SANDSTONE DIAGENESIS AS A FACTOR IN STIMULATION DESIGN

WILLIAM R. ALMON
Cities Service Oil Company

INTRODUCTION

The presence of clay minerals within a sandstone reservoir is a major factor in the sensitivity of that reservoir to treatment fluids. The exact type of fluid sensitivity (acid, fresh water, *etc.*) depends on the exact type of clay mineral present in the reservoir. In recent years, X-ray diffraction analysis has been extensively used to determine the type and amount of clay minerals present in reservoir sandstones.

There is a problem in designing a well stimulation on the basis of X-ray diffraction analysis or any other type of analysis which evaluates the properties of the reservoir sandstone in bulk. The problem is that clay minerals may be of two distinct origins which produce different distributions of clay minerals within the reservoir and different degrees of exposure to completion and stimulation fluids.

DISTRIBUTION OF CLAYS IN SANDSTONES

The clay minerals observed in sandstones have two general origins. They may have formed locally within the sandstone framework (diagenetic), or they may have formed at some point outside of the sandstone framework (detrital). Detrital clay minerals are usually incorporated into the sandstone at the time of deposition. Diagenetic clay minerals develop subsequent to burial due to precipitation of new minerals or recrystallization of existing minerals.

Detrital Clays

The most common distributions of detrital clay minerals which occur in a range of sizes, from discrete clay-sized particles to sand sized aggregates, are shown schematically in Figure 1. Individual clay particles may be dispersed as a matrix with the sandstone. This matrix material is deposited as terrigenously derived clay along with silt and sand-sized particles. As a result the clay completely fills

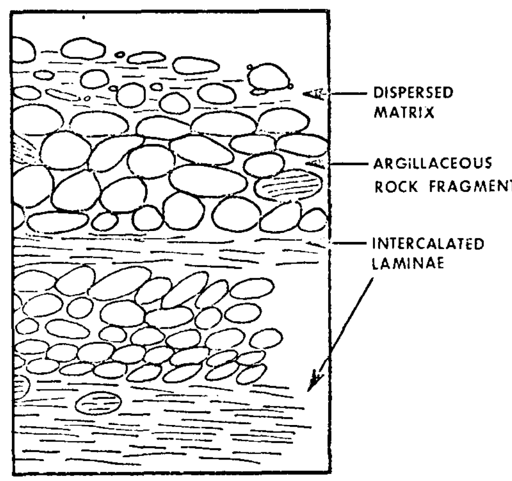

FIG. 1—THIS FIGURE ILLUSTRATES THE MOST COMMON OCCURRENCES OF DETRITAL CLAY MINERALS. DISCRETE CLAY-SIZED MATERIAL OCCURS IN RELATIVELY CONCENTRATED ZONES AS CLAY MATRIX OR SHALE LAMINATIONS. SAND- AND SILT-SIZED AGGREGATES OCCUR AS SCATTERED ARGILLACEOUS GRAINS.

FIG. 2—IN THIS PHOTOMICROGRAPH THE DETRITAL CLAY MATRIX CAN-BE SEEN COMPLETELY FILLING THE PORES, PRODUCING A RELATIVELY IMPERMEABLE ZONE.

the interstices between grains, and the zone is relatively impermeable and acts as a permeability barrier within the sandstone unit (Figure 2).

Individual clay flakes can be deposited as intercalated laminae (shale membranes) within a sand layer. These shale stringers act as permeability barriers and limit permeability in some directions (generally vertically) while leaving the permeability unaffected in other directions (Figure 3).

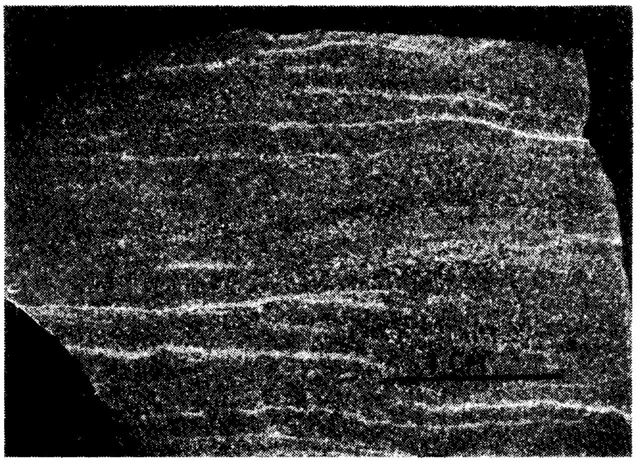

FIG. 3—THE DEVELOPMENT OF DETRITAL CLAY LAMINATIONS WITHIN A SANDSTONE, AS SEEN HERE, TENDS TO DIRECT THE PERMEABILITY PARALLEL TO THE LAMINATIONS.

