality (8). Contains shaly partings. Specimen thickness 1.5 cm.; cumulative injection 7 min. at 20

psi + 30 min. at 30 psi + 30 min. at 40 psi + 5 min. at 50 psi; fluid Ditriokon Exposure 60 Kv, 100 Ma for 10 sec. x1.

FIG. 6.—Irregular front in homogeneous Baseline Sandstone from locality (1). Specimen thickness 3.2 cm.; cumulative imbibition 46 min.; fluid Baridol. Exposure 70 Kv, 100 Ma for 11 sec. x1.

EXPLANATION OF PLATE 2

MISCELLANEOUS FLUID FLOW PATTERNS

FIG. 1.—Photograph of "isochromatic absorbtion rings" formed on surface of Frontier Sandstone from locality (5). Dark rings are wetted by injected fluids, light colored rings are dry surfaces. x1.3.

FIG. 2.—Radiograph of a diffused lobate front formed in prewetted specimen of Tonganoxie Sandstone from locality (7). Compare with "dry" specimen of figure 3, plate 1. Specimen thickness 2 cm.; cumulative injection 3 min. at approximately 8 psi.; fluid Ditriokon. Exposure 80 Kv, 85 Ma, 4 secs. x1.

FIG. 3.—Radiograph of secondary tongued front formed in preimbibed specimen of Dakota Sandstone from locality (4). Compare with exposure of preceding imbibition Plate 1, (fig. 4). Cumulative imbibition (secondary only) 3 min.; fluid Ditriokon. Exposure 60 Kv, 100 Ma, 12.5 secs. x1.

EXPLANATION OF PLATE 3

STEREORADIOGRAPHS OF A CONTROLLED FLUID FRONT IN A HOMOGENEOUS SAMPLE OF ILLIPAH SANDSTONE FROM HAMILTON, NEVADA

General explanation—shortened sequence of exposures revealing cryptostructural control of injected fluid. All exposures made at 60 Kv, 100 Ma for 7 secs. Specimen thickness 1.7 cm; fluid Ditriokon. Specimen injected from upright position with needle end at top.

FIG. 1.—Fluid pattern after cumulative injection of 7 min. at 3 psi. + 3 min. at 5 psi.

FIG. 2.—Fluid pattern after cumulative injection of 7 min. at 3 psi. + 7 min. at 5 psi.

FIG. 3.—Fluid pattern after cumulative injection of 7 min. at 3 psi. + 14 min. at 5 psi. + 7 min. at 10 psi.

FIG. 4.—Fluid pattern after cumulative injection of 7 min. at 3 psi. + 14 min. at 5 psi. + 13 min. at 10 psi.

EXPLANATION OF PLATE 4

STEREORADIOGRAPHS OF A CONTROLLED FLUID FRONT IN A HOMOGENEOUS TERTIARY UNIT CORED IN THE VENTURA BASIN

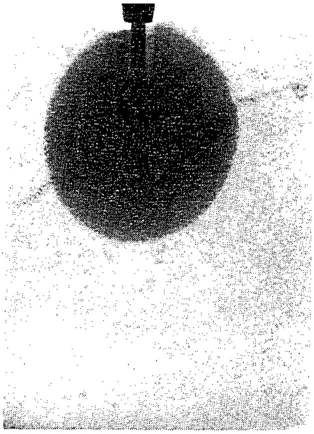
General explanation—shortened sequence of exposures revealing moderate cryptostructural control of injected fluid. All exposures made at 60 Kv, 100 Ma for 10 sec. Specimen thickness 1.5 cm.; fluid Ditriokon. Specimen injected from upright position with needle end at top.

FIG. 1.—Fluid pattern after cumulative injection of 4 min. at 10 psi.

FIG. 2.—Fluid pattern after cumulative injection of 4 min. at 10 psi. + 3 min. at 15 psi.

FIG. 3.—Fluid pattern after cumulative injection of 4 min. at 10 psi. + 9 min. at 15 psi. + 3 min. at 20 psi.

FIG. 4.—Fluid pattern after cumulative injection of 4 min. at 10 psi. + 9 min. at 15 psi. + 9 min. at 20 psi.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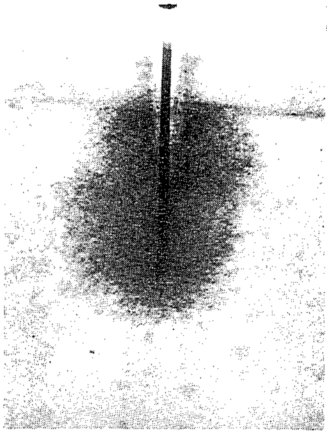
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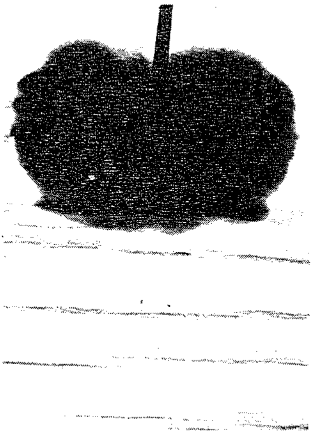
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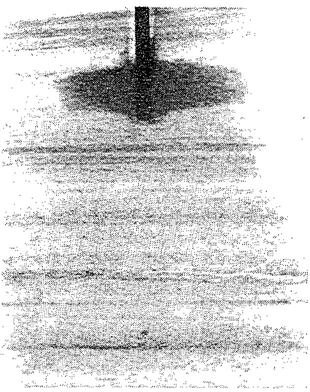
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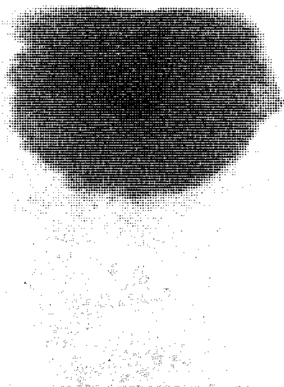
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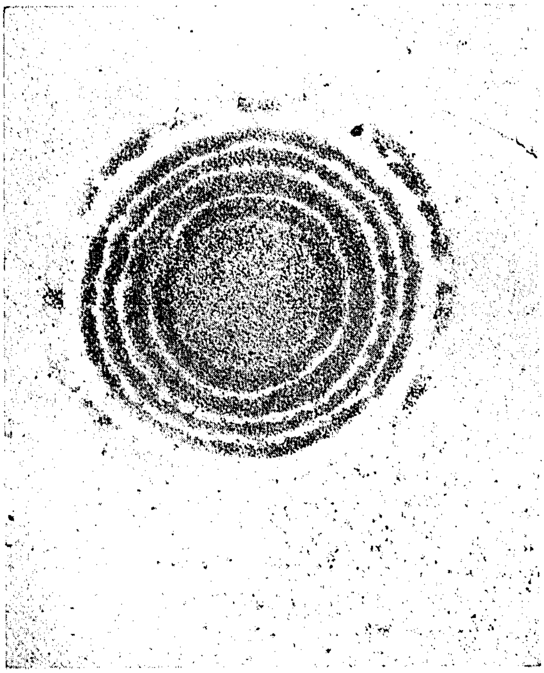
FLUID FRONTS IN VARIOUS SANDSTONES



