

Degradation of Reservoir Quality by Clay Content, Unayzah Formation, Central Saudi Arabia

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ABSTRACT

Reservoirs in Central Saudi Arabia are important new sources of light sulfur-free crude oil. Development work on these wells has shown the adverse effect of authigenic clay minerals on their productivity or injectivity. The clay minerals may be affected during drilling of the well, during completion, during production, and/or injection. Kaolinite, chlorite, illite, and ordered and random mixed layer illite/smectite are commonly occurring authigenic clay minerals within the Permian Unayzah reservoir rock. As little as 2 weight percent clay causes permeability to be drastically reduced. Formation damage due to clay minerals results from: (1) swelling of smectite caused by injection water or drilling fluids of low salinity; (2) clay mineral migration and subsequent pore blockage; (3) precipitation of gelatinous pore-blocking iron hydroxides caused by the dissolution of chlorite by acid; (4) high water saturations; and (5) disaggregation of poorly consolidated parts of the reservoir into its component sand grains if the weak clay cements are disturbed. The implementation of clay control measures has resulted in increased production while minimizing formation damage.

INTRODUCTION

Unayzah Formation reservoirs in Central Saudi Arabia are important new sources of light (48-52° API gravity) sulfur-free (0.02-0.07%) crude oil (Arabian Super Light) and also sweet gas. In June 1989 the first oil discovery was made at Hawtah. Subsequently, a number of other hydrocarbon discoveries were made at Abu Markhah, Abu Rakiz, Burmah, Dilam, Ghinah, Hazmiyah, Hilwah, Layla, Mulayh, Nisalah, Nuayyim, Raghil, Shiblih, Umm Jurf and 'Usaylah (Figure 1). The most recent discovery was Abu-Shadad-1 in January, 1997. These fields are structures of moderate relief, having 30-100 meters (m) of closure. Production from Central Saudi Arabia's fields started in 1995.

Because of the acute effect of clay minerals on rock petrophysical properties, productivity, and injectivity and their potential to damage the formation, an investigation of clay minerals in the Unayzah Formation was initiated in 1990. Over a six-year period more than 1,000 core samples from 10 fields and 51 wells were evaluated mainly by X-ray diffraction (XRD) and also by scanning electron microscopy (SEM). Additionally, formation damage and fluid compatibility tests were conducted on core plugs. A new laboratory method was also developed and applied to determine volumetric factors for Unayzah Formation clay minerals and their associated water that directly influence fluid flow in the reservoir. The main results of this study are discussed in this paper. An appendix describing analytical techniques is also included.

GEOLOGY

The geological description below is largely a summary of the Unayzah Formation by Al-Laboun (1987, 1988), McGillivray and Hussein (1992), Aktas and Cocker (1995) and Senalp and Al-Duaiji (1995) (Figure 2). A major regional unconformity (Hercynian) underlies the Unayzah. During the Late Permian the basal clastic unit of the Unayzah ("C" member) was deposited. It locally infilled low areas of the eroded pre-Unayzah surface. The overlying Unayzah "B" consists of medium- to coarse-grained fluvial sandstones whose reservoir quality ranges from good to excellent. The Unayzah "A" is mainly an alluvial to fluvial sequence of sandstones and siltstones. At its base is a discontinuous red siltstone or fine grained silty sandstone that separates the "A" and "B" members. The Unayzah "A" is the main reservoir. Its porosity and permeability vary considerably. In the reservoir section average porosity is usually greater than 20%, with permeability locally exceeding 4 darcies. An unconformity