Detrital clays are also deposited as various sand or larger sized particles. These large aggregates may take the form of argillaceous rock fragments, biogenic pellets, "rip-up-clasts" or clay flocules; however, they can all be treated as framework grains.

Diagenetic Clays

The common distributions of diagenetic clays, which occur as chemical precipitates directly from the formation waters or as alternation products from the interaction of existing minerals and the formation waters, are shown schematically in Figure 4. As a result of this genesis, diagenetic minerals are sensitive indicators of pore water chemistry at the time of the clay mineral's formation.

Chemically precipitated diagenetic clay minerals always develop within the sandstone pore system.

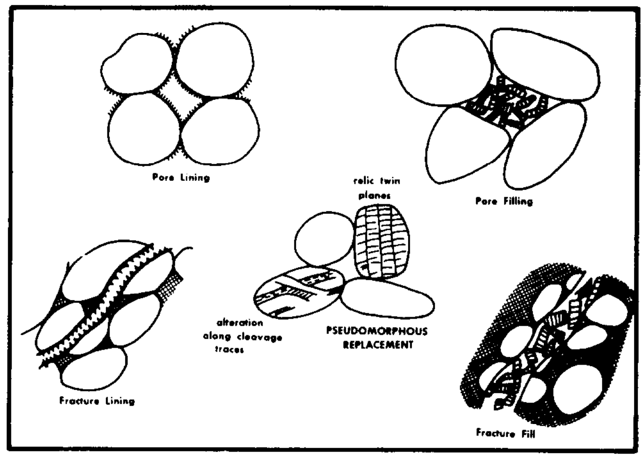

FIG. 4—DIAGENETIC CLAY MINERALS GENERALLY OCCUR AS CHEMICAL PRECIPITATES WITHIN THE SANDSTONE PORE SYSTEM, AS PORE OR FRACTURE COATINGS, OR AS PORE OR FRACTURE FILLS. DIAGENETIC CLAY MINERALS ALSO DEVELOP AS ALTERATION PRODUCTS OF DETRITAL GRAINS.

The major form of this development is as pore coatings which are deposited on the free surfaces of framework grains and do not develop at points of grain-to-grain contact. The individual clay particles or aggregates within the coating commonly exhibit a preferred orientation (normal to the grain surface). Coatings grow outward from the grain surfaces and may merge with linings on adjacent grains to form a continuous film. Clay coatings can form in any sort of void and are known to coat fracture surfaces as well as pore surfaces (see Figure 4). Such clay coatings are a major cementing agent in many friable sandstones.

Diagenetic clay mineral precipitates also occur as loose pore filling aggregates (Figure 4). Such clay fillings occur with equal ease within pores or fractures. In clay fillings, the individual flakes or aggregates of flakes exhibit no preferred alignment relative to the surfaces of the void. The interaction of formation waters and unstable minerals often causes diagenetic clay minerals to develop as partial or complete replacements of the unstable detrital grains (Figure 4). In some cases, the replacement is pseudomorphic and original grain textures are observed in the replacement.

The preceeding discussion makes it clear that diagenetic clay minerals occur almost exclusively within the pore system of the sandstone reservoir, and consequently the full amount of clay mineral present in the reservoir is exposed to the effects of any stimulation fluids. Detrital clay minerals are concentrated in clay-rich zones where the full amount of clay mineral may not be exposed to the effects of any stimulation fluids. However, the clay rich zones may impart a directional permeability to the reservoir which might not otherwise exist.

