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SOME IMPORTANT ASPECTS OF WATER FLOODING IN ILLINOIS

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Some Important Aspects of Water Flooding in Illinois*

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Abstract

The history of primary oil production in Illinois, including vacuum and repressuring operations, is reviewed. Early attempts at water flooding and the more recent developments in pattern flooding are discussed, and the results of three major water flood projects are presented. The use of earth resistivity measurements in locating fresh water for injection purposes is discussed, and two examples of field measurements are presented. The complex problems of simultaneously flooding several stratigraphic horizons are considered, and the importance of clay mineralogy in water flooding is discussed. An estimate of the secondary oil reserves in Illinois is included.

Introduction

The use of water flooding as a means of secondary recovery is destined to have widespread effects on the oil productive capacity of Illinois. At present, less than ten percent of the total productive acreage of the state is being flooded, but the successes that have accrued in the past few years indicate that a great future lies ahead in the proper application of this method of oil recovery. This seems to be the general consensus of the operators in Illinois, because the development of water flooding is currently proceeding at a rapid pace. Several recent publications have presented adequate resumes of current water flood operations in Illinois, including detailed factual data (1,2,3).** Therefore, it may be of more interest at this time to review the background and to discuss a few important features of these operations.

Primary Oil Production

Oil was first discovered in Illinois quite by accident during some coal exploration work near the city of Litchfield in 1879 (4). The oil producing formation, a Pennsylvanian sand at 680 feet, was limited in extent and had an accumulated recovery of only 22,000 barrels from an estimated 100 productive acres when abandoned in 1904. In the same year significant quantities of oil were found in eastern Illinois near the town of Casey in what is now known as the Westfield pool of Clark County (5). Subsequent drilling from 1905 to 1911 revealed a series of oil fields trending slightly southeastward from the Westfield pool for a distance of 70 miles along the eastern edge of Illinois. Two or more producing zones were found in practically every field at depths ranging from 400 to 2,300 feet. The producing formations are predominantly sandstones of Pennsylvanian and Mississippian ages, although one Mississippian limestone, which was misnamed the McClosky "sand," has been a prolific oil producer.

Of the old fields the Lawrence pool, which was discovered in 1907 in Lawrence County near the south end of the trend, has had the highest oil production, due no doubt to the presence of five producing horizons. By the end of 1918, the average recovery was 6,000 barrels per acre; and by the end of 1950, the recovery was 9,200 barrels per acre from 26,000 productive acres, or a total oil production of almost 245 million barrels. This is 50 percent of all the oil that has been produced in the old fields, although the Lawrence field has only 25 percent of the productive acreage that was drilled in these early developments.

Early geological studies (5,6) of these oil fields revealed the lenticular nature and the unpredictable thickening and thinning of the productive horizons. They were usually irregular domes of varying areal extent, and field development was limited either by edgewater or by a sand pinching out into Shale. Water was also reported (6) within the productive limits of many fields beneath the oil zones.

The major structural features were found to coincide with a trend of anticlines that has become generally known as the LaSalle anticlinal belt. The relation of this regional trend of anticlines to the position of the oil fields is shown in Figure 1. The LaSalle anticlinal belt is a series of en echelon folds and cross-folds forming a steep-sided boundary on the eastern edge of the Illinois basin. A general outline of the deep part of the basin is included on Figure 1.

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** All references at end of paper.

During the early drilling, only salt water was encountered whenever test wells were located outside the oil fields on the steep western flanks of the LaSalle anticlinal belt. This knowledge plus the lack of detailed structural data on the Illinois basin led many to believe that the basin was probably a flat-bottomed geosyncline without the necessary structural oil traps. Consequently, further prospecting for oil was carried on largely in the shallower beds on the outskirts of the basin. The success of such ventures is shown on Figure 1 by the limited number of small pools that had been found in western Illinois by 1930.

After oil was discovered on local anticlines in the deeper parts of major structural basins in Michigan and West Texas, Bell suggested in May 1930, that "production similarly located with respect to structure should be looked for in Illinois"(7). Later in the same year Bell presented a map classifying the State into areas according to the relative probabilities of finding new oil fields. His area classifications are included in Figure 1.

During the 1930's, the exploration for oil was slowly intensified, but only one new field had been found by 1936. In 1937, however, the discovery of ten new oil fields in the Illinois basin marked the beginning of a second oil boom that lasted several years. Many are familiar with this period of rapid development, high initial productions, and lack of proration. Figure 2 shows the State's yearly oil production since 1905 and the producing wells completed annually, excluding dry holes. The high productivity of the large number of wells completed in the second boom is reflected in the abrupt increase in oil production from four million barrels in 1936 to 148 million barrels in 1940. As a result, Illinois was raised from the fourteenth largest oil producing state to the fourth largest in a period of four years.

As in the old fields, multiple producing zones were found in many of the new pools at depths ranging from 1,000 to 4,500 feet. The "pay" zones are practically all limestones and sandstones of Mississippian age. A few Pennsylvanian sands are productive, as are limestones of Silurian, Devonian, and Ordovician ages. The Salem field, which was discovered in 1938 and has three sand and four lime horizons, is undoubtedly the most prolific pool of appreciable size in Illinois. At the end of 1951, this field had produced 217 million barrels of oil from 9,500 productive acres, or an overall average of 22,800 barrels per acre.

Prospecting for oil in the Illinois basin has been highly successful. By the end of 1951, the accumulated oil production for the State was 1,568 million barrels from 413,000 productive acres. Of this volume, 500 million barrels have been recovered from 113,000 acres in the old fields, and 1,068 million barrels have been recovered from 300,000 acres in the new fields drilled since January 1, 1937. Discoveries of new fields and extensions to existing pools have continued each year since 1937. The location of all oil fields of significant size in Illinois as of January 1, 1952, is shown on Figure 3. It will be noted that Bell's selection of the area with the best oil possibilities, as discussed in connection with Figure 1, is repeated on the index map of Figure 3. It is interesting to observe that Bell's choice in 1930 of the area with the best possibilities for future production comes remarkably close to the area that has been so intensively developed since 1937.

Vacuum and Repressuring Operations

The first attempts to improve oil recoveries by the use of vacuum were started in 1910 in the Clark County Fields (8). By 1920, vacuum was being widely used in many of the old fields, although the published evidence as to its effectiveness in increasing oil production is inconclusive (5). Air and gas repressuring usually followed the vacuum operations because the equipment for the latter was easily adaptable to the needs of repressuring. The injection of air and gas first started in 1921 and was being extensively used in the old fields of Clark and Crawford Counties by 1932 (9).

After the new fields were discovered in 1937, large volumes of gas were available in some places, and extensive gas repressuring operations were begun in a number of new fields, particularly in the Salem, Louden and New Harmony fields. Meanwhile, air and gas repressuring operations were continually being expanded in the old fields. Many of these projects are still operating today although there is a slow trend toward conversion to water flooding. The Ohio Oil Company has had an unusual reaction in their air repressure operations in the Colmar-Plymouth field in McDonough County. This repressure project was started in 1935 and has responded favorably to air injection but not to water injection operations that were started in 1943 and discontinued in a few years.

As of January 1, 1947, it was reported (10) that a total of 18,000 acres were being repressured, or five percent of the oil productive acreage of the State. Over a nine-year period, 12,500 of these repressured acres were credited with having produced 4.7 million barrels of oil by air and gas injection. It is estimated that the total oil recovery by these methods is currently of the order of ten million barrels, or less than one percent of the State's cumulative oil production.

Water Flooding Operations

Early investigators (11) recognized the fact that unusual oil recoveries were being obtained in certain parts of the old fields due to some form of water invasion. Squires and Bell made a series of investigations of these conditions from 1931 to 1937 and have summarized their findings in a comprehensive report (12). They identified eleven "natural" floods and 27 small accidental floods scattered over various parts of the old fields. Some abnormally high oil recoveries were found where a natural water movement was active in the McClosky "sands" of the Lawrence field. This will partially explain the high oil recovery that has been obtained in this field. The accidental floods in other fields were attributed to upper waters invading the oil sands through old plugged holes or casing leaks. Squires and Bell report (12) that at the time of their investigations more than 412,000 barrels of oil had been recovered in the old fields by accidental flooding of 115 acres, or almost 3,600 barrels per acre.

One of these accidental floods at the north end of the Main pool in Crawford County was converted into the first intentional water flood in 1924. Only produced water was available, and it was injected into two wells that were no longer economical producers as a result of the previous accidental flood. This operation produced 38,500 barrels of oil from seven acres over a period of nine years, or 5,500 barrels per acre (12).