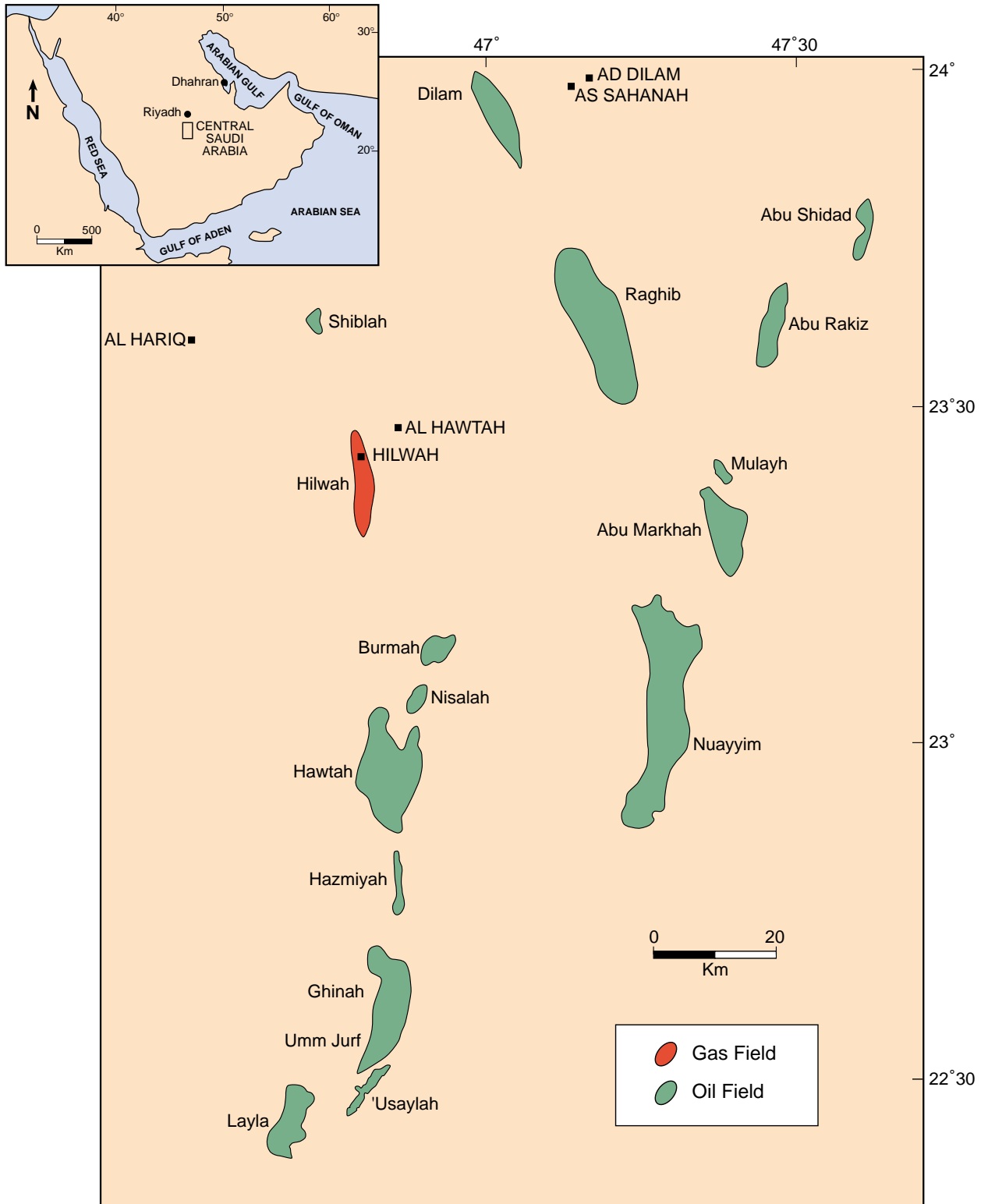


Figure 1: Location map of the Central Saudi Arabian fields.

underlain by a paleosol is present at the top of the Unayzah Formation. Shales and evaporites form the top seal of the reservoirs. The upper Permian Khuff Formation overlies the Unayzah. At its base are marginal marine sandstones. Above this lies massive limestones that are the beginning phase of a major marine carbonate transgression.

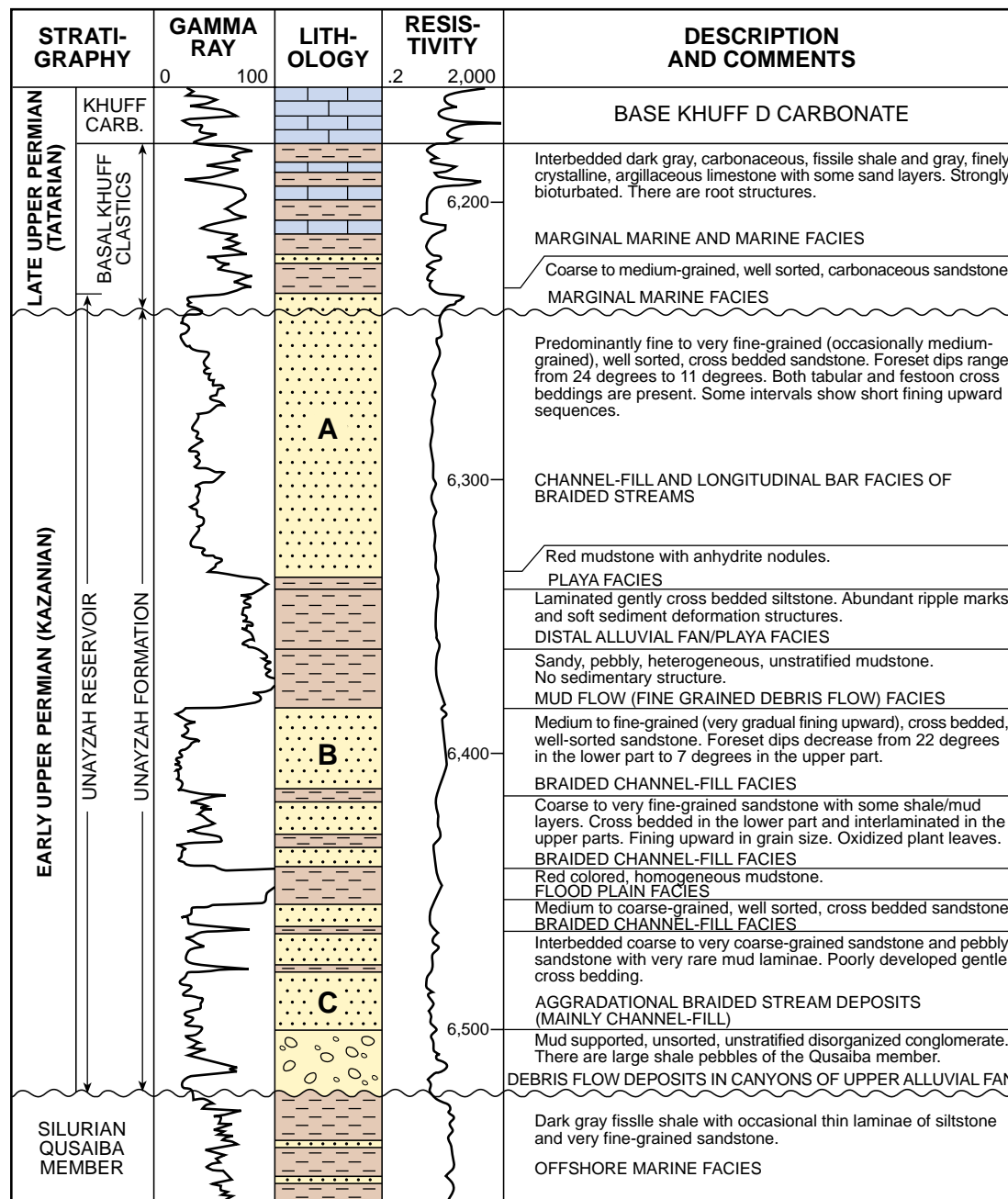


Figure 2: Unayzah Formation stratigraphic column (after Senalp and Al-Duaiji, 1995). Depth is in feet from derrick floor in Hawtah-6 well.

MINERALOGY

1,010 core samples from 10 fields and 51 wells in Central Arabia have been analyzed by XRD. Analytical methods are listed in the Appendix. Framework grains consist mainly of quartz. Both K-feldspar (chiefly microcline) and sodic plagioclase feldspar (chiefly albite) are usually the second most abundant framework constituent. Feldspar content is highly variable. Most samples are relatively feldspar-free, others contain a maximum of 36% feldspar. The red beds have the highest feldspar content. Amphibole has been detected in a few samples at less than 0.5% levels. Secondary quartz overgrowth is the most abundant cementing material. In places, the carbonate minerals calcite, dolomite, ankerite, and siderite, as well as anhydrite, may be abundant. However, most samples only contain minor amounts of these cements. Hematite, and occasionally goethite, are present in the red beds.