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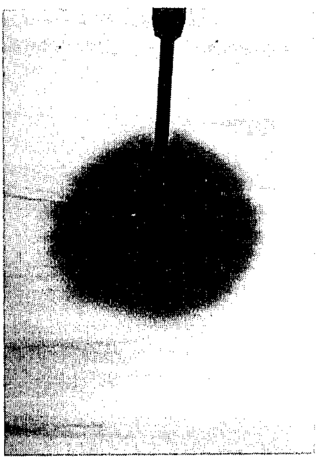

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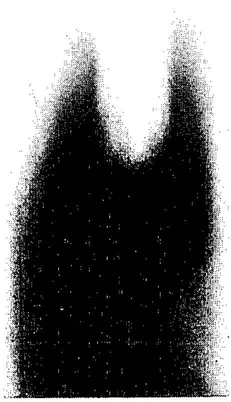

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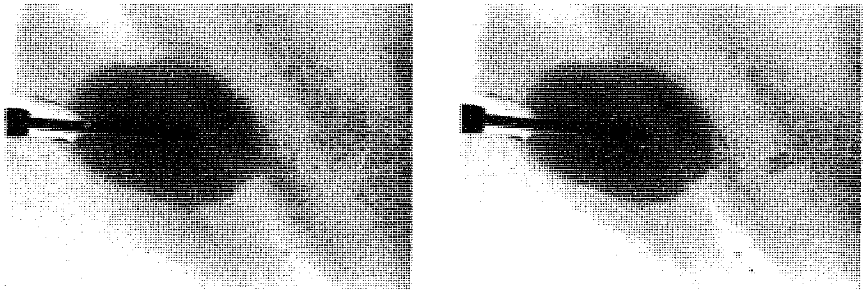
MISCELLANEOUS FLUID FLOW PATTERNS



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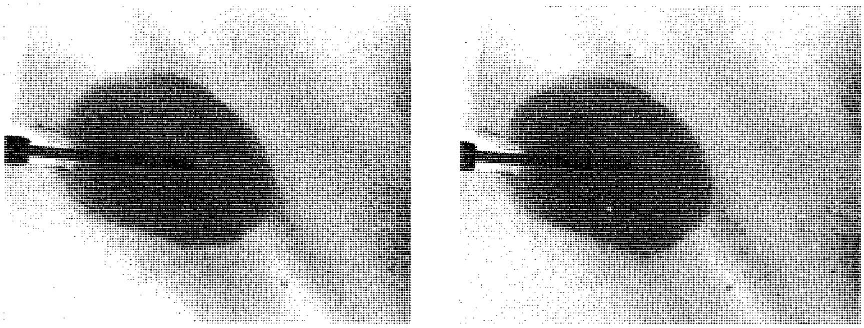

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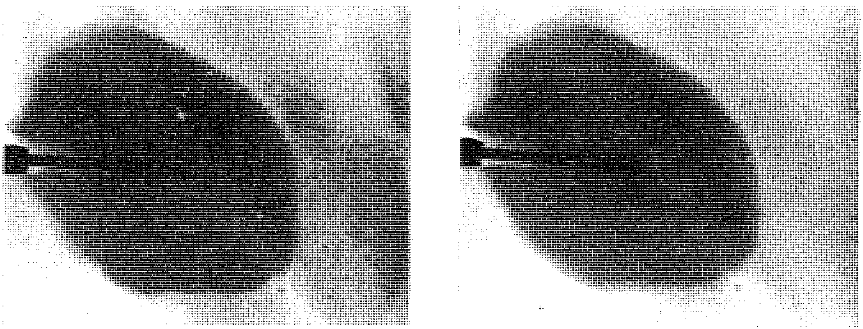

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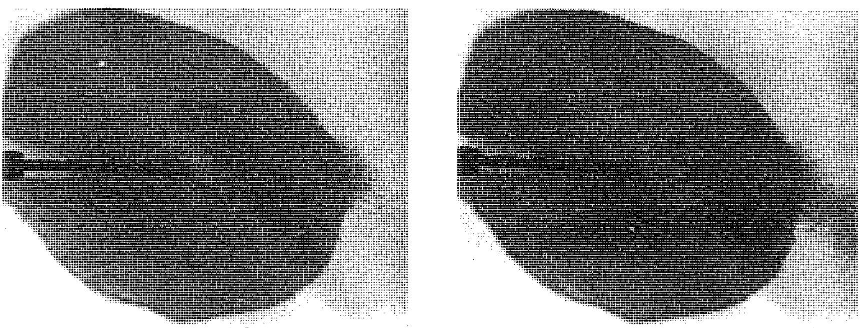