On June 8, 1933, water flooding was legalized in the State of Illinois, and in August 1933, the Tide Water Associated Oil Company started the first legal water injection project on their Drake No. 2 Lease in the Main pool in Crawford County. Fresh well water and produced salt water were mixed and injected without treatment in one input well. The lease increased from two barrels per day in 1933 to a peak of seven barrels per day in October 1935, and had produced 17,000 barrels of oil, or 1200 barrels per acre, by July 1943 (13). Several other similar one-well floods were started by various operators in the following years with either no benefit to production or relatively small increases.

In June 1942, the Forest Oil Corporation started the first five-spot pattern flood in Illinois in the Siggins pool in Cumberland County. This project started as a 40-acre pilot flood in the First Siggins sand at a depth of 400 feet. Forest has extended their operations several times until now there are 1,400 developed acres on 4½ acre spacing (440 feet between like wells). In December 1946, the Pure Oil Company began flooding operations on adjoining properties using the same spacing. They have developed 402 acres in the First Siggins sand and 269 acres in a Second Siggins sand at 465 feet. Details of the development and operational procedures of both companies have been described elsewhere (2). As of January 1, 1952, the combined operations have recovered 5,250,000 barrels of water flood oil from 1,868 developed acres, or 2,800 barrels per acre. The accumulated water input is 28,580,000 barrels or a ratio of 5.4 barrels of water injected for each barrel of oil recovered. The ultimate water flood oil recovery will be considerably higher because some of the developments have been made only in the past few years.

In September 1943, the well known Patoka Benoist water flood was started in the Patoka field, in the northwest corner of Marion County. This project is in the Benoist sand at a depth of 1,410 feet. The flood is operated by the Sohio Petroleum Company and covers 527 acres developed on 10-acre spacing (660 feet between like wells). Barger has presented a detailed discussion of all phases of this project (14).

Figure 4 summarizes the water flood performance as of January 1, 1952. It is interesting to note that the peak oil production in July 1946, was 4,560 barrels per day or almost 70 percent of the water input rate, which indicates an unusually high degree of efficiency of oil movement. This peak water flood oil production compares with a peak primary production of 2,050 barrels per day in January 1938. As of January 1, 1952, the Patoka Benoist water flood had produced 5,840,000 barrels of oil, or 11,000 barrels per acre compared to a primary recovery of 4,950 barrels per acre. The accumulated water input was 23,720,000 barrels or an input water-oil ratio of 4:1. Barger estimated the ultimate water flood recovery will be 12,100 barrels per acre, or 460 barrels per acre-foot (14). This unusually high oil recovery is by far the best water flood result that has been obtained from pattern flooding in Illinois.

After the Siggins and Patoka floods were developed and their successes became generally known, the Illinois operators began to take more interest in water flooding. As a result, water flood projects have developed more rapidly in the last few years. Figure 5 shows the number of floods that have been developed each year since 1942 and that are still in operation. The recent interest in water flooding is very evident.

In November 1949, the Shell Oil Company initiated a major water flood operation in their Benton Unit in Franklin County. This project is receiving much attention at present because it currently is producing the largest volume of water flood oil in the State. Cameron has presented a detailed analysis of the development and initial operation of this project (15).

Figure 6 summarizes the water flood performance as of January 1, 1952. The drop in production after July 1949 was the result of converting alternate producing wells to water injection during the period of initial development. The oil production was back to its former level by September 1951, and was almost 8,000 barrels per day in December 1951. This compares with 1,500 barrels per day prior to flooding. The cumulative water flood recovery to January 1, 1952, was 1,750,000 barrels, or 800 barrels per acre for the 2,200 developed acres. It is estimated that the ultimate secondary recovery will be at least 7,500 barrels per acre, or 200 barrels per acre-foot (15).

An unusual feature of the Benton Unit is that the producing horizon at a depth of 2,100 feet is completely overlain by an extensive coal mining operation at a depth of 500 feet. In the original drilling on ten-acre spacing, adequate precautions were taken to locate all wells in order that drilling would penetrate mine pillars (about 200 feet square), after which casing strings were set through the coal bed. Further infill drilling was undesirable in developing a water flood, and consequently, a 20-acre spacing pattern (935 feet between like wells) was adopted by converting alternate producing wells to injection. All input wells are equipped with tubing and packers set at the bottom of the production string. The casing annulus is kept filled with chemically treated water under a slight surface pressure so that leakage, as indicated by any pressure changes, may be more easily detected. This is the first pattern flood in Illinois to operate under such unusual conditions and to use such wide spacing.

In December 1951, a disastrous explosion occurred in a part of the coal mine that immediately overlies the oil reservoir. The cause of the explosion was the ignition of methane gas from the coal which in turn set off several coal dust explosions. To date, there has been no indication that water flood operations were affected in any way.

The location of all water floods in operation during 1950 is shown in Figure 7. Included on this map are the locations of several pressure maintenance projects which are using water as their injection medium. Also shown is the general area in which the "dump" floods have been active. The word "dump" has been used to describe this method of flooding because water zones overlying the oil-producing horizon are opened in selected wells, thus allowing water to flow by gravity into the oil zone with very little control. The main reason this type of operation has been possible is because the oil reservoir is a highly permeable, oolitic limestone called the McClosky lime (the same formation as the prolific McClosky "sands" of the Lawrence field).

A detailed report on water flood operations in Illinois during 1950 has recently been published (3). A few general statistics have been taken from this report and are summarized in Table 1 for use in identifying the numbered projects shown on Figure 7. At the end of 1950, a total of 14,000 acres were being flooded, excluding the "dump" flood areas, or about 3½ percent of the total productive acreage in Illinois. These operations produced three million barrels of water flood oil in 1950, or five percent of the State's yearly production. The accumulated water flood recovery as of January 1, 1951, is 20 million barrels, which includes an estimated 6½ million barrels from the "dump" floods (3). It will be noted on Figure 2 that water flooding has increased production slightly in the old fields, but this effect is not noticeable on the production curve for the entire State.

Locating Injection Waters

Locating an adequate supply of water is sometimes a major problem in water flood operations in Illinois. The State Geological Survey has been of some assistance in solving this problem through the application of geophysical methods. Inasmuch as these methods may not be well known among water flood operators, a brief discussion of the theory and applications is included.

Earth resistivity measurements can be used as a means of locating water-bearing sands and gravels which occur in the glacial drift that covers more than ninety percent of the State. These gravel beds vary widely in their dimensions, are usually highly permeable, and under favorable hydrologic conditions can produce large volumes of fresh, naturally filtered water. Many operators use this water without treatment.

The earth resistivity studies conducted by the Survey are made using the Wenner four-electrode method. A simplified drawing of the electrical system used is shown on Figure 8. Two steel electrodes are driven in the ground at C_1 and C_2, and two copper electrodes, P_1 and P_2, are placed on a stright line between C_1 and C_2 such that the distance "a" between any two adjacent electrodes is the same. An electric current (cummutated D.C.) is passed through the ground between the steel electrodes, and the potential drop across the space betwen the copper electrodes is measured. The apparent resistivity of the earth to a depth approximately equal to the length of the electrode spacing "a" can then be computed. The depth of investigation can therefore be varied simply by changing the electrode spacing.

Water-bearing sands and gravels are usually detected by their resistivities being significantly higher than the underlying shales and overlying glacial tills. However, the proper interpretation of such measurements requires a knowledge of the general subsurface geology of the area under investigation. Considerable field experience is also needed because there are various other strata than can produce high resistivity readings.

The results of an earth resistivity survey are shown on Figure 9 and will serve to illustrate the data obtained and its interpretation, This figure is taken from a recent paper by Buhle (16). The resistivity measurements shown are a small part of an extensive investigation that was made in connection with the water requirements for a large flood. This particular traverse was made across part of a flat creek bottom starting at A' and proceeding westward to A with observation stations located 200 feet apart. Since the electrode spacing was 50 feet, the high resistivity between stations 157 and 162 indicates a possible sand or gravel deposit between the surface and a depth of 50 feet. By varying the electrode spacing from 10 to 100 feet, measurements of the variation of resistivity with depth were made at stations 159, 160, 161, and 164. From these data and other similar traverses nearby, it was felt that the best possibilities for water production were in the vicinity of station 160.