CLAY MINERALS

XRD methods were mainly used to characterize the clay minerals. Clay analytical procedures are listed in the Appendix. Some samples were also analyzed by SEM. Clay-size (<2 micron equivalent spherical diameter) material constitutes 0.25-24.65% (average 5.39%) of the core samples. Minor amounts of quartz, and infrequently K-feldspar, are present in the clay-size fraction. The actual clay mineral content of some samples is much greater than the clay-size fraction because some of the clay mineral particles (chiefly kaolinite) are much larger than clay-size. Actual clay mineral contents range from less than 0.5% to greater than 35%. Although small quantities of detrital clay may be present in shale clasts and finely interbedded shale in some samples, almost all clay is authigenic in nature, having formed diagenetically after burial at depth. These clay minerals meet the criteria of Wilson and Pittman (1977) for recognizing authigenic versus allogenic clays.

The clay minerals kaolinite, chlorite, illite, randomly interstratified mixed layer illite/smectite (I/S), and ordered interlayered I/S are all present in the formation, but not necessarily all present in the same samples. Discrete smectite also occurs in some cores. It is felt to be due to drilling mud invasion of the cores. This smectite always occurs in cores having high permeability and is frequently associated with barite, a common drilling mud additive. Drilling mud invasion of the cores is often observed during examination with petrographic or scanning electron microscopes. Table 1 lists concentrations of the clay minerals by field for the analyzed samples.

Table 1
Clay Content of Central Arabian Unayzah Formation (Weight Percent)

Field	# of samples	Statistic	Kaolinite	Chlorite	Illite	I/S	Clay-size Fraction
Dilam	88	Maximum	17	3	5	2	-
		Minimum	0	0	0	0	-
		Average	1.8	0.1	0.1	0.3	-
Ghinah	155	Maximum	31	6	2.8	1.9	24.65
		Minimum	0.2	0	0	0	0.79
		Average	2.4	0.3	0.03	5.1	7.40
Hilwah	27	Maximum	3	3	0.3	24	-
		Minimum	0	0	0	0	-
		Average	0.6	1.0	0.04	6.0	-
Hawtah	390	Maximum	25	8	8.2	15	17.08
		Minimum	0	0	0	0	0.25
		Average	2.6	0.4	0.3	2.5	5.28
Hazmiyah	125	Maximum	10	3.4	5.7	12	13.14
		Minimum	0	0	0	0	0.68
		Average	2.0	0.3	0.1	1.9	3.55
Nisalah	3	Maximum	10.4	0	0	0	10.36
		Minimum	1.2	0	0	0	1.17
		Average	7.2	0	0	0	7.14
Nuayyim	39	Maximum	24	4	19	10	-
		Minimum	0	0	0	0	-
		Average	2.8	1.0	0.6	2.4	-
Raghib	75	Maximum	15	4	33	30	-
		Minimum	0	0	0	0	-
		Average	2.2	0.3	0.4	1.5	-
Talhah	7	Maximum	4	1	0	9	10.51
		Minimum	0.3	0.3	0	2	2.51
		Average	1.6	0.4	0	5.0	5.96
Umm Jurf	25	Maximum	4.1	2	1.5	8	10.41
		Minimum	0.4	0.2	0	0.4	1.33
		Average	1.4	0.8	0.1	3.5	5.21

Kaolinite is a common constituent. It usually occurs in a pore filling mode in localized concentrations that suggest alteration of unstable framework grains such as feldspar (Figures 3 and 4). Some core samples consist entirely of kaolinite (10%) and quartz (90%).

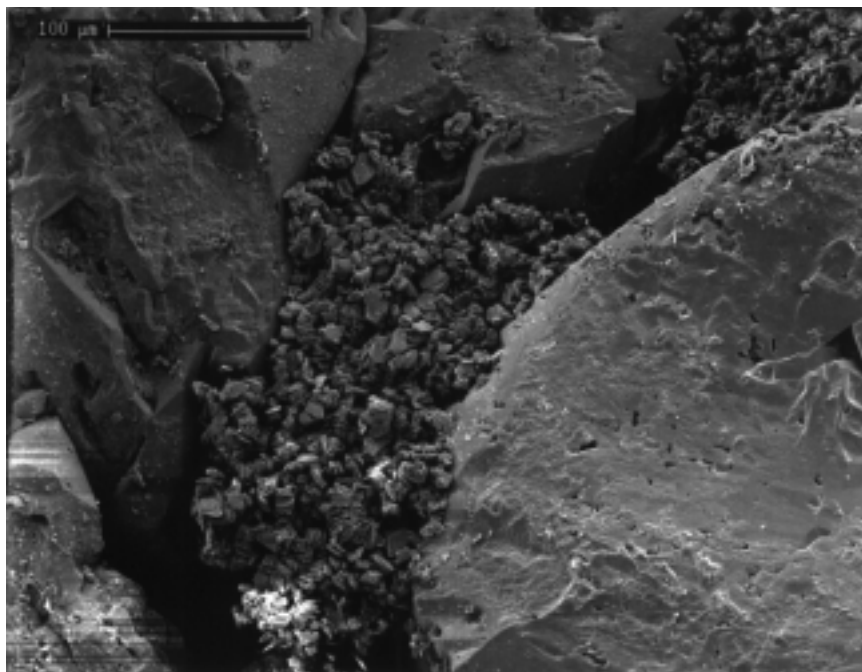


Figure 3: Scanning electron microscope (SEM) photomicrograph of kaolinite in a pore filling mode. Scale is in upper left hand corner.