EFFECT ON RESERVOIR QUALITY

SEM (scanning electron microscope) observations of sandstone cores (Figure 5) clearly indicate that the pore network in sandstones contains thousands of interconnected pores per cubic inch.[1] These pores vary greatly in size and shape, and the entrances and exits between pores are always considerably smaller than the pores themselves. This irregular pore geometry imposes a tortuous path on any fluid transported through the pore network. Thus, fluids moving through the pore system will be subjected to frequent variations in velocity and direction. Diagenetic clay mineral development aggravates this situation by increasing the tortuosity of the pore system as well as the pore surface area.

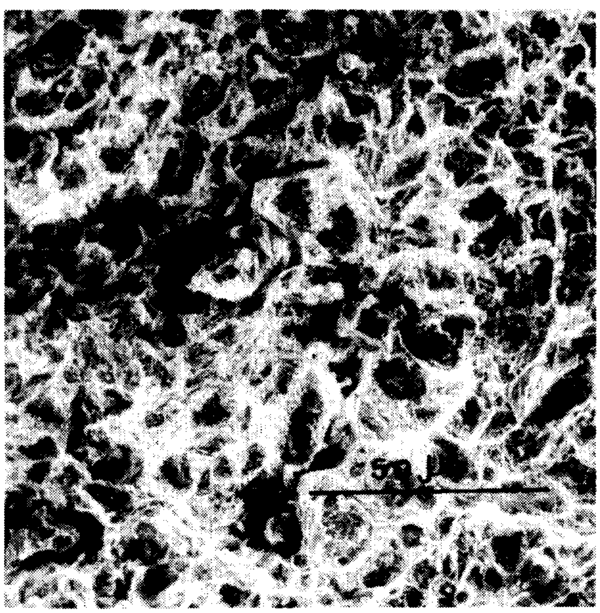

FIG. 5—THE PORE NETWORK IN SANDSTONES CONTAINS THOUSANDS OF INTERCONNECTED PORES PER CUBIC INCH. THESE PORES VARY GREATLY IN SIZE AND SHAPE AND THE ENTRANCES AND EXITS BETWEEN PORES ARE ALWAYS CONSIDERABLY SMALLER THAN THE PORES THEMSELVES.

The impact on permeability can be seen by comparing these SEM photographs of a clean pore system (Figure 5) and various clay coated pores (Figures 6, 7, and 8). The development of pore coats tends to subdivide the pores into a myriad of micropores. These pore coatings present an extremely large surface area to any fluids present which facilitates extensive chromotographic adsorption and ion exchange between pore fluids and the clay minerals.[2]

The pore coating clay minerals have a much more pronounced effect on permeability than on porosity. The extreme fibrosity of some of the clay coating minerals greatly increases the tortuosity of the pore system due to the partitioning of individual pores into thousands of smaller pores without the clay mineral's physically filling a significant fraction of the pore volume (note especially Figure 7). The fibrosity of the pore coating clay minerals also tends to reduce permeability by forming clay bridges at pore exits where the pore coatings on opposing pore faces interfinger (Figure 9).

The pore filling clays (mainly kaolinites) reduce permeability by reducing the pore size and altering the pore geometry (Figure 10). The loose aggregates developed by pore filling clays can physically occupy a significant fraction of the pore volume and force fluid to flow through the numerous tiny passages within the clay aggregate. In the event of high velocity flow through the pore, the pore filling can be forced to migrate until it becomes lodged in a pore exit where it will function as a check valve.[3] Sandstone reservoirs often contain a large number of such diagenetic pore fillings which can be dislodged by fluid flow and can then act as barriers to migration.

EXPOSURE TO FLUIDS

Because diagenetic minerals are the principal agents in the reduction of porosity and permeability in a sandstone reservoir, they should be a principal concern in well completion and stimulation designs. Diagenetic minerals occur almost exclusively within the pore system of the sandstone, as pore coatings and pore fills. Thus, they are exposed to any fluids involved in the completion process to a much greater degree than the detrital clay minerals which occur in concentrated clay rich zones and are not dispersed throughout the pore system.