Test drilling at a later date started at station 161 and encountered gravel from 25 to 36 feet and a non-water-bearing sandstone from 36 to 76 feet. The log of this well is plotted opposite the previously measured depth resistivity profile under TH_1. A second test well was drilled at Station 160, and some water-bearing gravel was found as shown under TH_2. A third test well was drilled at station 164, where low resistivity readings had been obtained at all depths. As shown under TH_3, the well encountered only glacial till and a small amount of non-water-bearing sandstone. A fourth test well was drilled 500 feet west of the third well near the edge of the present stream bed on the assumption that any sands beneath the creek should contain water. As shown under TH_4, a small amount of sand was found, but it yielded a negligible amount of water. Test hole No. 5 at station 159 found the most favorable gravel deposits and was completed as a 250 GPM (8,500 barrels per day) water well.

A second example has been taken from Buhle's (16) paper to illustrate one of the difficulties encountered in the interpretation of resistivity measurements. Figure 10 shows two depth resistivity profiles made along a river flat. The first depth profile was made at the Bridgeport No.3 location. The results of the resistivity measurements were favorable, and the subsequent drilling found a clean, unconsolidated sand from 30 to 96 feet. After completion, this well was capable of producing 1,200 GPM (41,000 barrels per day) with very little drawdown. A large number of additional resistivity surveys were made, and a second location was recommended at which Test Hole No. 26 was drilled. From the apparent similarities of the two depth resistivity profiles, one would have surmised that a sand section similar to that of the first well should have been encountered. As shown by the well log, a thick sand section was found, but there were so many clay laminations in it that the well was not completed as a producer. It is estimated that the water production would have been 300 GPM (10,000 barrels per day), which is a substantial producing rate, but it was insufficient for the purposes of the water flood operator.

Other difficulties have also been encountered with this type of geophysical exploration, but over a period of 20 years, the Survey has acquired much valuable experience and by actual count has had an accuracy of over 90 percent in its predictions, most of which have been for municipal water supplies (16). Such earth resistivity surveys can obviously save considerable sums that would otherwise be required if the exploration for water supplies in the glacial drift were conducted by random drilling.

Flooding Multiple Producing Zones

It was previously mentioned that multiple producing zones have been found in a great many of the oil fields of Illinois. As flooding operations continue to expand, the problem arises concerning the feasibility of simultaneously flooding several stratigraphic horizons. This problem has recently been accentuated in the Salem field, which covers approximately 9,500 productive acres and has seven oil "pays" of which five are considered worth flooding at the present time.

The first step in preparing to flood an oil field of this size is unitization, and Love (17) has presented a detailed analysis of the manner in which the interests of some 2,000 royalty owners and 25 operators have been successfully unitized. Much of the factual data that follows is taken from Love's paper.

The present unitized acreage comprises 8,800 acres, and the current problem is the selection of the most economical plan of flooding. As one might expect, the producing zones do not have the same areal extent, although they overlie one another generally and are all located on an elongated asymmetrical anticline having about 200 feet of closure. Within the unitized area the Benoist sand at 1,770 feet has approximately 8,000 productive acres. The Renault and Aux Vases sands at 1,825 feet have about 4,900 productive acres and will be flooded together because they have the same areal extent and are separated only by a thin shale break. In addition, there are 7,700 acres of McClosky lime at 1,990 feet and 5,400 productive acres in the Devonian lime at 3,430 feet. The average thicknesses of these four zones range from 15 to 35 feet. To flood each of the zones one at a time would prolong the operations over an undesirably long period of time. Detailed engineering studies have therefore been directed toward a program of simultaneously flooding all four horizons.

Additional complications arise from the fact that the McClosky lime has three distinct porosity zones which are separated throughout the field and cover different areas within the total McClosky productive acreage. Further, there is a fourth stray zone that is found in scattered parts of the field. The Devonian reservoir has three productive zones, of which one has been the principal oil producer because of its vuggy characteristics. Permeabilities will probably range widely with the highest being in the vuggy Devonian lime, and the lowest in the Renault-Aux Vases section, which averages 64 millidarcies.

In the original drilling the general practice was to complete all three sands in one well, all McClosky producing zones in a separate well, and all Devonian zones in a third well. Consequently, there are 1,012 sand wells on ten-acre spacing and 644 McClosky and 369 Devenian wells on ten- and twenty-acre spacing.

The magnitude of the problems involved may be further appreciated by considering a few general statistics. It is estimated that the water flood reserves in the Salem Unit are approximately 200 million barrels (17). If it is assumed that the accumulated water input will be ten times the recovery and that 20 years is an economically desirable flood life for the entire field, then the average injection rate will be of the order of 300,000 barrels per day. This volume of water must be proportioned to each of the four zones to get a relatively even flood-out. This means selecting the location of injection wells in such a way as to establish the desired flood pattern in each of the productive horizons of varying areal extent. In view of the wide range of permeabilities, wellhead injection pressures will vary considerably and are an additional factor to consider in designing a common water injection system. It is planned to obtain the required large volumes of water from fresh water-bearing sands and gravels along a nearby river. Therefore, some thought must be given to the compatibility of this water with the connate waters, as well as with the clay minerals present in each of the various formations.

From the foregoing discussion, it is apparent that flooding several productive horizons over an extensive area involves a multitude of complex problems. Examples of other fields in Illinois in which a similar situation may develop are the Louden field, which has 21,000 acres and four producing zones, and the Centralia field with 3,600 acres and three producing zones. The Salem, Louden, and Centralia fields have produced a total of 417 million barrels of oil and, assuming the secondary recovery will be of the same order, the problems of multiple zone flooding in these three fields are concerned with substantial reserves.

Clay Mineralogy and Water Flooding

Much research in recent years has revealed that clays and shales are composed of extremely small crystalline particles that have been classified into a few groups known as the clay minerals (18). The individual ultimate units are predominantly sheet- or flake-shaped particles of the order of 2/25,000 of an inch (2 microns) in size or smaller. There are four common groups of clay minerals that have been identified in the oil sands of Illinois: the kaolinites, illites, chlorites, and montmorillonites.

These clay minerals occur as discrete particles mixed with the quartz grains and are usually very closely associated with the sand grain surfaces. In investigating the bonding action of clays in carefully sorted molding sands, Grim and Cuthbert (19) have presented sketches showing the arrangement of two different clay minerals on sand grain surfaces as shown on Figure 11. These sketches are based on photomicrographs of sands that compare in size with a medium grained oil sand. The amounts of clay shown are about ten percent by weight. Illinois oil sands usually have a wider range in grain size and seldom exhibit well rounded quartz surfaces. Further, the clay contents range from 1 to 15 percent. However, the sketches serve to illustrate the general arrangement of clay particles that one might expect to find in an oil sand in which either montmorillonite or kaolinite (also illite) is the principal clay mineral present. The actual arrangement of clay particles in Illinois oil sands is probably more like that shown on the right hand sketch with less clay usually present.

Of importance in water flooding operations is the reaction of some of the clay minerals to certain changes in environment. Such reactions may be permanently detrimental if the clay particles become separated from the sand grains and cause clogging. Montmorillonite is the worst offender in this respect because of its ability under certain conditions to adsorb indefinite amounts of fresh water into its cyrstalline structure. This is familiar to many as the so-called "clay swelling" in oil sands. In discussing the base-exchange properties of the montmorillonite group, Grim (20) has pointed out that brines are not necessarily compatible with all montmorillonite clays and may cause clogging if certain components in the brines are adsorbed by the clay particles.

The situation is much less critical if the kaolinites make up the clay minerals because they are relatively more stable. The illite and chlorite clay minerals are intermediate between kaolinite and montmorillonite but more closely resemble the kaolinites in their reactions to environmental changes (20).

Two or more clay minerals are often found intimately mixed with one another in oil producing sands. In studying a number of Illinois samples, Grim (21) and his associates have usually found more than one of the kaolinite, illite, and chlorite groups present. In one or two sands, small amounts of montmorillonite have also been identified.

These mixtures of clay minerals may be interlaminated on an exceedingly minute scale. Under such conditions the presence of montmorillonite would cause the whole mixture to be more sensitive to environmental changes. Thus, the structure of clay particles will have potential planes of weakness whenever montmorillonite is present, even in small percentages.

To date, clay swelling has apparently not been a troublesome factor in Illinois flooding operations. However, field observations indicate that in certain pools the Aux Vases sand contains clay minerals that need to be investigated as to their stability under various flooding conditions. Inasmuch as the identification of clay minerals is not particularly difficult, it would seem desirable before initiating a major water flood project to know the character not only of the abundant clay mineral components in a sand but of the minor fractions as well.