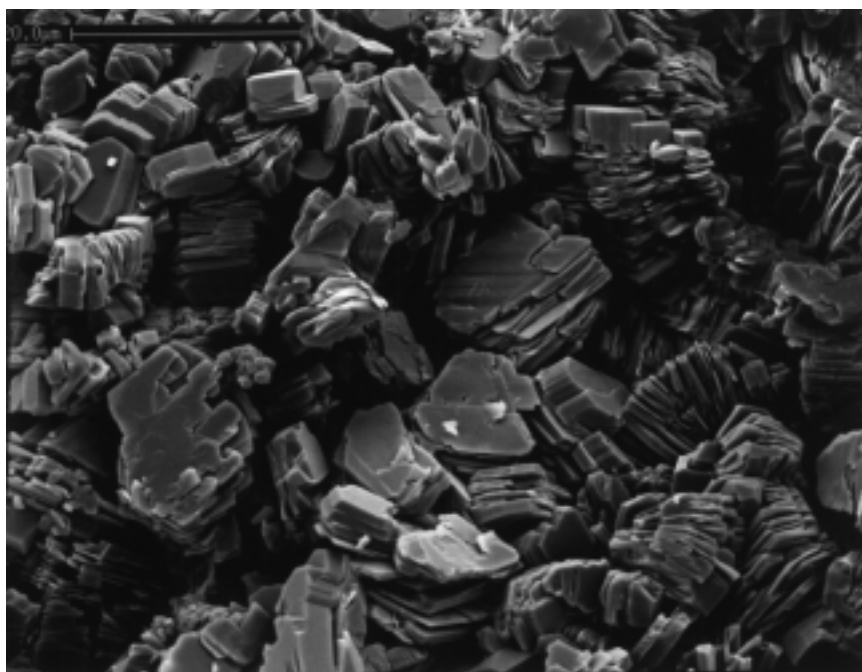


Figure 4: SEM photomicrograph of kaolinite, close-up of Figure 3.

Chlorite is a less common constituent (Figure 5). It occurs most frequently in the red beds, but is also found in lower concentrations throughout much of the formation. It is frequently intermixed with the other clay minerals, mainly kaolinite, where unstable framework grains have been altered in situ. Because of the poor development of the (001) and (003) peaks in X-ray diffractograms, much of the reported 14Å chlorite may in reality be 7Å berthierine.

Pure illite is a relatively uncommon clay constituent (Figure 6). It usually occurs in a pore lining mode. Most illite is interstratified with smectite to form mixed layer clay.

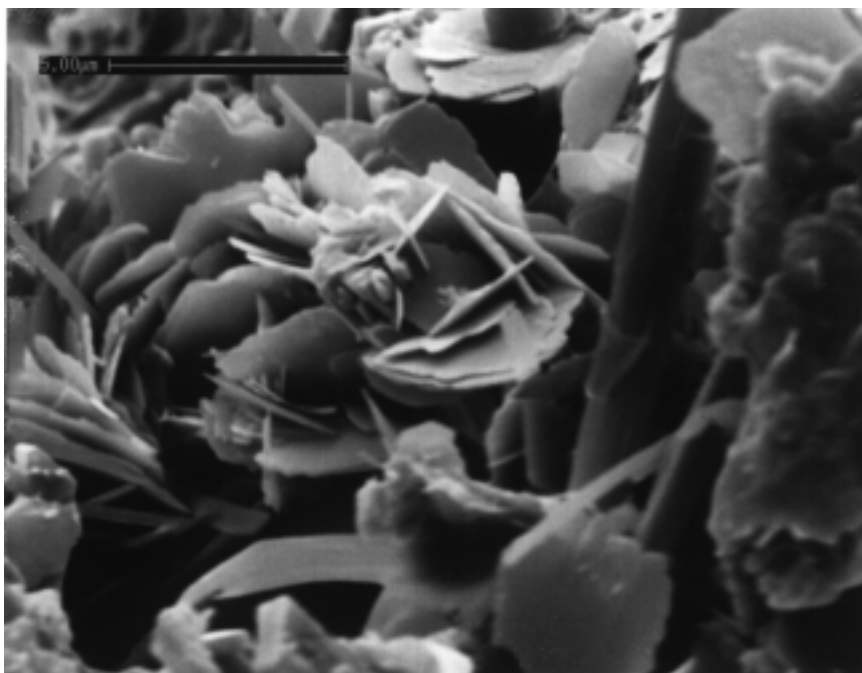


Figure 5: SEM photomicrograph of chlorite.

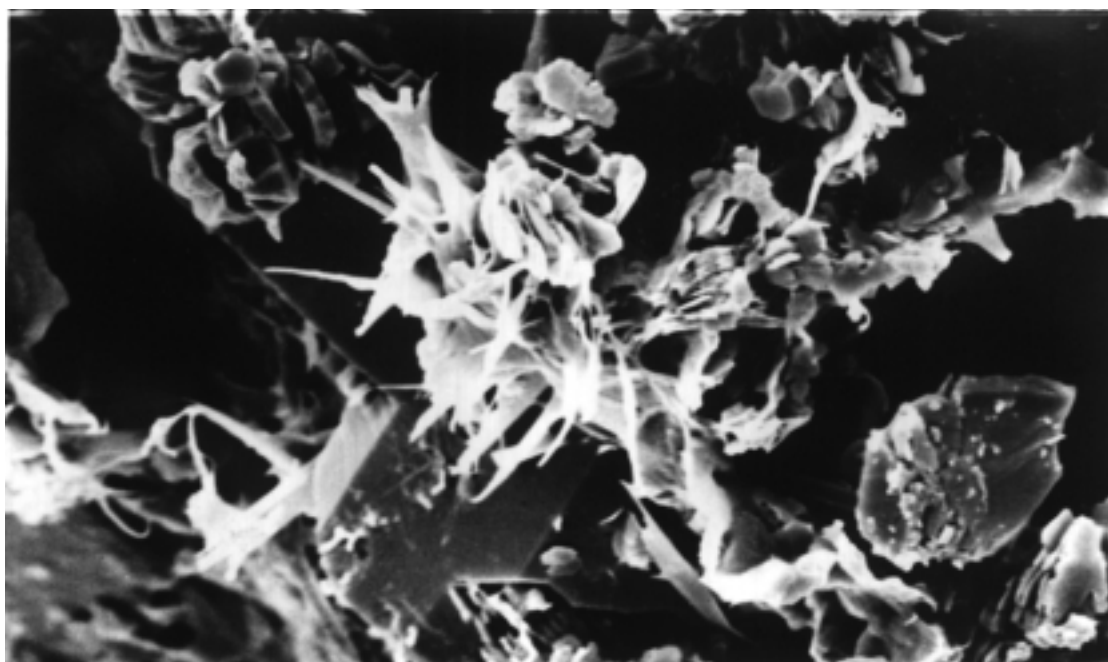


Figure 6: SEM photomicrograph of illite. Photo is 25 X 41 microns.