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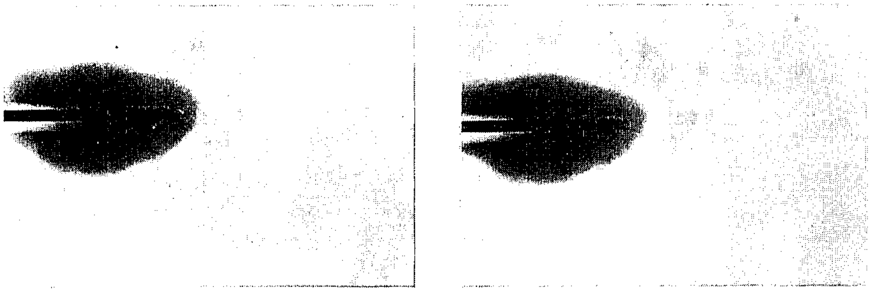
FLUID FRONTS IN ILLIPAH SANDSTONE



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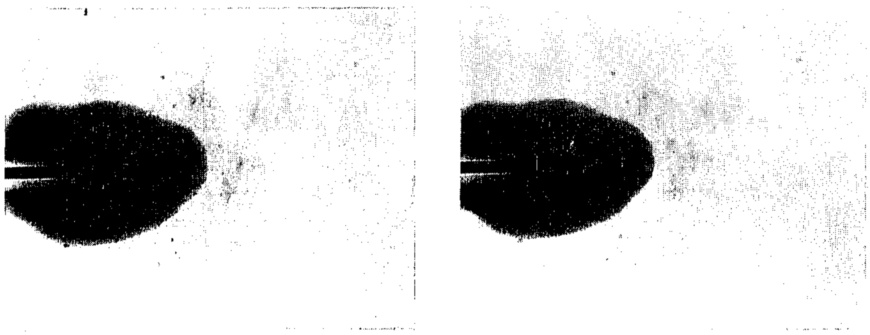

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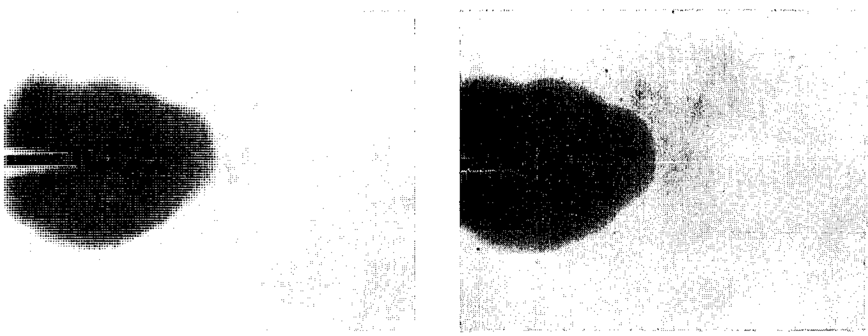

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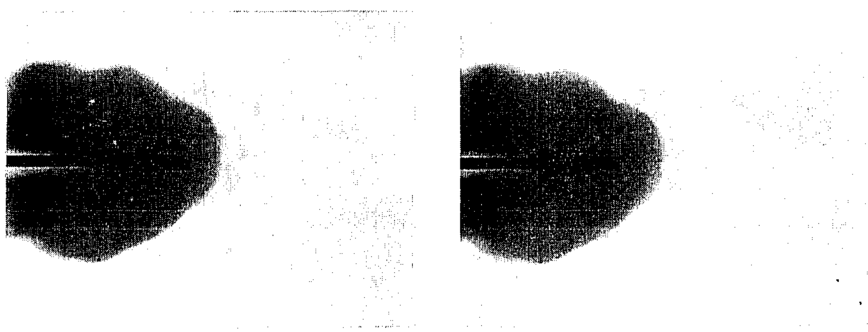

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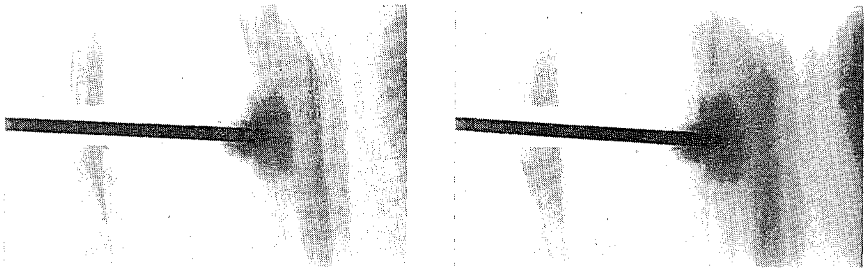
FLUID FRONTS IN HOMOGENEOUS TERTIARY SANDSTONE



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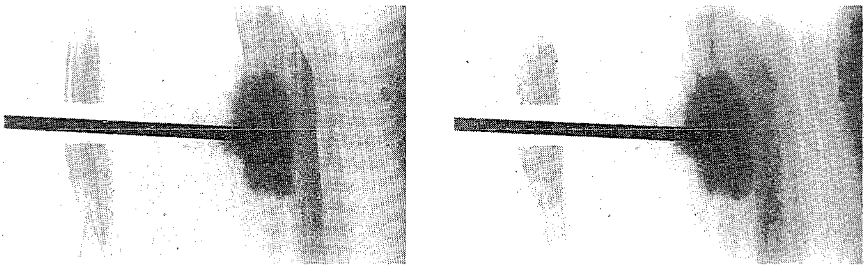

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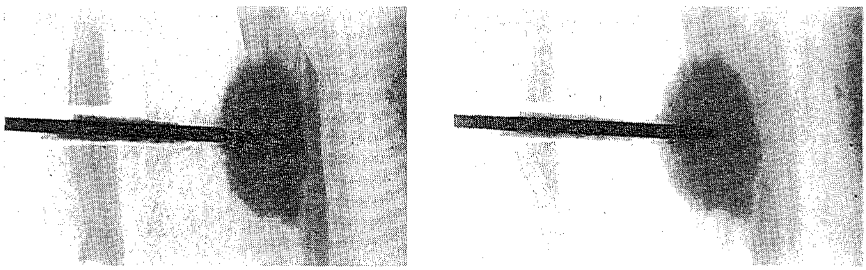