Another property of clays according to Grim is that "some organic compounds can be adsorbed on the surface of the clay minerals - probably to a very limited extent for kaolinite and to a very great extent for montmorillonite" (20). It is possible therefore, that wetting in an oil sand is closely associated with the type of clay minerals present as well as with the arrangement of clay particles over the sand grain surfaces. An investigation of the surface chemistry of oil and water in contact with complex mixtures of clay minerals and quartz grains should be a fruitful field for research.

Estimated Secondary Oil Reserves

In a recent paper, Barger and Campbell (22) have estimated the potential secondary oil recovery of Illinois to be 850 to 900 million barrels. Torrey (23) has considered 700 million barrels to be indicative of the magnitude of secondary reserves for the State. Past production in both the old and new fields has generally been obtained by the solution-gas drive mechanism. Natural water drives and accidental floods in parts of the old fields have undoubtedly been a minor contributing factor as has the use of air and gas re-pressuring. The oil recovery therefore is probably of the order of 25 percent of the original "stock tank" oil in place. Barger and Campbell state that primary recoveries amount to 10 to 25 percent of the stock tank oil in place (22). Since the accumulated recovery for the State is approximately 1½ billion barrels, the volume of oil that still remains in the known producing fields is apparently in excess of four billion barrels. With this in mind, a secondary recovery of 800 million barrels is believed to be a conservative estimate. As more water flooding experience is gained in the variety of conditions that exist in Illinois, better estimates of secondary recoveries will be possible.

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TABLE 1

WATER-FLOOD OPERATIONS IN ILLINOIS DURING 1950

Map No. (1)	Field	Project	Producing Formation (2)		Avg. Depth	Operator	Date Started
1	Aden Consolidated	Aden	Aux Vases	(S)	3,200	Texas	8-46
2	Aden Consolidated	Aden	McClosky	(L)	3,350	Texas	8-46
3	Albion Consolidated	Biehl Unit #1	Biehl	(S)	2,000	Yingling	8-49
4	Albion Consolidated	Biehl Unit #2	Biehl	(S)	1,950	Yingling	12-50
5	Albion Consolidated	S.Albion Bridgeport	Bridgeport	(S)	1,900	Superior	8-46
6	Assumption North	Assumption Benoist	Benoist	(S)	2,750	Nat'l Assoc.	6-50
7	Bellair	Forest - Bellair	Bellair	(S)	550	Forest	7-48
8	Bellair	Fulton	Bellair	(S)	560	Pure	7-48
9	Benton	Benton Unit	Tar Springs	(S)	2,100	Shell	11-49
10	Birds	J. W. Lindsay	Robinson	(S)	960	Yingling	8-50
11	Blairsville	Blairsville	Aux Vases	(S)	3,275	Texas	6-48
12	Boyd	Boyd Repressure (3)	Benoist	(S)	2,050	Superior	6-45
13	Browns East	Bellmont North	Cypress	(S)	2,600	Magnolia	11-47
14	Calhoun Consolidated	Bohlander Lease	McClosky	(L)	3,150	Phillips	6-50
15	Casey	Casey	Casey	(S)	450	Forest	3-50
16	Centerville East	East Centerville	Tar Springs	(S)	2,530	Sun	10-50
17	Clay City-Noble Con	(4)	McClosky	(L)	3,000	Pure	
18	Cordes	Cordes	Benoist	(S)	1,230	Shell	8-50
19	Dix	Dix Pres. Main. (3)	Benoist	(S)	1,950	Carter	1-48
20	Elbridge	Elbridge	Fredonia	(L)	950	Nat'l Assoc.	
21	Friendsville North	Friendsville North	Biehl	(S)	1,500	Magnolia	7-47
22	Iola Consolidated	Iola East	Aux Vases	(S)	2,350	Texas	3-48
23	Iola Consolidated	Iola North	Weiler	(S)	2,125	Texas	4-48
24	Iron	Iron Unit	Hardinsburg	(S)	2,500	Shell	12-50
25	Johnson North	Clark Co. #1	Casey	(S)	465	Tidewater	2-50
26	Johnson North	McMahon	Casey	(S)	450	McMahon	5-49
27	Johnson South	South Johnson	Partlow	(S)	490	Forest	3-49
28	Lawrence	Griggs Bridg. #1	Kirkwood	(S)	1,350	Ohio	7-47
29	Lawrence	Robins Bridg. #2	Bridgeport	(S)	900	Ohio	8-49
30	Louden	Louden Cypress	Cypress	(S)	1,495	Carter	
31	Louden	Louden Devonian (3)	Devonian	(L)	3,000	Carter	9-43
32	Main	Ikemire-Henry	Robinson	(S)	935	Tidewater	2-48
33	Main	Hughes-Robinson #3	Robinson	(S)	890	Ohio	9-48
34	Main	Wilkin Robinson #2	Robinson	(S)	950	Ohio	5-48
35	Mattoon	Mattoon Lease	Rosiclare	(S)	2,000	Phillips	10-50
36	Maud North Con.	West Maud	Benoist	(S)	2,750	Skiles	10-50
37	Maunie South	Tar Springs Unit	Tar Springs	(S)	2,200	Magnolia	8-47
38	Mt. Carmel	1st Nat'l Pet.Trust	Biehl	(S)	1,350	1st Nat'l	1-50
39	New Harmony Con.	Evans Lease	Aux Vases	(S)	2,800	Tidewater	10-49
40	New Harmony Con.	Ford "A" Lease	McClosky	(L)	2,900	Sun	5-48
41	New Harmony Con.	Greathouse	Benoist	(S)	2,759	Sun	1-49
42	New Harmony Con.	Greathouse	McClosky	(L)	2,900	Sun	8-47
43	New Harmony Con.	Helm Lease	Waltersburg	(S)	2,150	Luboil	12-50
44	New Harmony Con.	Waltersburg	Waltersburg	(S)	2,220	Superior	8-46
45	Odin	Odin	Cypress	(S)	1,700	Ashland	10-49
46	Olney Consolidated	Olney	McClosky	(L)	3,060	Texas	11-46
47	Omaha	Omaha Pres. Main (3)	Palestine	(S)	1,700	Carter	10-44
48	Patoka	Patoka Benoist	Benoist	(S)	1,410	Sohio.	9-43
49	Patoka	Patoka Rosiclare	Rosiclare	(S)	1,550	Sohio	11-48
50	Phillipstown Con.	Calvin North	Biehl	(S)	1,800	Magnolia	9-47

TABLE 1 (Continued)

Map No. (1)	Field	Project	Producing Formation	(2)	Avg. Depth	Operator	Date Started
51	Phillipstown Con.	North Calvin	Penn. Sd.	(S)		British Amer.	5-49
52	Ste. Marie	Ste. Marie	McClosky	(L)	2,860	Lebow	10-48
53	Salem	Rosiclare Sand Unit	Rosiclare		2,090	Texas	4-50
54	Salem	Salem Unit	Benoist	(S)	1,800	Texas	10-50
55	Salem	Salem Unit	Renault	(S)	1,800	Texas	10-50
56	Salem	Salem Unit	Aux Vases	(S)	1,800	Texas	10-50
57	Salem	Salem Unit	Devonian	(L)	3,400	Texas	10-50
58	Siggins	Queen Lease	Siggins	(S)	450	Bell	
59	Siggins	Siggins	1st Siggins	(S)	400	Forest	6-42
60	Siggins	Union Group	1st Siggins	(S)	400	Pure	12-46
61	Siggins	Union Group	2nd Siggins	(S)	465	Pure	12-46
62	Siggins	Vevay Park	L. Siggins	(S)	600	Partlow	
63	Westfield	Parker	Gas Sd.	(S)	270	Forest	6-50
64	York	York	Penn Sd.	(S)	590	Partlow	

NOTE: (1) Refers to numbers shown on Figure 7.
(2) (S) - sand, (L) - lime.
(3) Pressure maintenance operation.
(4) Dump floods.