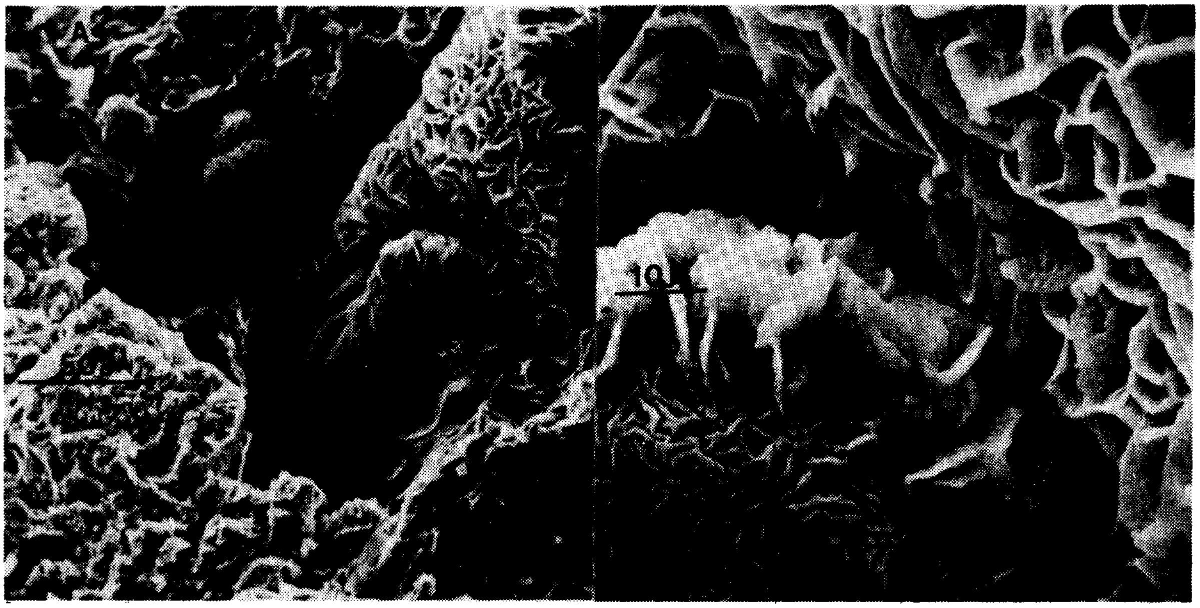

FIG. 6—CHLORITE IS A CLAY MINERAL WHICH DEVELOPS PORE COATINGS. THE COATINGS GROW FROM FREE SURFACES OUTWARD INTO THE PORE PRODUCING HOUSE OF CARDS NETWORK ON THE PORE SURFACE. SEM MICROGRAPH B ILLUSTRATES HOW THIS PORE COATING SUBDIVIDES THE PORE INTO MANY MICROPORES.