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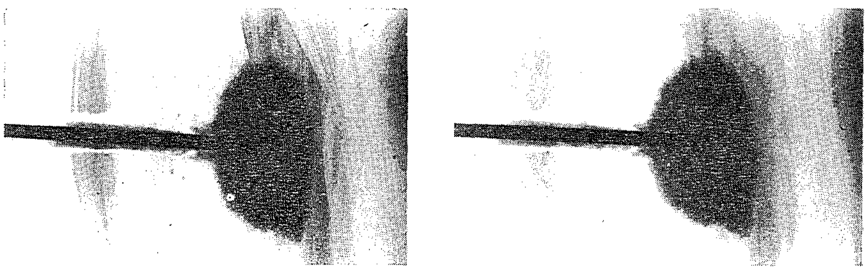

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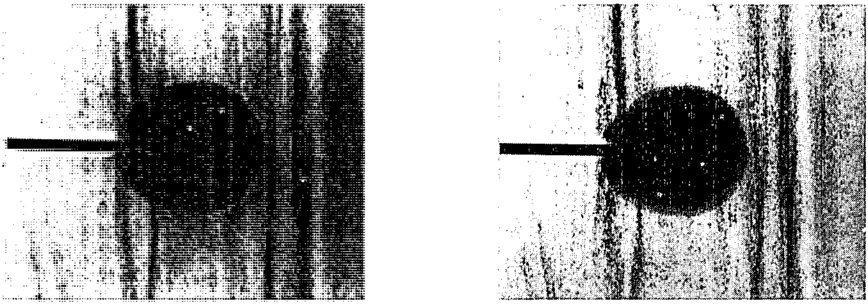

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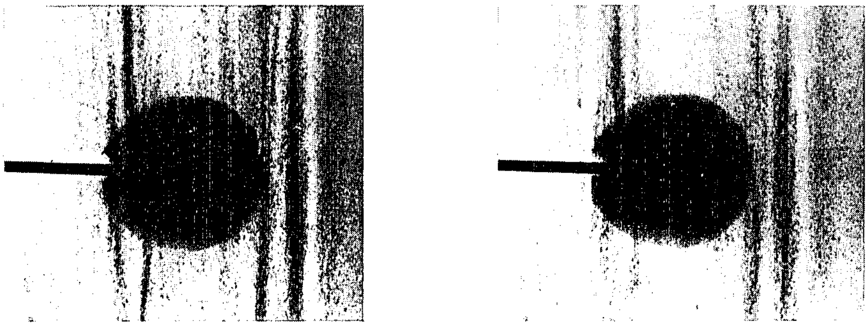

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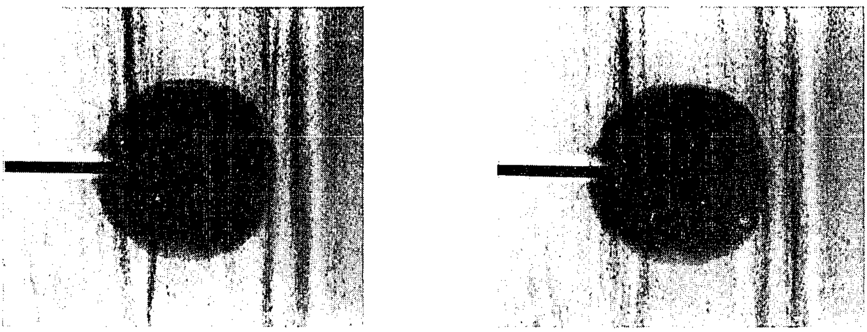

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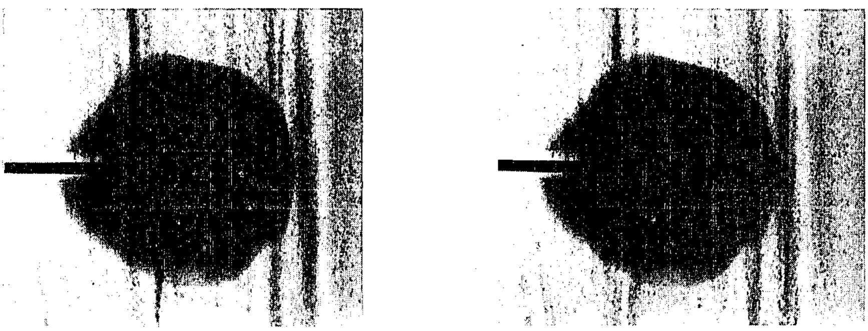

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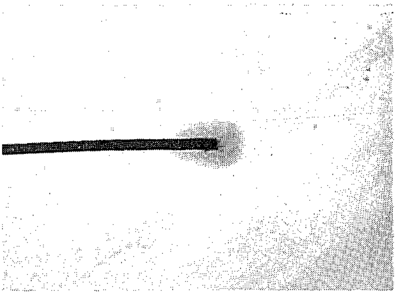

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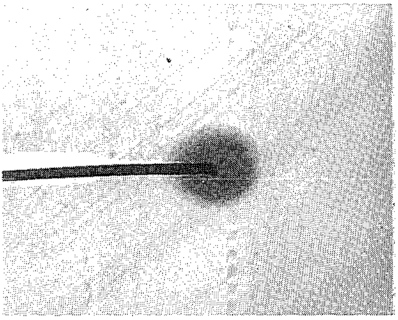

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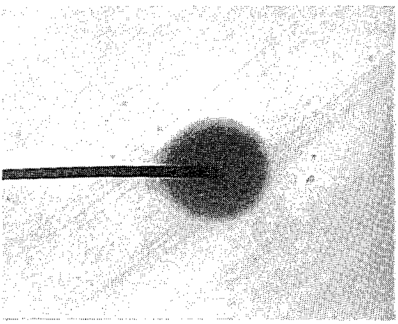