Interstratified I/S is common (Figure 7). It occurs randomly interstratified containing between 1-25% (average 4%) smectite. The illite and smectite also occur in ordered interstratifications having ratios of 1:1, 2:1, 3:1, and 4:1. Ordered I/S always occurs in the presence of random I/S or illite. Feldspar content often correlates well with illite and I/S content, suggesting that these clays have formed diagenetically from feldspar.

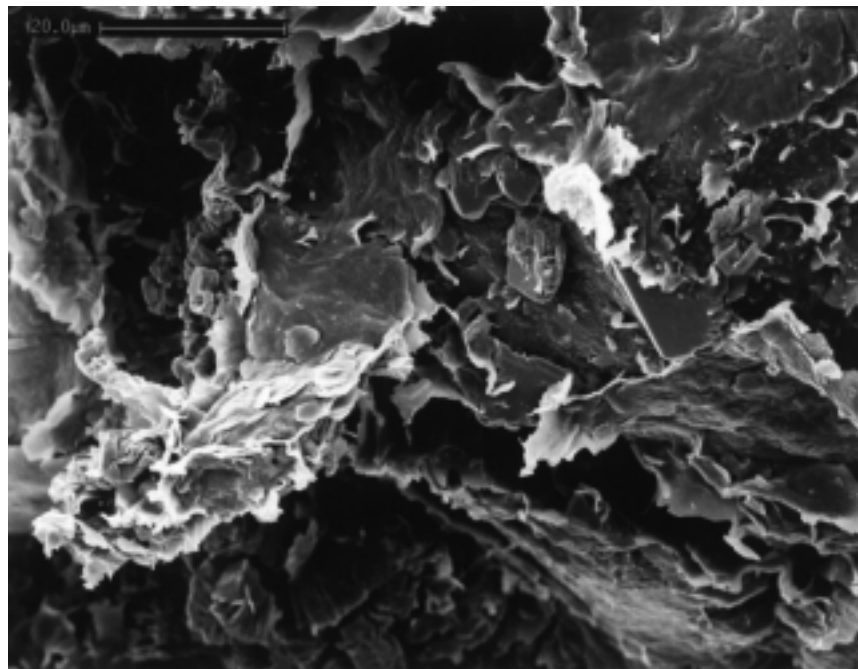


Figure 7: SEM photomicrograph of mixed layer illite/smectite.

CLAY AND PERMEABILITY

Figure 8 is a plot of porosity versus nitrogen permeability for 36 samples from 5 fields and 13 wells that represent a variety of rock types ranging from very fine to coarse grained sandstones. It can be seen that there is no clear cut relationship. Good permeability (>100 md) only occurs in rocks having

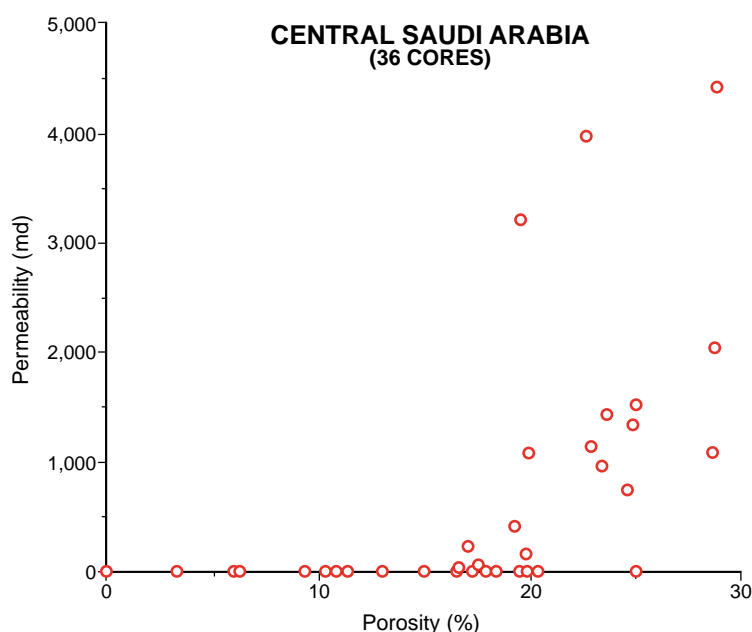


Figure 8: Porosity is plotted versus permeability for 36 cores from the Central Arabia Unayzah reservoir. The cores represent a wide variety of rock types from five fields and thirteen wells. The plots are not logarithmic to emphasize the relationships of clay content to permeability.

greater than 18% porosity. The porosity permeability relationship is dependent on both rock texture and mineralogy. Because of their presence in the pore system and their large surface area, authigenic clays have the most potential of any minerals that are present at low concentrations to affect permeability.

Neasham (1977) discusses the effects of various types of occurrences of clays on petrophysical properties. Figure 9 displays a negative relationship between permeability and the clay-size fraction for these same 36 samples. If the clay-size material content is greater than 3%, permeability is drastically reduced even in coarse grained sandstone. If clay content is less than 3%, permeability can be extremely variable but is usually high. The same relationship for a single Hawthah Field well is shown in Figure 10. For

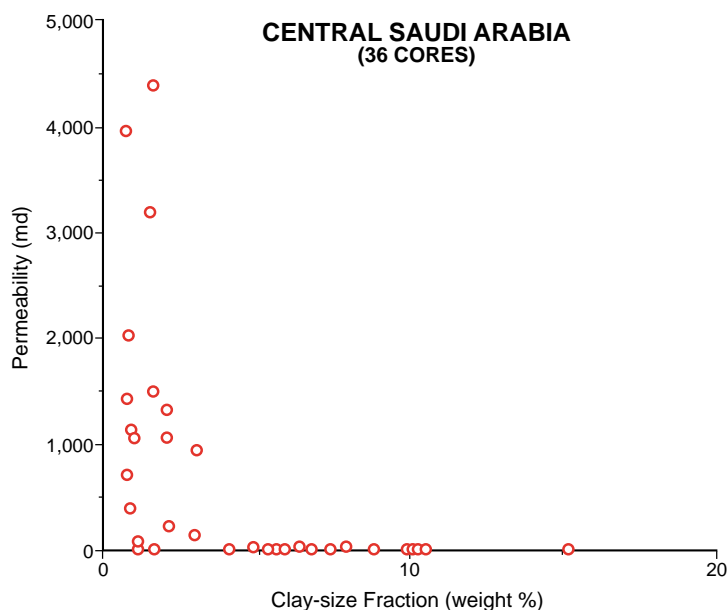


Figure 9: Permeability is plotted versus weight percent clay-size material for the same 36 Central Arabia Unayzah cores. A clay-size material content of >3% results in drastic permeability reduction.