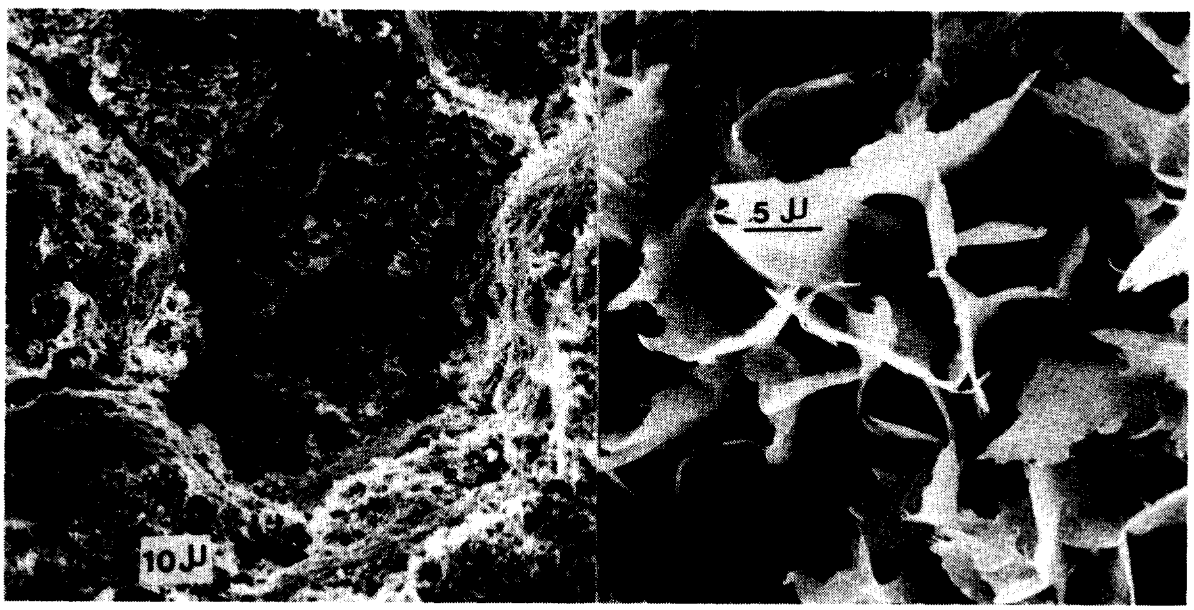

FIG. 7—THE CLAY MINERAL ILLITE DEVELOPS DIAGENETIC PORE COATINGS (A). THE PORE COATING GROWS INTO THE PORE SPACE FROM THE FREE SURFACES OF A PORE (B). THE HOUSE OF CARDS SUBDIVISION OF THE PORE AND FIBROUS TEXTURE OF THE PORE COATING ARE OBVIOUS.

EXAMPLE CASE HISTORY

The benefits of a treatment based on a bulk analysis (such as X-ray diffraction) of the mineral content of a reservoir may be cancelled or greatly reduced by the undesirable reaction between treatment fluid and the diagenetic minerals.[4, 5] An example of such an unfortunate reaction concerns the treatment of a reservoir which analyzed 1 percent illite, 2 percent chlorite, 5 percent calcite, 87 percent quartz, and 5 percent feldspar (6.5 per cent less than five micron sized material). On the basis of

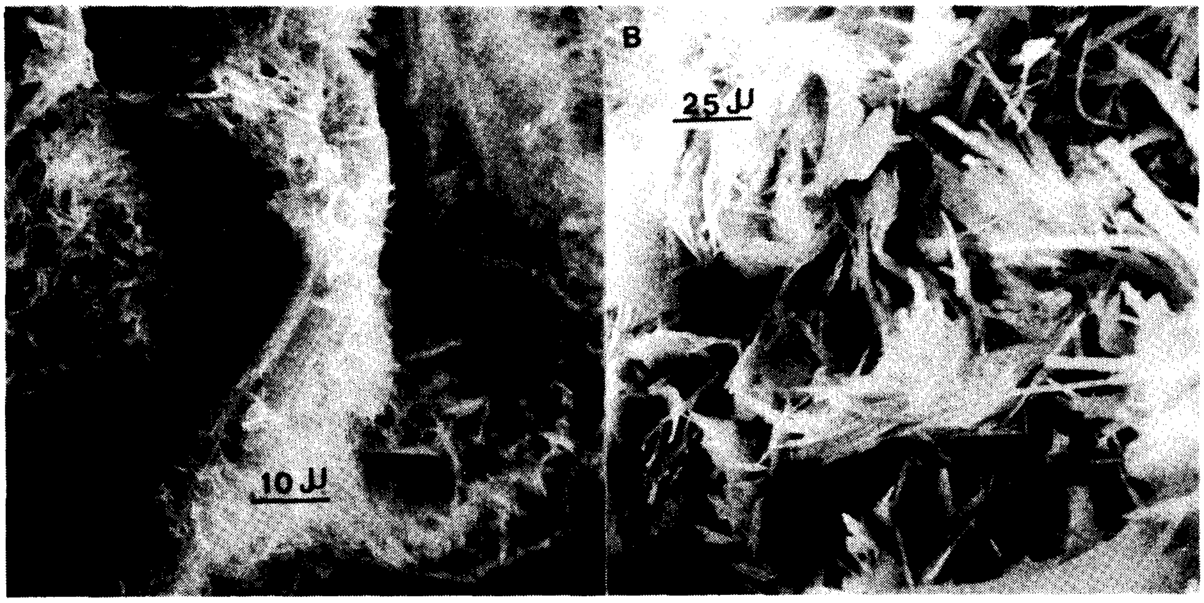

FIG. 8—MONTMORILLONITE DEVELOPS DIAGENETIC PORE COATINGS. (A) THE MODE OF DEVELOPMENT IS MUCH THE SAME AS WITH OTHER MINERALS. (B) THE EXTREME FIBROSITY OF MONTMORILLONITE PORE COATINGS EXPOSES A TREMENDOUS SURFACE AREA TO ANY PORE FLUID.