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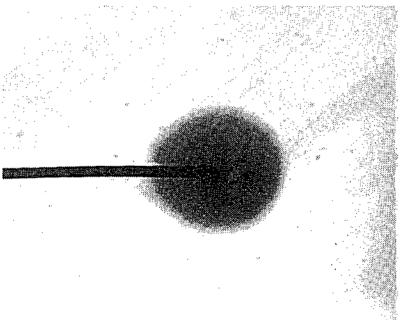

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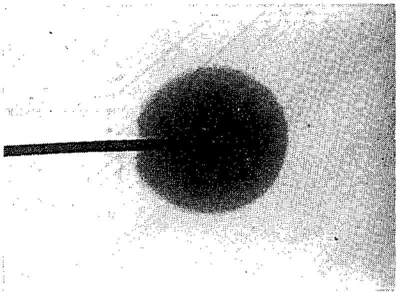

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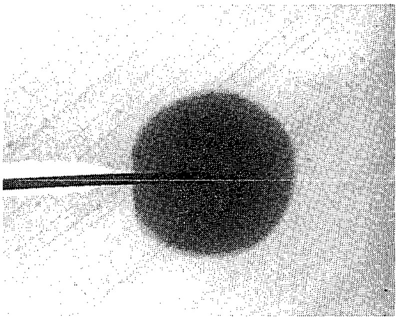

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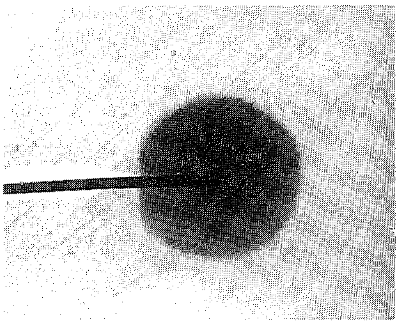

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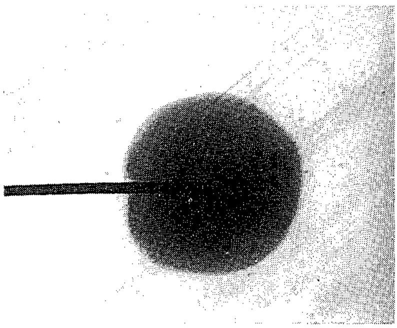

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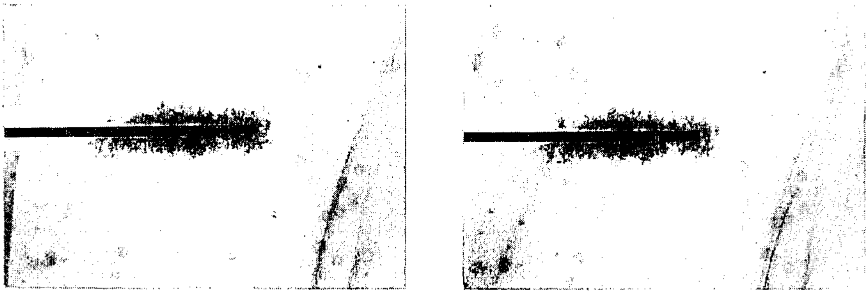
FLUID FRONTS IN FRONTIER SANDSTONE



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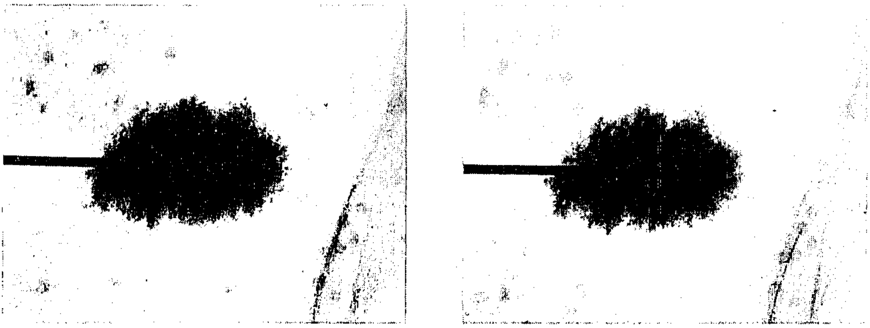

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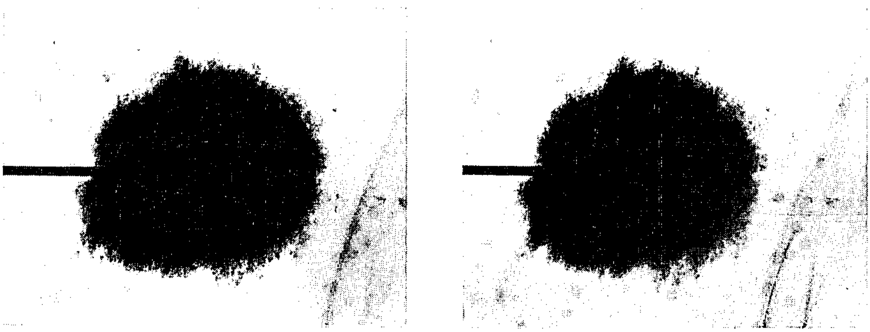

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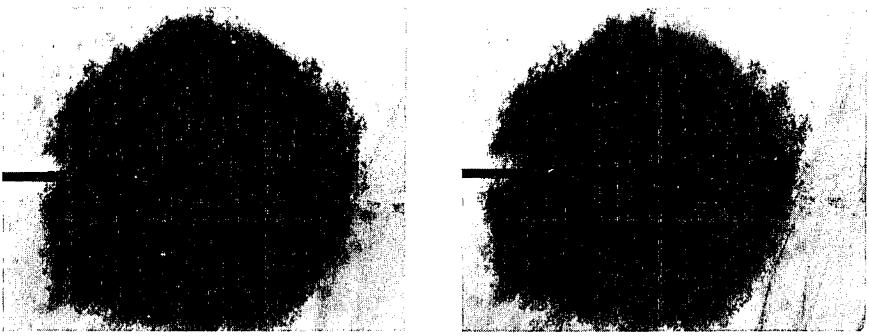

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FLUID FRONTS IN ENGLEVALE SANDSTONE

EXPLANATION OF PLATE 5

STEREORADIOGRAPHS OF CRYPTOSTRUCTURAL CONTROL IN A STRATIFIED CORE OF BEREA SANDSTONE FROM ILLINOIS

General explanation--shortened sequence of exposures revealing unexpressed cross-stratification and structural influence on fluid migration. All exposures made at 45 Kv, 100 Ma for 20 sec. Specimen thickness 1.3 cm., fluid Ditriokon. Specimen injected from upright position with needle at top. x1.