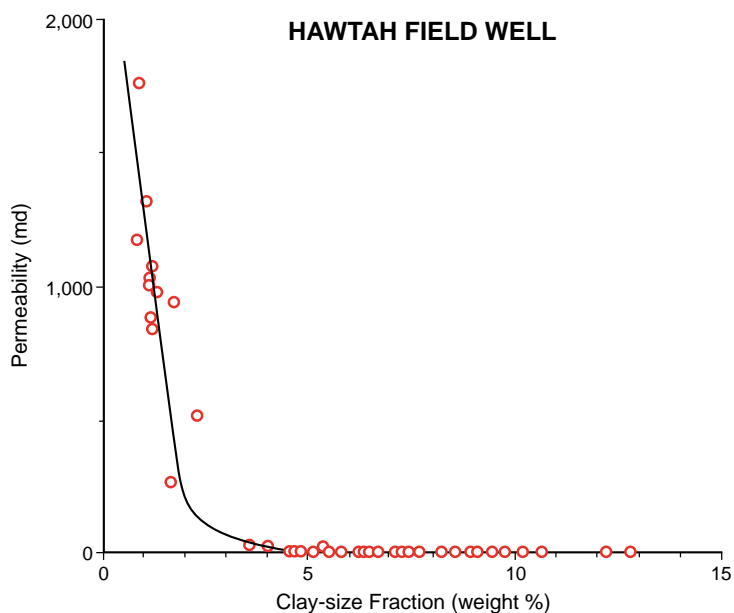


Figure 10: Permeability is plotted versus weight percent clay-size fraction for samples from one Hawthah well. Severe permeability reduction occurs in rocks that contain >2% clay-size material.

this well, over 2% clay-size material dramatically reduces the permeability. The relationship is not as well defined if actual clay mineral content is plotted versus permeability. Figures 11 and 12 depict high permeability, low clay content rock and low permeability, clay-choked rock.

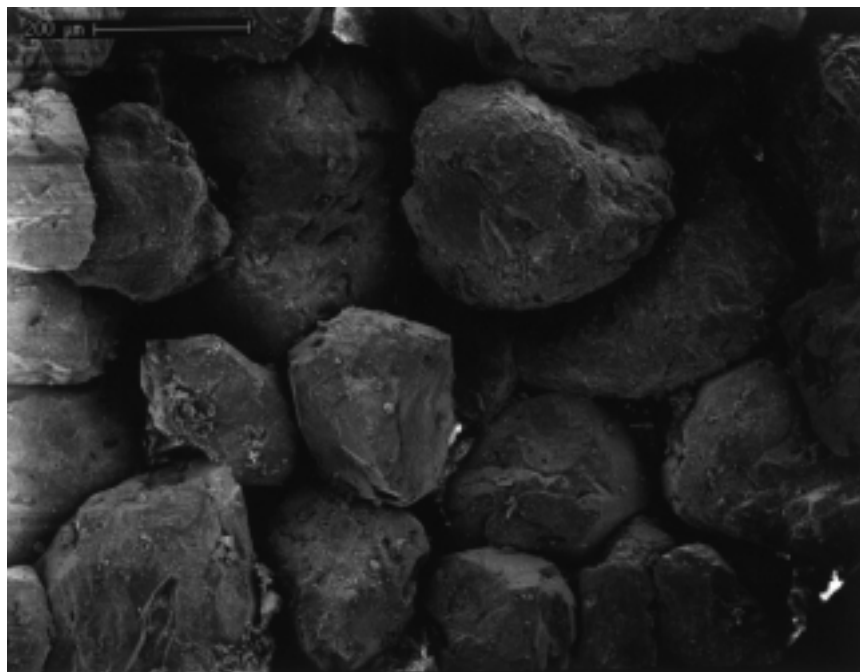


Figure 11: SEM photomicrograph of high permeability (4394 md), low clay content (0.68%) rock.

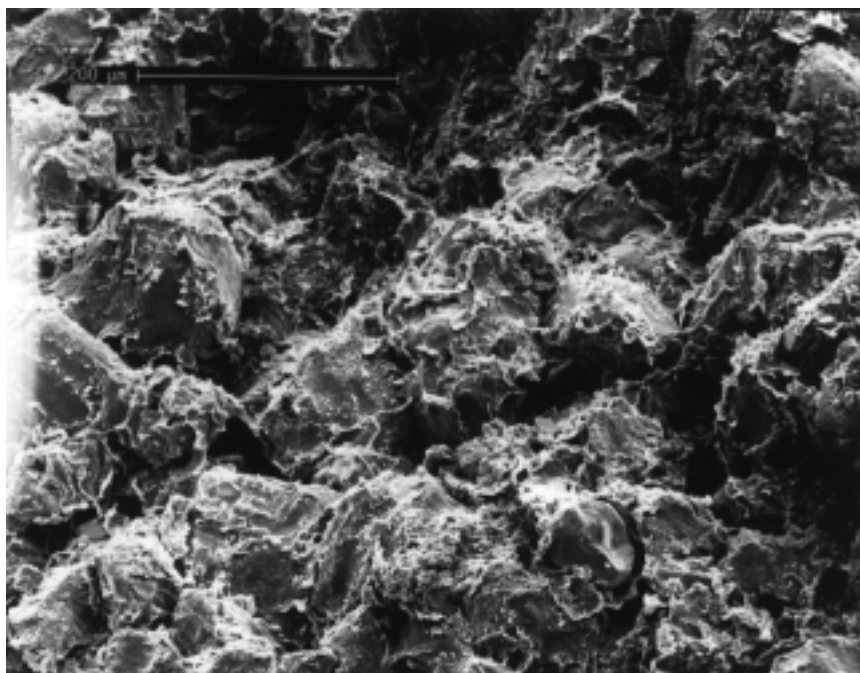


Figure 12: SEM photomicrograph of low permeability (24 md), high clay content (7.91%) rock.