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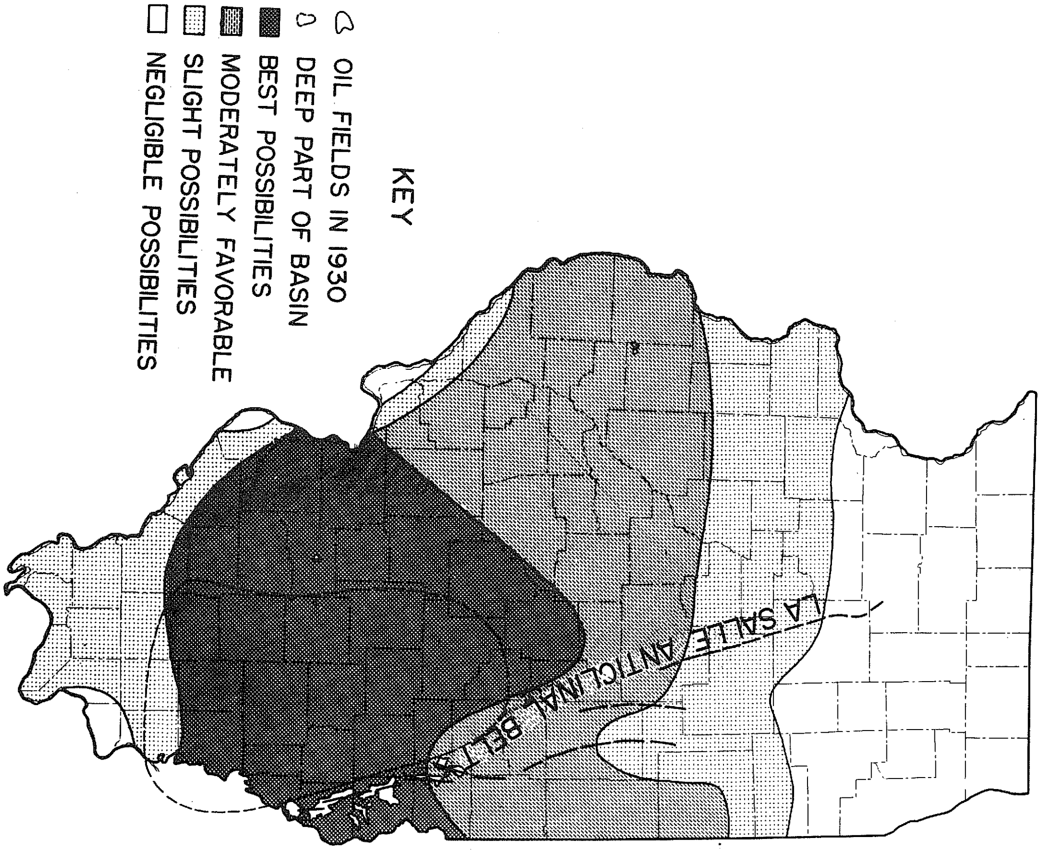

Figure 1. Oil Fields in Illinois and Classification of Possibilities for Future Production as of 1930 (After Bell)