FIG. 1.—Fluid pattern after cumulative injection of 3 min. at 15 psi. + 3 min. at 20 psi.

FIG. 2.—Fluid pattern after cumulative injection of 3 min. at 15 psi. + 7 min. at 20 psi.

FIG. 3.—Fluid pattern after cumulative injection of 3 min. at 15 psi. + 12 min. at 20 psi.

FIG. 4.—Fluid pattern after cumulative injection of 3 min. at 15 psi. + 18 min. at 20 psi.

EXPLANATION OF PLATE 6

STEREORADIOGRAPHS OF INEFFECTIVE STRUCTURAL CONTROL OF FLUID MOVEMENT IN A STRATIFIED SAMPLE OF WEBER SANDSTONE FROM BLUE MOUNTAIN. COLORADO

General explanation—shortened sequence of exposures revealing- seemingly isotropic permeability in a visibly stratified sandstone. All exposures made at 60 Kv, 100 Ma for 9 secs. Specimen thickness 1.8 cm; fluid Ditriokon. Specimen injected from upright position with needle end at top. x1.

FIG. 1.—Fluid pattern after cumulative injection of 1 min. at 5 psi.

FIG. 2.—Fluid pattern after cumulative injection of 4 min. at 5 psi.

FIG. 3.—Fluid pattern after cumulative injection of 10 min. at 5 psi. + 1 min. at 10 psi.

FIG. 4.—Fluid pattern after cumulative injection of 10 min. at 5 psi + 2 min. at 10 psi + 1 min. at 20 psi. Sample waxed on front and back surfaces just prior to making 1 min. injection at 20 psi.

EXPLANATION OF PLATE 7

RADIOGRAPHS OF INEFFECTIVE STRUCTURAL CONTROL OF FLUID MOVEMENT IN A HOMOGENEOUS SAMPLE OF FRONTIER SANDSTONE FROM THE VICINITY OF VERNAL, UTAH

General explanation—condensed sequence of exposures revealing isotropic fluid flow across laminated cryptostructures. All exposures made at 60 Kv, 100 Ma for 8 sec. Specimen thickness 1.8 cm, fluid Ditriokon. Specimen injected from upright position with needle end at top. x1.

FIGS. 1-3.—Fluid pattern after cumulative injections of 1, 3, and 6 min. at 5 psi.

FIG. 4.—Fluid pattern after cumulative injection of 9 min. at 5 psi. + 2 min. at 15 psi.

FIG. 5.—Fluid pattern after cumulative injection of 9 min. at 5 psi. + 7 min. at 15 psi. + 5 min. at 25 psi.

FIG. 6.—Fluid pattern after cumulative injection of 9 min. at 5 psi. + 7 min. at 15 psi. + 15 min. at 25 psi.

FIG. 7.—Fluid pattern after cumulative injection of 9 min. at 5 psi. + 7 min. at 15 psi. + 20 min. at 25 psi. + 5 min. at 30 psi.

FIG. 8.—Fluid pattern after cumulative injection of 9 min. at 5 psi. + 7 min. at 15 psi. + 20 min. at 25 psi. + 30 min. at 30 psi.

EXPLANATION OF PLATE 8

STEREORADIOGRAPHS OF OBSCURE STRUCTURAL CONTROL OF FLUID MOVEMENT IN THE ENGLEVALE SANDSTONE MEMBER OF THE LABETTE SHALE OF EAST KANSAS

General explanation—shortened sequence of an obscurely controlled anisotropic pattern advancing along a fingering front. All exposures made at 60 Kv, 100 Ma for 10 secs. Specimen thickness 1.5 cm; fluid Ditriokon. Specimen injected from upright position with needle at top. x1.

FIG. 1.—Fluid pattern after cumulative injection of 1 min. at 5 psi.

FIG. 2.—Fluid pattern after cumulative injection of 5 min. at 5 psi. + 1 min. at 10 psi.

FIG. 3.—Fluid pattern after cumulative injection of 5 min. at 5 psi. + 7 min. at 10 psi.

FIG. 4.—Fluid pattern after cumulative injection of 5 min. at 5 psi. + 27 min. at 10 psi.

horizontal planes 0.5 to 4 cm. apart; however, when x-rayed, a profusion of delicate micro-cross-laminations was evident—comprising in effect the dominant type of internal feature present in the structural framework of the specimen.

It is commonly known that the expression of stratification is a result of prominent depositional changes in texture, composition, cementation or possibly fabric and that it is often enhanced by post-depositional conditions such as diagenesis, differential weathering, and oxidation. When, however, primary structural units are delimited by surfaces containing concentrations of accessory minerals, similar in color and texture to the surrounding grains or even by differently colored accessory minerals sparcely distributed along the interfaces, stratification will seldom be detected by the eye. On the other hand, any subtle variations in the forementioned properties will result in density differences readily detected by radiographic methods. These density differences, however, are rapidly modified or reduced as increasingly thicker samples are used and when the inherent structural planes are oriented toward a position perpendicular to the x-rays.

FLUID FRONT PATTERNS IN A VARIETY OF SANDSTONES

As the radiographic contrast solutions were injected and imbibed into the sandstone samples, zones and channel-networks of greatest permeability were distinctly outlined on the radiograph sequences. The degree to which the samples were anisotropic were reflected in the spherical, elliptical or irregular configurations of the emplaced fluid interfaces. Homogeneous sands characteristically develop basic isotropic or spherical forms such as illustrated in figure 1, Plate 1. Sands with a preferred direction of permeability developed an eccentric anisotropic form (see Plate 3), and sands reflecting inhomogeneous conditions developed an irregular form (see Plate 1, fig. 6).