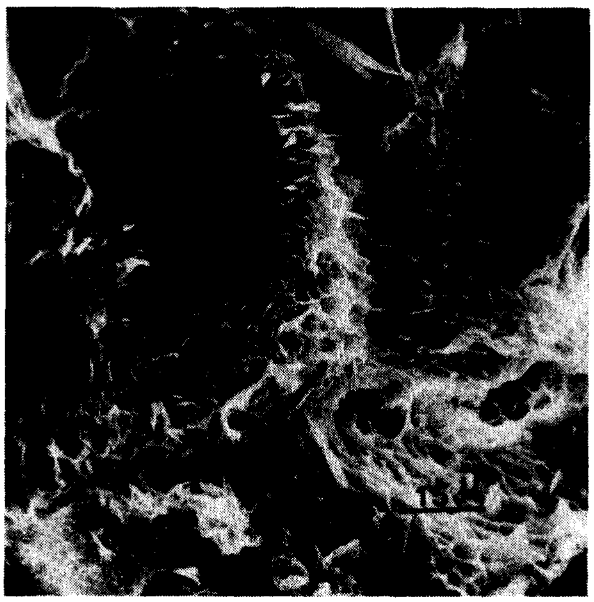

FIG. 9—THE FIBROSITY OF THE PORE COATING CLAY MINERALS TENDS TO REDUCE PERMEABILITY BY FORMING CLAY BRIDGES AT PORE EXITS WHERE THE PORE COATINGS ON OPPOSING PORE FACES INTERFINGER.

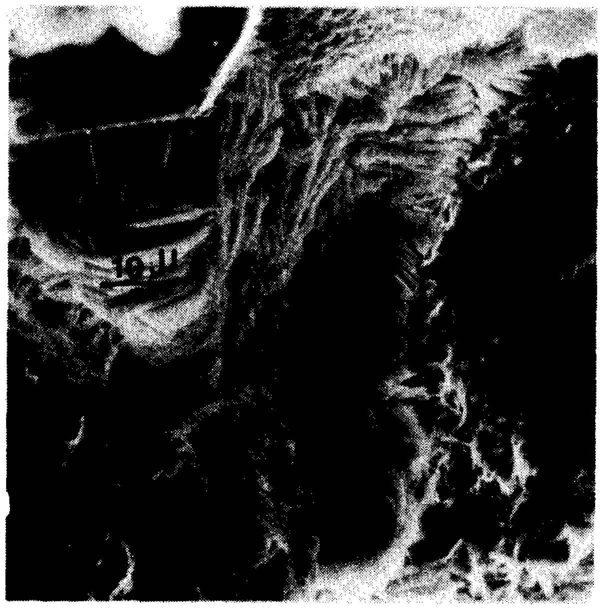

FIG. 10—PORE FILLING CLAYS (MAINLY KAOLINITE) REDUCE PERMEABILITY BY REDUCING THE PORE SIZE AND ALTERING THE PORE GEOMETRY.

this analysis the well was treated with 500 barrels of 7.5 percent HCl to remove the calcium carbonate and improve production from the 1.1 MMCFPD tested before treatment. After partial recovery of the acid the well tested at approximately 200 MCFPD.

Subsequent investigation has shown that the reduction in production was due to the precipitation of iron hydroxide in the pore system of the reservoir (Figure 11). The small percentage of chlorite in the reservoir was present as diagenetic pore coatings (Figure 12) which were perfectly placed to react with the acid introduced to remove the calcium carbonate cement. The formation damage caused by the precipitation of iron hydroxide from the spent, unrecovered acid more than cancelled any benefit derived from the removal of calcium carbonate cement. It should be obvious, then that diagenetic mineralogy must be taken into account whenever a well treatment is designed.