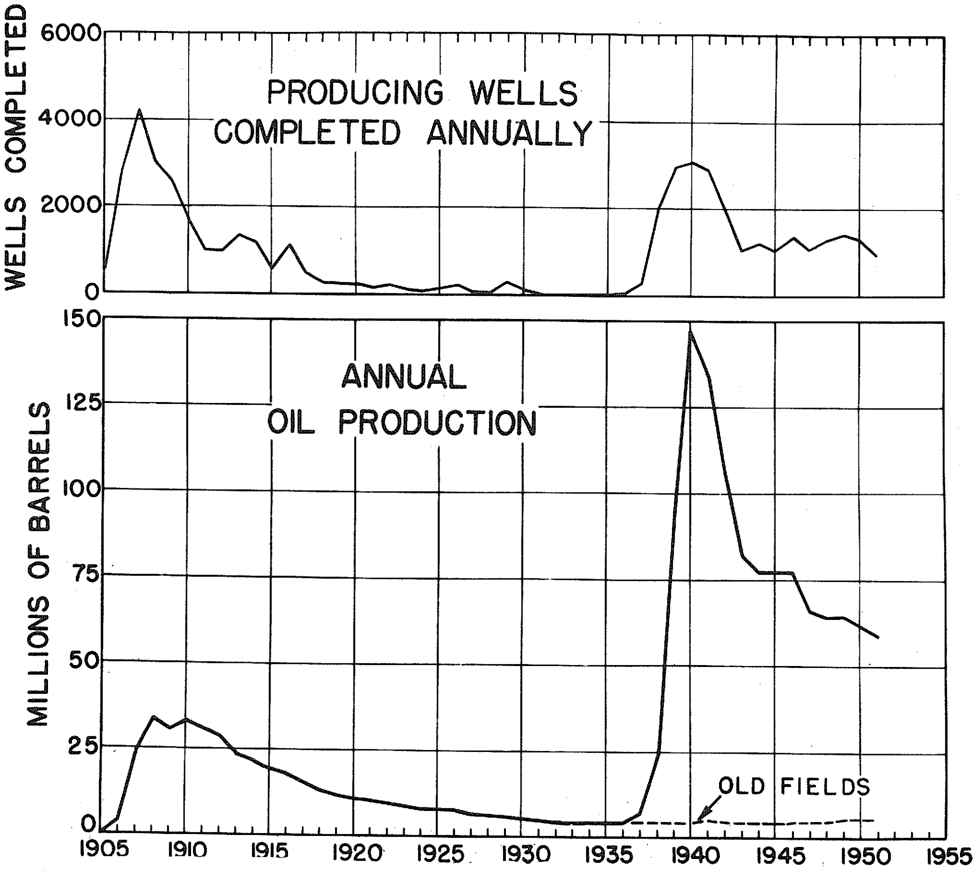

Figure 2. Annual Oil Production and Producing Wells Completed in Illinois

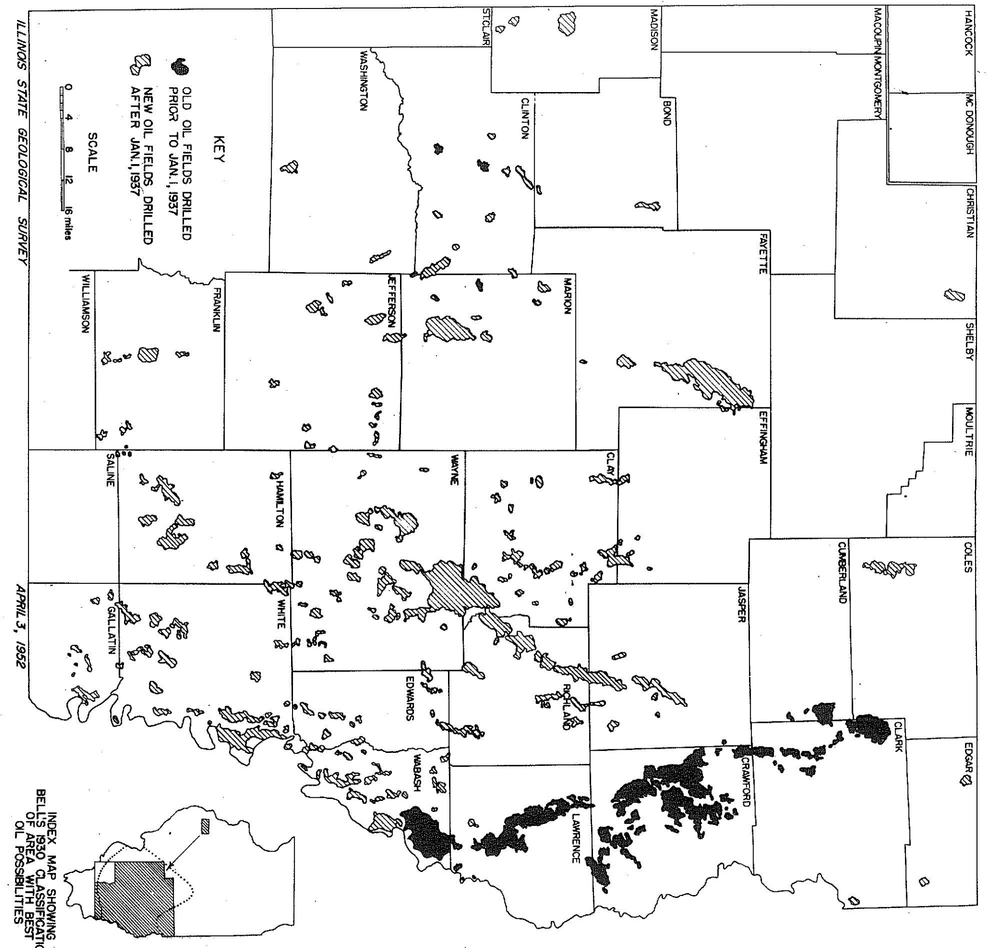

Figure 3. Illinois Oil Fields as of January 1, 1952

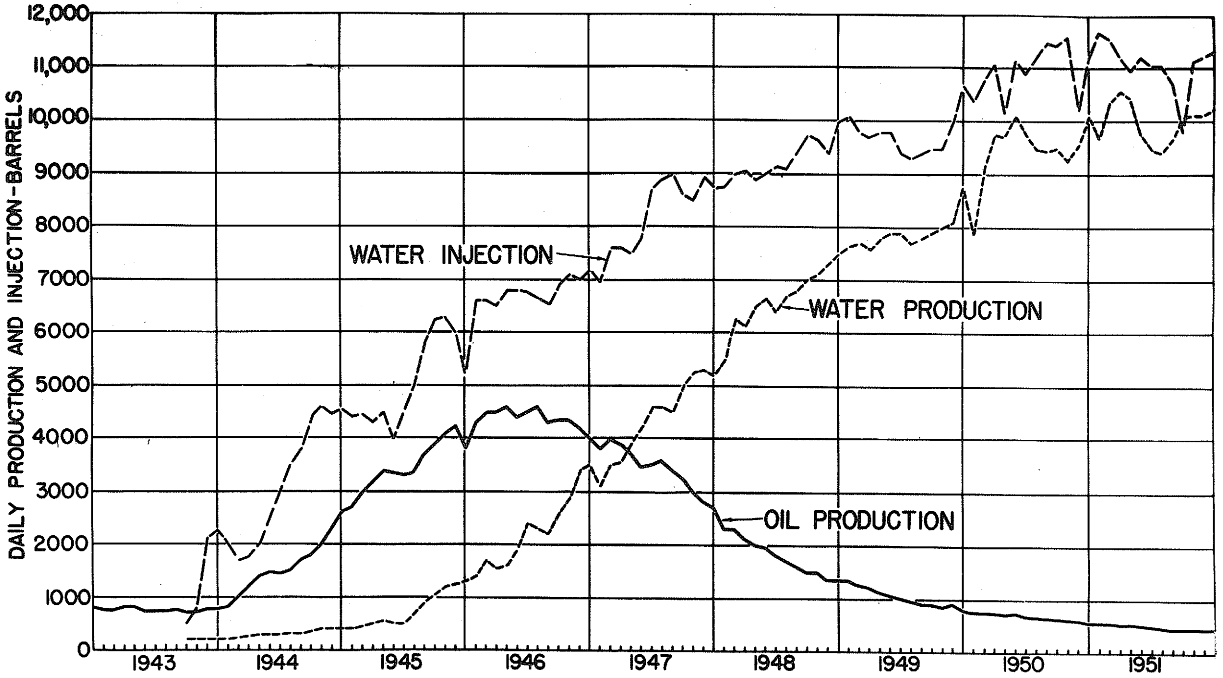

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Figure 4. Patoka Benoist Water Flood Performance

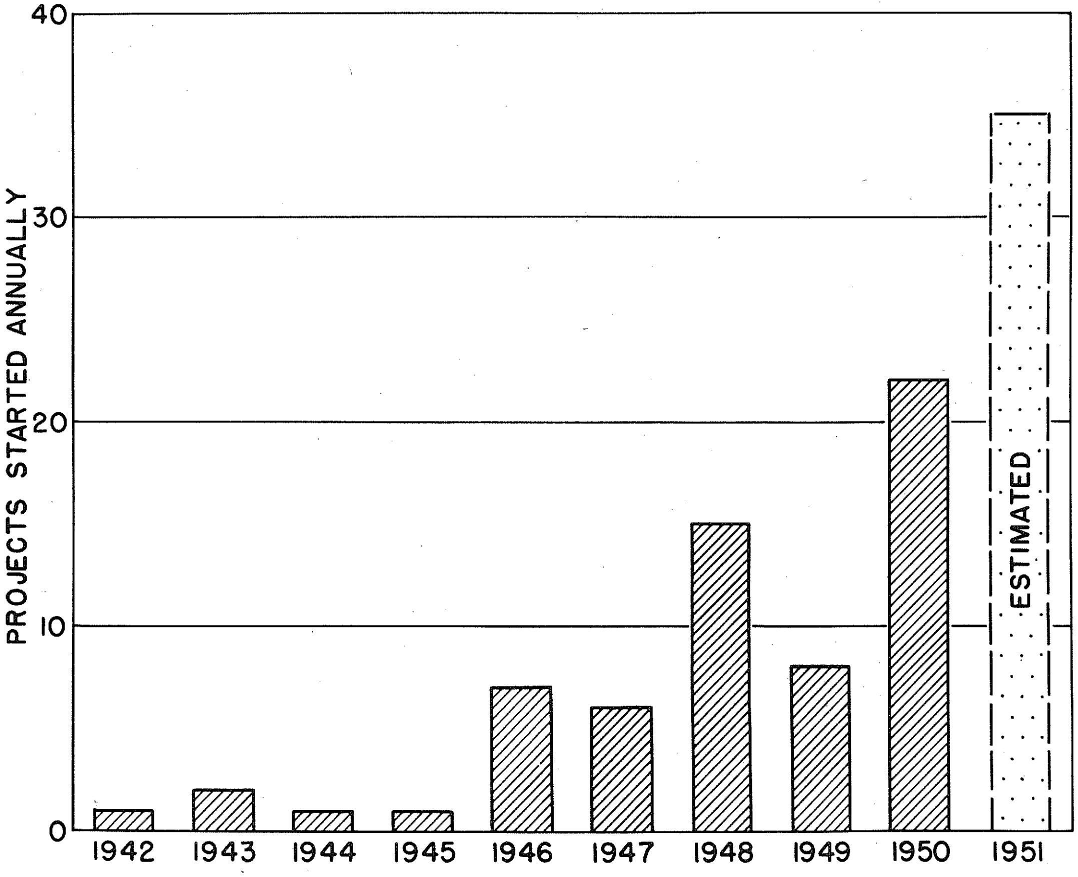

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Figure 5. Development of Water Flood Projects in Illinois

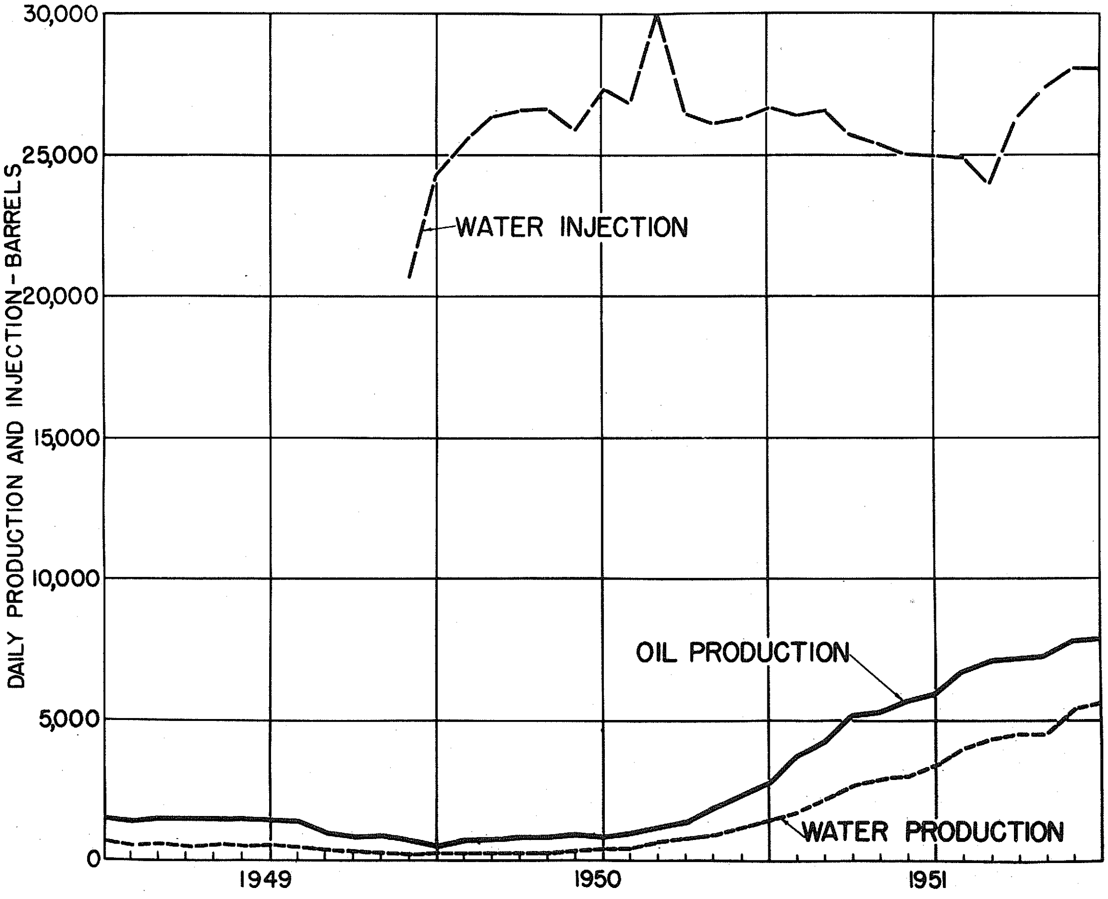

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Figure 6. Benton Unit Water Flood Performance