EFFECTIVE CLAY VOLUME

Most clay relationships are expressed using weight percentages and not volumetric factors. However, it is the volumetric factors that are directly related to pore occlusion and therefore directly influence fluid flow in the rock's pore system. The pore volume affected by the clay is influenced by both the volume of the clay and the volume of its associated water. During separation of clay-size material in the laboratory, it has been commonly noted that less than 1 cubic centimeter (cc) of whole rock consisting only partly of clay minerals can often give clay volumes greater than 20 cc. This is largely the effect of distilled water on the expandability of smectite clay. Clearly, most of the effective volume of the clay minerals is due to the presence of large amounts of associated water that other methods such as XRD do not measure.

In order to study this phenomena, an experiment was designed to evaluate the volumetric effect (see Appendix for details). During clay separation by sedimentation in our laboratory, the suspended clay-size material is recovered by centrifuging the slightly acidified clay-laden fluid. The clay settles to the bottom of the centrifuge tube and its volume can be measured. By repeating centrifuge cycles of the same duration, the clay volume can be measured and plotted as it compacts with time (Figure 13). The clay compacts rapidly for a few cycles and then more gradually. By projecting the high initial linear compaction rate back to the Y-axis, time zero, the original volume of the clay and associated water can be determined.

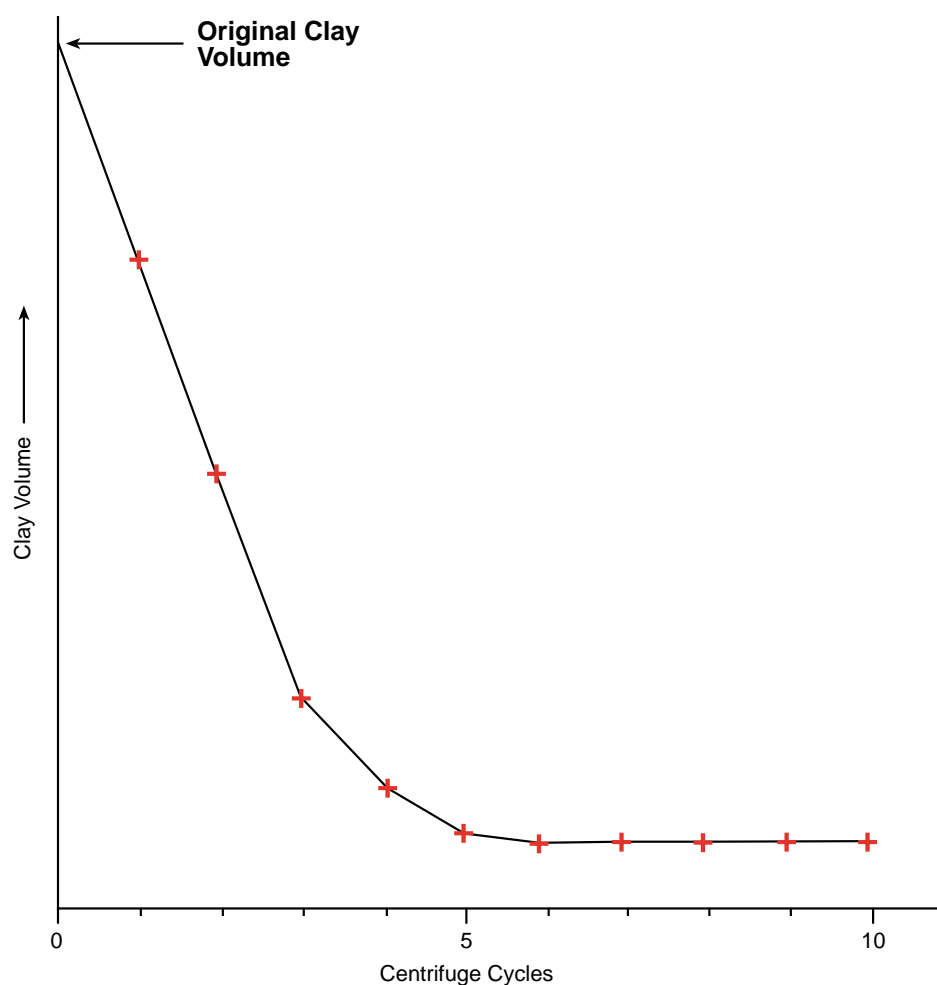


Figure 13: Clay volume is plotted versus number of centrifuge cycles. The original volume of clay and associated water can be determined.

Twenty samples from a Hawtah well were evaluated. Each individual clay mineral's effective water-saturated volume was determined by solving simultaneous equations using XRD-determined concentrations of the individual clay minerals (see Appendix). These results are listed in Table 2. It should be realized that these values reflect experimental conditions (clay in contact with distilled water) and not necessarily those of natural rock (clay in contact with saline connate water). However, similar relationships should also be present within the formation. Tests could be run in the laboratory with simulated formation brine or connate water instead of distilled water to determine the clay volumetric factors at reservoir conditions. (Unfortunately, for these samples the compositions of the associated formation and connate waters were not known.) Only the volumetric factors for smectite containing clays should be expected to change significantly.

Table 2
Clay Volumetric Factors

Clay Mineral	Volume (cc/g)
Kaolinite	13
Random illite/smectite	132
Ordered illite/smectite	1299

It can readily be seen from the data in Table 2 that the presence of large amounts of swellable smectite in the ordered I/S greatly increases this clay's effective volume as compared to the other clay minerals. A small amount, much less than 1%, of this mineral when exposed to fresh water can effectively occlude all porosity in a rock, resulting in very low permeability. This is likely to occur if fresh water is used for drilling or injection purposes. On the other hand, the presence of kaolinite will have a minimal impact on the permeability that is related to clay volumetric factors.