The advances of the flood front extremities in the basic forms were characterized by a variety of fronts. Four types of fluid fronts were recognized and are illustrated on Plate 1. They are herein referred to as:

(1) Smooth front—a sharply defined front which develops in sandstones in which cementing materials are of relatively little importance; pore systems are dependent on grain packing and seemingly interconnect around every grain. They are most commonly developed in homogeneous units. A typical example of this front is illustrated in a massive sample of the Weber Sandstone (Plate 1, fig. 1).

(2) Fingering or dendritic front–a branching front which advances along a selective network of hairlike channels because of significant amounts of cementing material between grains and because of increased capillary action. This type of front was noted with various degrees of prominence in all but the well-stratified sandstones used in this study. Dendritic fronts appear to be the most basic form of frontal advance; however, they are seldom developed sufficiently to be noted apart from the smooth type of front. Well developed examples of this front formed in samples of the Englevale Sandstone Member of the Labette Shale of east Kansas (Plate 1, fig. 2).

(3) Lobate, tongued, and lateral fronts—types of lobed, wedged and elongated fronts which derive their distinct forms from zones of differing permeability coincident with stratification. Lobate forms were most common to well-laminated units and tongued fronts to cross stratified units. Sandstones possessing shale-like microlaminations or exceptionally variable porosity normal to bedding planes, such as in graded turbidite sands, developed highly restricted flow zones. Examples of these types are noted in Plate 1, figures 3, 4, and 5.

(4) Irregular front—fronts exhibiting extensive abnormalities reflecting either inhomogeniety or minute structures which were not detected by the type of radiation used (Plate 1, fig. 6).

Extraneous patterns were repeatedly developed in two relatively homogeneous sandstone types. Plate 2, figure 1 is a photo of the surface appearance of one such pattern on the Frontier Sandstone. The darker rings are wet surfaces and the lighter ones dry surfaces. X-rays reveal the continuation of these ring-like structures within the sample, often in greater numbers than expressed on the exterior surface. The number of rings appears to coincide with the number of intermittent injections that were introduced. This is borne out by the fact that such rings did not form during continuous injection procedures. Most rings formed on the back surface of the sample which was in contact with the film plate during injections and exposures, but variations showing some rings on the front surface and the remainder on the back were also noted. It has been tentatively suggested that this phenomenon represents isochromatic absorption resulting from a reaction between the clay and silt constituents and the fluid. Verification of such a suggestion was not pursued as these incidents represented only anomolous sidelights to the intent of this study.

EFFECTS OF CRYPTOSTRUCTURES ON FLUID FLOW

Flow conditions were produced in 34 of the 44 sandstone samples by utilizing pressures under 58 psi. The remainder of samples were impervious to fluid movement under the limitations of these conditions. Flood front advances in permeable samples were variously affected by structural interfaces; in some a strong controlling influence was noted while in others the complete lack of such influence was inversely evident. About two-thirds of the samples were rerun, some as many as five times, in order to ensure the repeatability of the phenomena observed.

The results of observations made on seemingly homogeneous sandstones containing cryptostructures proved most interesting. Out of five samples available for fluid flow tests, four of them developed flood front patterns reflecting control by cryptostructures. The massive Illipah Sandstone (Plate 3) is an example which exhibits a strong degree of control. One notes in this shortened sequence of pictures how the axis of elongation of the flooding front aligns itself parallel to the poorly developed stratification. Inclination of the anisotropic ic axis noted in the last radiograph of the sequence may possibly reflect an inherent imbricated fabric which became more evident under slow capillary movement. The extremities of the anisotropic form are also seen to advance in a weak fingering manner. The more prominent frontal edge of the bottom photo resulted from crystallization of the fluid which remained in the sample overnight prior to taking the last radiographs.

Plate four illustrates moderate cryptostructural control on a fine-grained, homogeneous Tertiary sand cored in the Ventura Basin. The faint discontinuous laminae revealed by x-rays are undoubtedly responsible for the lobate form developed by the fluid as matching indentations on either side of the pattern parallel the laminae. Encroachment of fluid across certain of the laminae is, of course, retarded by reduced permeability. A more controlled front would undoubtedly have resulted if the laminae had been more continuous. Note also the smooth front which is continuously expressed.

The results of relatable, observable control in a calculated 30 percent of all the homogeneous sandstones in these experiments are significant. Many massive appearing sandstones with good porosity may fail to be good aquifers or reservoirs for this reason rather than erratic cement distribution, et cetera.

It is also noted that similar occurrences of flood front control by unexpressed cryptostructures are evident, though to a lesser degree, in sandstones which express only a part of their stratification to the eye. Laminar planes viewed on the cut surfaces of a cored section of Berea Sandstone for example, are delicately displayed on radiographs as highly developed micro-cross-laminations interbedded with less prominent horizontal microlaminations (Plate 5). Upon injection, a degree of structural control by even the more delicate structures is noticed. Hair-like extensions of the flood front are seen to favor a planar orientation parallel to structures. Note also how the thin threads of fluid curl over to parallel the laminae on the left side in the vicinity of the needle in latter exposures. Most rapid advances of the fluid front occur along particular structural interfaces in the micro-cross-laminated section and a portion of the microlaminated section as can be noted particularly in the top stereo pairs. The front continuously reveals a notable parallelism with the microlaminations of the left side while on the right side and bottom it abuts against a near impervious barrier formed by the interface of one of the micro-cross-laminae. In effect the nestled form developed by the emplaced fluid would hardly be expected if one were to approximate the configuration of such a front by considering only the visible laminae.

On the other hand, both hidden and visible structures were noted to impart little or no effect upon advancing flood fronts in a number of other samples.