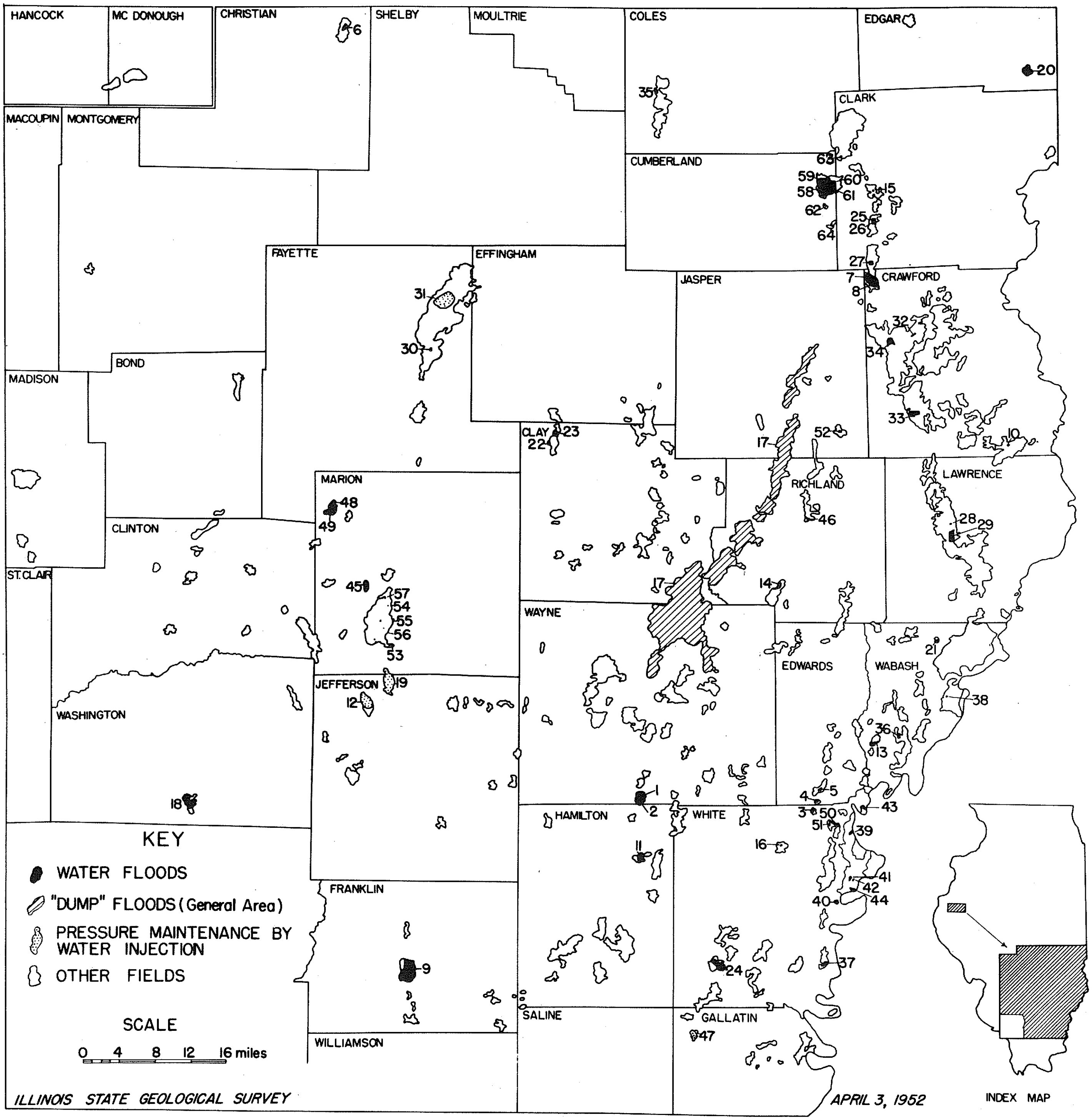

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Figure 7. Water Flooding Operations in Illinois During 1950

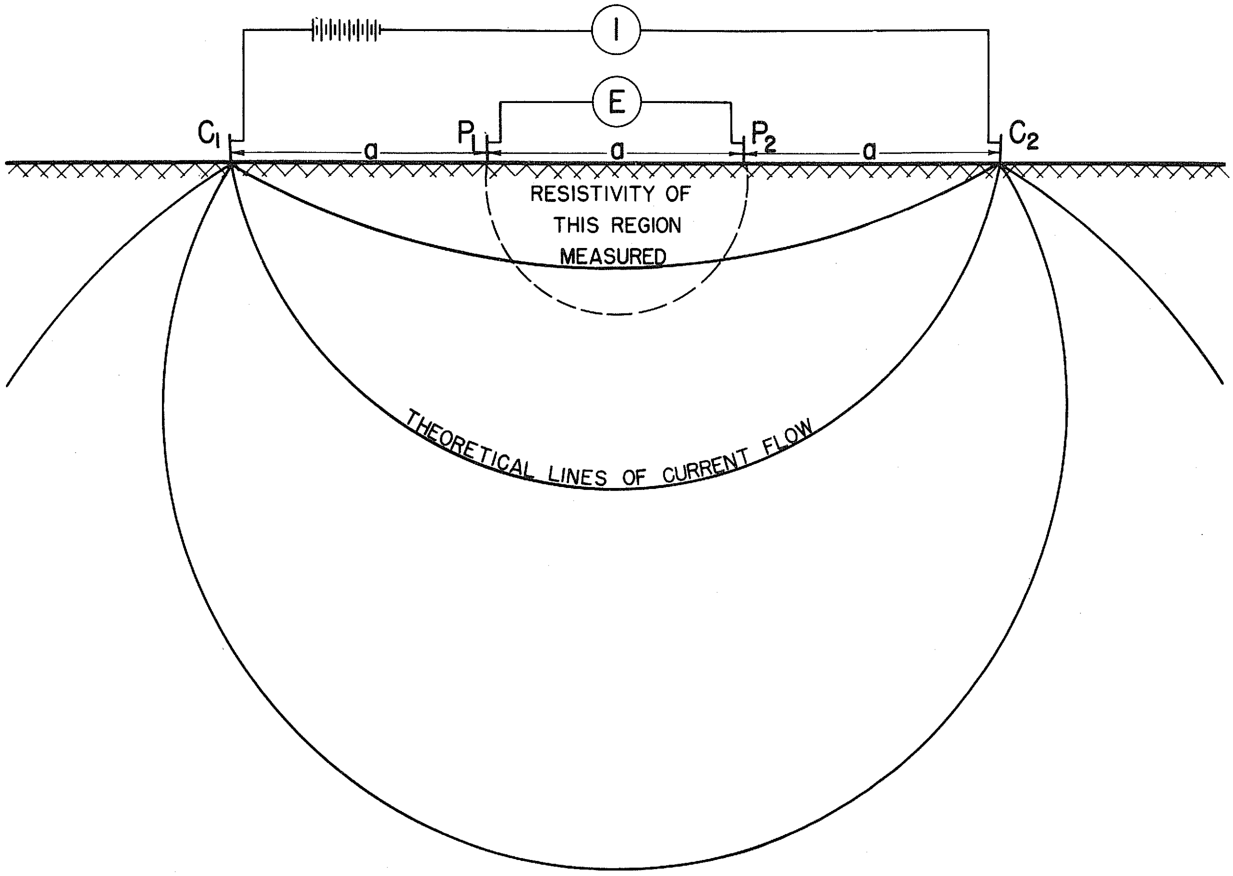

Figure 8. Wenner Four Electrode Configuration Used in Earth Resistivity Measurements.