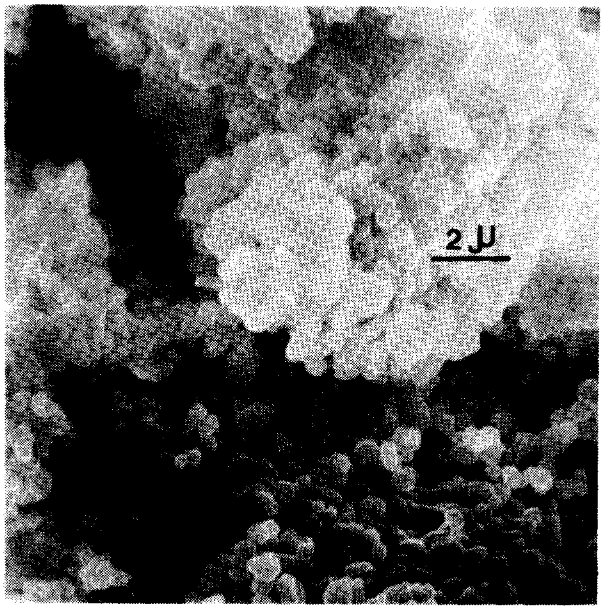

FIG. 11—IRON HYDROXIDE PRECIPITATED FROM SPENT ACID IS AN EXCELLENT DESTROYER OF PERMEABILITY.

A more positive example of the benefits of tailoring a well stimulation to the diagenetic mineralogy of the particular reservoir can be obtained from the numerous published examples of stimulations in the Morrow Formation in the Texas and Oklahoma Panhandles.[5] In a well in Texas County, Oklahoma, X-ray diffraction analysis indicated the reservoir to be composed of 84 percent quartz, 3 percent feldspar, 5 percent calcite, 2 percent dolomite, 2.5 percent Kaolinite, 2.3 percent chlorite (high iron variety), and 1.2 percent montmorillonite (8 percent less than five micron sized material). Pre-stimulation observations with the SEM indicated that the montmorillonite and kaolinite were present as detrital clay laminae within the sandstone reservoir (Figure 13) and that the chlorite (Figure 14) was present as extensively developed pore coatings. Some of the kaolinite was present as loose diagenetic pore fills (Figure 15). On the basis of this combined X-ray diffraction and SEM observation pre-stimulation evaluation, the well was treated with 10,000 gallons jelled 3 per cent HCl + 0.6 percent HF with 2 gallons fluorocarbon surfactant and 50 pounds of citric acid per 1000 gallons. This stimulation resulted in an eight-fold increase in production.

FIG. 12—CHLORITE CLAY COATINGS IN THE PORE SYSTEM OF A RESERVOIR WILL CAUSE A FORMATION TO BE ACID SENSITIVE EVEN IF THEY ACCOUNT FOR ONLY A TINY FRACTION OF THE BULK RESERVOIR ROCK.

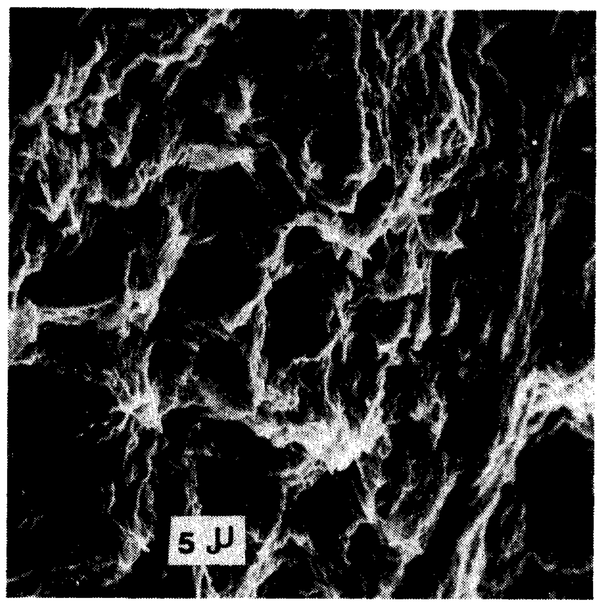

FIG. 13—DETRITAL CLAY LAMINATIONS, EVEN WHEN COMPOSED OF SENSITIVE CLAYS, DO NOT PRODUCE EXTENSIVE SENSITIVITY IN A FORMATION AS ONLY A SMALL PERCENTAGE OF THEIR CLAY CONTENT IS EXPOSED TO TREATING FLUIDS.