In these cases flood fronts developed essentially spherical, isotropic-like forms. Such occurrences were noted in 23 percent of the visibly stratified sandstones and 20 percent of the cryptostructured "homogeneous" units. A prominently stratified hand sample of Weber Sandstone, for example, developed little structural control on the fluid front until late in the sequence (see Plate 6). A spherical form is maintained by the front while crossing a number of horizontal laminae. Upon reaching the upper cross-laminated unit increased permeability results in a bulge in the spherical form (bottom exposure). Other minor fluctuations in permeability are noted at this point but do not greatly affect the general sphericity of the pattern.

A seemingly homogeneous sample of Frontier Sandstone provides even a more striking example of this phenomena (see Plate 7). One immediately notes the total ineffectiveness of the thin laminae in deflecting the isotropic form. In repeated experiments on this unit the effect was always the same. As the sample is so nearly void of any indications of stratification when viewed with the eye, one would hardly expect other than this type of result, but as it has been demonstrated such expectations are often unrewarded.

It should be noted that all the structural interfaces which exhibit controls on the flood front pattern may not be expressed on the radiographs because of the intensity of radiation used. Similarly, poorly developed structures with little contrast may not be noted if they are not perfectly aligned with the incoming x-rays. Also another control seldom detected on radiographs is that of an isotropic fabric. When such a fabric is strongly influential in vertical sections cut parallel to the fabric mean, then the major axis of an introduced fluid pattern will generally be inclined to the stratification. In sections cut perpendicular to the fabric mean, this inclination may be occasionally noticed but only in stereo or otherwise it would appear parallel to the stratification planes.

An example approaching the non-detected presence of a permeability control is illustrated in a specimen of the Englevale Sandstone (Plate 8). As one examines the exposed area which is later occupied by the flooding front, it appears to be quite homogeneous. The advancing fingering front, however, quickly denotes a preferred direction of advance which is noted to subparallel the distinct cross-laminations at the bottom of the sample. This effect then draws attention to the very faint trends of stratification within the flooding area seen in the right hand sets of the stereo pairs. Had the exposure position of the right hand set been slightly different then the reasons for a preferred direction of permeability would have been so easily deduced. Nevertheless, "hidden" stratification is again noted to develop a distinct control on fluid migration.

Cryptostructures are summarily seen to act as barriers or conduits similar to many visible structures when, and if, differences in effective porosity exist across them. If, however, no aggregate difference exists, fluid flow will not be affected. There are several reasons why structural interfaces may not affect fluid flow:

(1) the accessory minerals, common constituents of structural interfaces, may have textures relatively close to the surrounding particles.

(2) if much smaller sized clasts of accessory minerals are involved then their increased angularity may counteract the effective-porosity reduction expected from mixing grain sizes along the contact.

(3) accessory minerals denoted by x-rays may be too scattered along structural planes and the immediate area of decreased permeability may be surrounded and bypassed by the fluid and the effect go unnoticed.

OBSERVATIONS OF FLUID PATTERNS IN PREWETTED SAMPLES

Flow conditions were initiated in a number of prewetted specimens to simulate more closely conditions found in nature. The saturant fluid and the induced opaque fluid were in each case miscible. When prewetted fluid patterns were compared to patterns produced in equivalent "dry" specimens, essentially no differences were noted in the manner of advance in three out of four sandstone types. Note, for example, the similarity of the tongued advance in the dry and re-imbibed sample of Dakota Sandstone of Plate 1, figure 4 and Plate 2, figure 3. Low contrasts between the fluids are responsible for the poor reproduction of the picture on Plate 2 denoting the prewetted front.

The prominently lobated front typically developed in dry specimens of the well-laminated Tonganoxie Sandstone, however, was smoothed out into a diffused spherical shape during one series of injections conducted on a prewetted sample (Plate 2, fig. 2). During a rerun of this experiment on a new specimen of the same unit, relatively no diffusion occurred even though the sample was shown to be well saturated. Because of these inconsistencies, it would be premature to draw any definite conclusions about these limited observations without additional work being conducted in this area.

COMPARISON OF FLOOD FRONT PATTERNS TO FABRIC

Attempts to determine the aggregate fabric of previously injected specimens with stereoradiography were unsuccessful. Thin slices three to four millimeters in thickness were made from the specimens but proved to be too thick to distinguish one individual grain from the superimposed images of other grains lying within the same plane. By making much thinner slices the aggregate fabric would not be evident and thin-section procedures would have to be instituted. To be useful in fabric studies radiography must be able to supplant the tedious task of making numerous thin section, grain counts and orientations.

CONCLUSIONS

Stereoradiography provides an excellent method to visually study natural fluid flow conditions on a small scale. The major advantage is that it offers a three-dimensional view of fluid interfaces within the structural framework of a rock. This method is limited, however, by the small sample size suitable for making good radiographs.

The effect of cryptostructures of fluid movement appears to be largely dependent upon effective porosity. Like visible structures, they act as barriers or channels when differences of permeability exist across them and exhibit essentially no effect when the differences are insignificant or dispersed. Unexpressed structural control may therefore have a profound effect upon the permeable potential of a sandstone unit.

SAMPLE LOCALITIES

(1) Baseline Sandstone—outcrop sample from vicinity south of Glendale Junction, Clark Co., Nevada.

(2) Beria Sandstone—cored sample from well in Illinois.
(3) Englevale Sandstone member of the Labette Shale—outcrop sample from T 26 S, R 25 E, Bourbon Co., Kansas.
(4) Dakota Sandstone—outcrop sample 20 miles west of Salina, Saline Co., Kansas, on Highway 40.
(5) Frontier Sandstone—outcrop sample three miles north of Vernal, Uintah Co., Utah, on Highway 44.
(6) Illipah Sandstone—outcrop sample from Mt. Hamilton, White Pine Co., Nevada.
(7) Tonganoxie Sandstone—outcrop sample from Dietman Crossing, Douglas Co., Kansas.
(8) Unidentified Cretaceous Sandstone—outcrop sample from vicinity north of Judith Mountains, Judith Basin Co., Montana.
(9) Unidentified Tertiary Sandstone—cored sample from Ventura Basin, California.
(10) Weber Sandstone—outcrop from Blue Mountain, Moffat Co., Colorado.

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