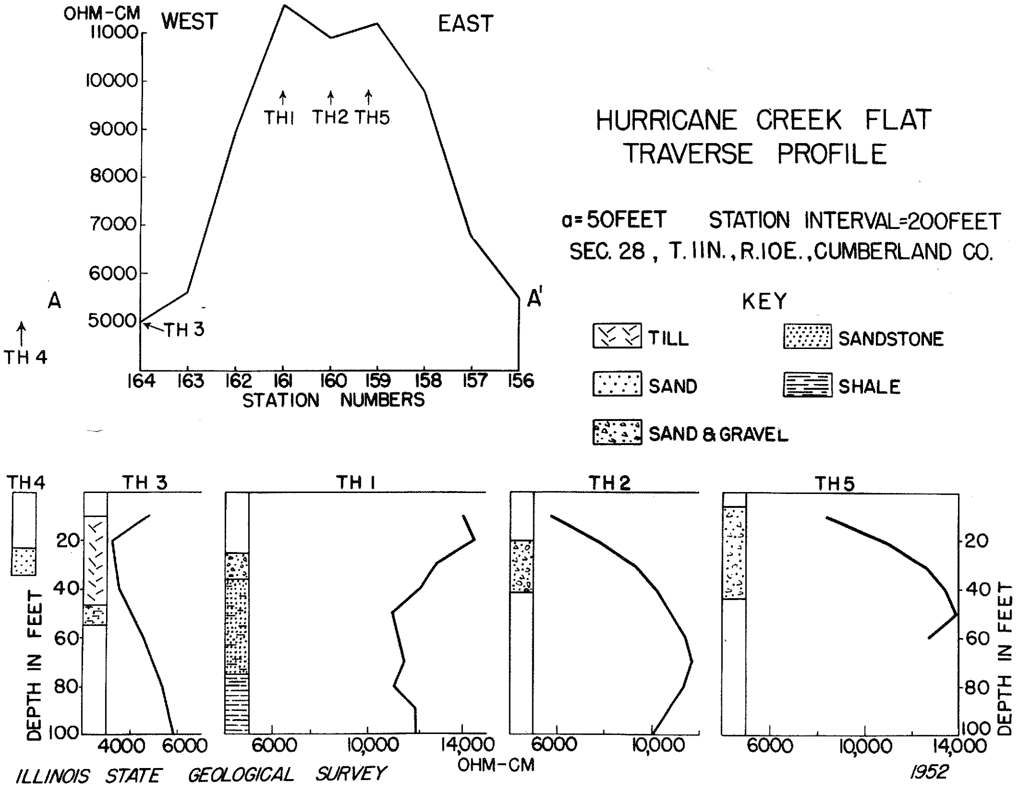

Figure 9. Earth Resistivity Measurements on Hurricane Creek Flat (After Buhle)

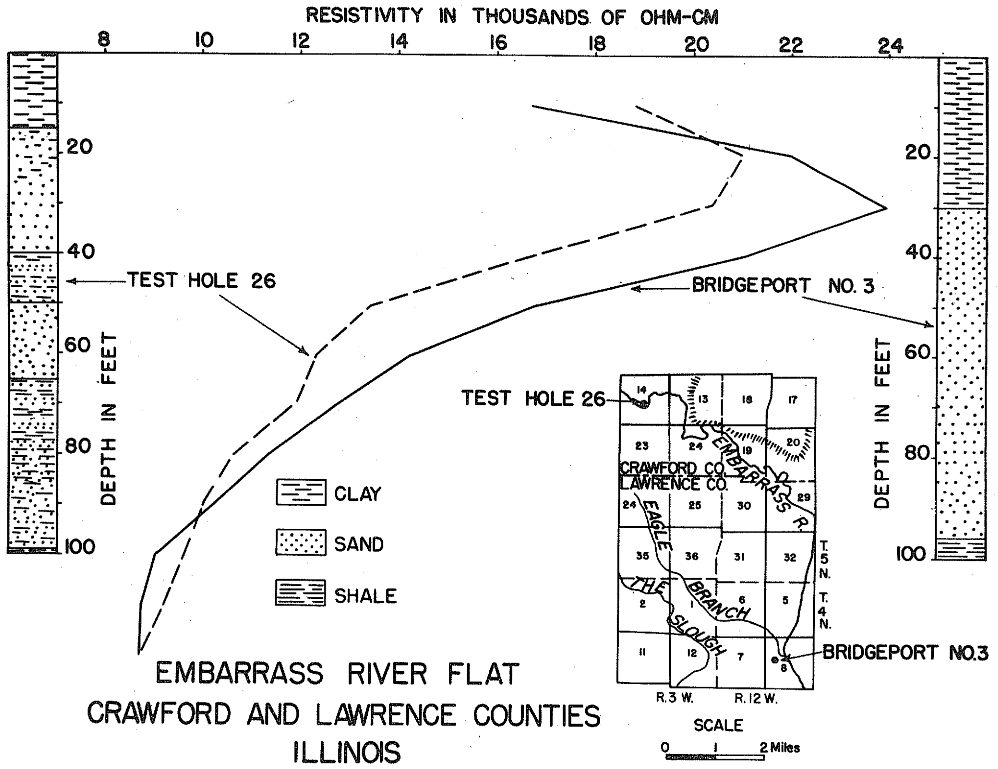

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Figure 10. Earth Resistivity Measurements on Embarrass River Flat (After Buhle)

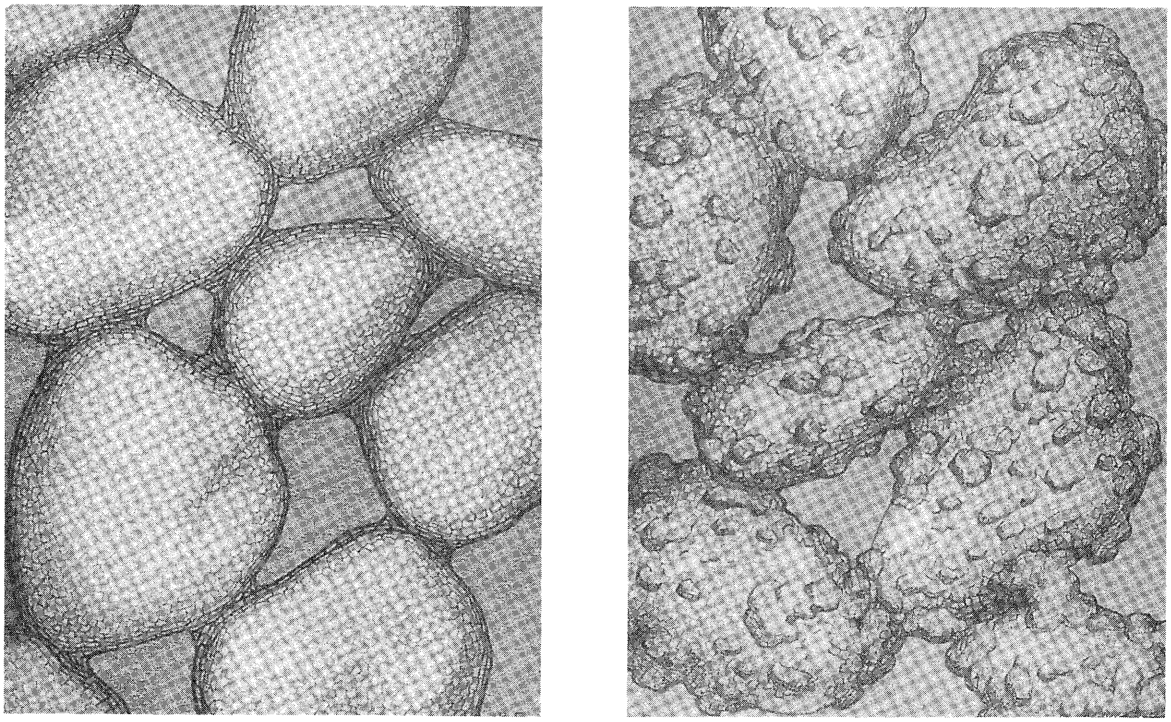

Figure 11. Sketch on Left of Montmorillonite Clay-Bonded Sand to Illustrate the Smooth Even Coating of Quartz Grains with Montmorillonite Flakes. Sketch on Right of Kaolinite Clay-Bonded Sand to Illustrate the Irregular Coating of Quartz Grains with Small Flakes and Large Lumps of Flakes. Based on Microscopic Examinations. (After Grim and Cuthbert)