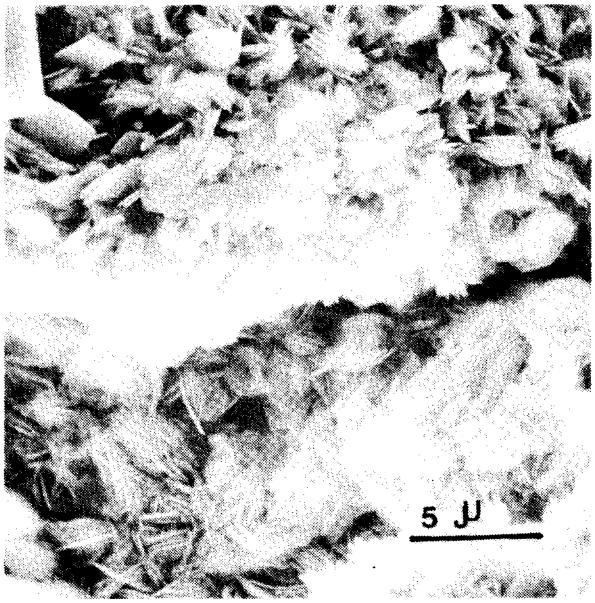

FIG. 14—CLAY PORE COATING IN A RESERVOIR WILL PRODUCE EXTENSIVE SENSITIVITY IN THE FORMATION AS ALL OF THEIR MATERIAL IS EXPOSED TO TREATING FLUIDS. ALSO THE GREAT SURFACE AREA OF PORE COATINGS WILL SPEED REACTIONS BETWEEN THE CLAY AND THE STIMULATION FLUID.

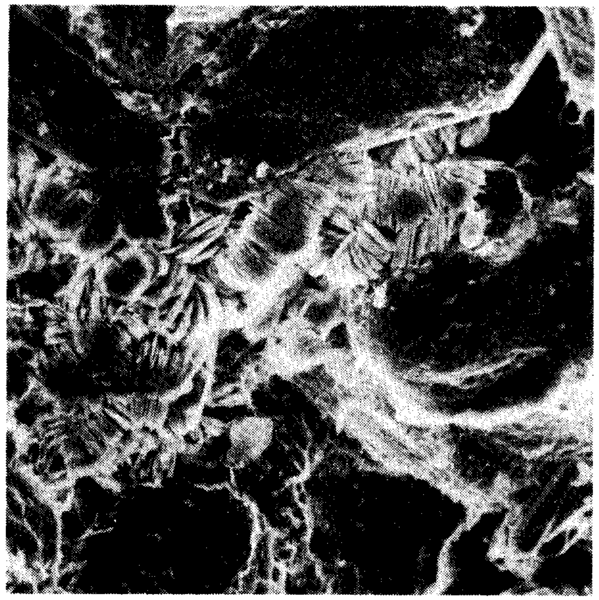

FIG. 15—LOOSE DIAGENETIC PORE FILLS CAN BE INDUCED TO MIGRATE BY HIGH FLUID FLOW RATES AND WILL ACT AS CHECK VALVES.

CONCLUSIONS

1. Clay minerals in sandstone reservoirs may have either of two distinct origins: detrital or diagenetic.
2. Diagenetic and detrital clay minerals have different modes of occurence within a sandstone reservoir, which reflect their different origins.
3. Detrital clay minerals generally develop in concentrated zones which produce permeability barriers and thus tend to direct permeability while reducing it mildly.
4. Diagenetic clay minerals are generally diffusely developed within the pore system of the reservoir and tend to reduce permeability greatly.
5. Diagenetic pore coating clays are much more destructive of permeability than of porosity.
6. Diagenetic pore-filling clays reduce porosity at least as much as they reduce permeability.
7. Stimulation of a diagenetically altered sandstone reservoir should be aimed at removal of diagenetic clay minerals as they are the minerals which most drastically reduce permeability.
8. The presence of diagenetic clay minerals in a sandstone reservoir renders the reservoir more sensitive to stimulation fluids than a similar volume of detrital clay minerals.
9. Well stimulations should be tailored to the particular diagenetic problems expected in the reservoir to be stimulated through the use of prestimulation evaluations.

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