CLAY-RELATED FORMATION DAMAGE

Not all clay present in the formation will damage the formation. The clay in interbedded shale and shale clasts has little potential to cause damage because it is only minimally exposed to the sandstone's pore system and associated fluids. However, pore-filling (Figure 3) or pore lining (Figure 14) clay

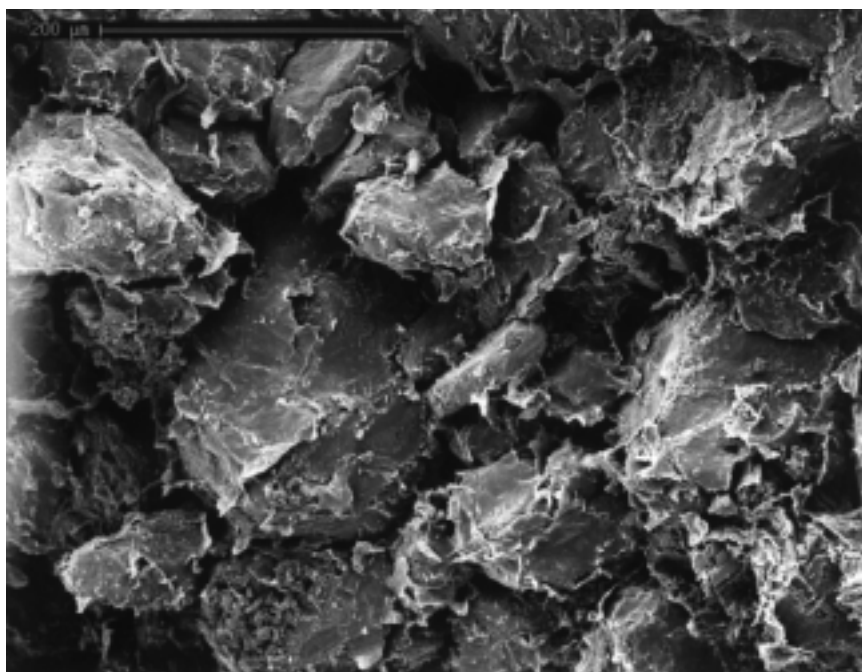


Figure 14: SEM photomicrograph of clay (mainly illite/smectite) in a pore-lining mode.

minerals have the potential to cause damage to the formation by several mechanisms. First, some poorly indurated areas of the formation are weakly cemented solely by clay minerals. Any fluid that affects the clay minerals (fresh water, mud acid) can result in the disaggregation of the formation into component sand grains. The resulting sand influx into the well has deleterious effects on down hole pumps and other equipment and results in sand production. Second, the expandable lattice smectite component of I/S can swell to many times its volume if contacted by fluids of low salinity. This can happen during drilling, completion, workover, or injection. Third, all clay minerals can be broken off from pore walls by fluid flow. They will migrate with the fluid until they become lodged in pore restrictions, thereby greatly lessening the formation's permeability. Almost all Unayzah cores show this type of damage when tested in the laboratory. Fourth, retention of water by clay minerals can lead to further occlusion of pores, water blocks, and a lowering of permeability. Again, this can happen during drilling, completion, workover, and injection. Fifth, if acidized, chlorite will dissolve (along with iron oxides and iron-containing carbonate minerals) liberating iron into solution. When the acid spends, this iron can be precipitated as gelatinous masses of pore-blocking iron hydroxides.

FORMATION COMPATIBLE FLUIDS

Consideration should be given to minimizing formation damage at all stages of development. A damaged well may have no production, or its production may be drastically reduced. Although stimulation may recover some of the well's permeability, care should be taken originally to restrict formation damage. Drilling fluids should be designed to minimize mud invasion of the formation and also to minimize fluid leakoff.

Potassium chloride (KCl) is an effective fluid additive to temporarily stabilize clay minerals. It can be used in any aqueous fluid that will contact the formation. It will protect against both clay swelling and migration and will minimize disruption of weak clay cements. KCl has been found effective at 1-2% critical salt concentration (J.D. Lynn, Saudi Aramco, 1995, written communication) and is now used at 10% concentration in drilling mud. Ammonium chloride at 0.6-0.8% critical salt concentration can also be used in completion fluids for this purpose (J.D. Lynn, Saudi Aramco, 1995, written communication), but it is more corrosive and also serves as a nutrient for the growth of sulfate-reducing bacteria.

For permanent clay control, a polymeric clay stabilizer can be used. It forms a thin film over the clay locking it in place and isolating it from further fluid contact and interaction. Clay stabilizers are appropriate for use in drilling and completion fluids. The Jilh Formation injection water (16,000-20,000 milligram/litre of total dissolved solids (mg/L TDS)) used for pressure maintenance is not completely compatible with the Unayzah Formation (estimated 200,000 mg/L TDS for connate water) because of its low salinity. These permanent clay stabilizers can be used to treat the near well bore area to minimize formation damage and maintain injectivity.

The effects of water imbibition can be lessened by using surfactants that aid in water recovery such as fluorosurfactants.

Use of weak acids is another way to minimize formation damage. Acetic acid dissolves less iron from the formation than hydrochloric acid, and also lessens formation disaggregation. Likewise, weak mud acid is preferable to stronger mud acid. Acids should contain citric acid, EDTA or other compounds for iron precipitation control. The hydrogen ion in acids acts in a similar way to the potassium ion in KCl for providing temporary clay stabilization. Alternatively, KCl-based breakdown and clean-up fluids could also be used instead of acids. Special blends of surfactants soften and disperse drilling mud and other fine particulate matter that may be blocking the formation's pores without the potential dangers of acid usage.

Of all fluid types, oil-based fluids (oil or invert emulsion) have the least impact on clay minerals with 95-100% return permeability in laboratory tests (J.D. Lynn and A.M. Ezzat, Saudi Aramco, 1995, written communication).

CONCLUSIONS

Although possibly present at low levels, clay minerals have a profound effect on the permeability of the formation. As little as 2-3 weight percent of authigenic clay reduces the formation's permeability drastically. Clay minerals also have the potential to damage the formation during drilling, completion, workover, or injection. Clay control measures have proven effective for the Unayzah Formation in Central Arabia. This results in higher hydrocarbon production at lower production costs.

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APPENDIX

Analytical Techniques

XRD

A good discussion of basic X-ray diffraction (XRD) methods for clay minerals is given in Brindley and Brown (1984). For this study, a Philips PW1710 X-ray diffractometer (PW1820 goniometer) using $K\alpha_{1+2}$ radiation from a Philips Type PW2233/20 normal focus copper tube was used. A monochromator and a proportional detector were used in conjunction with a fixed 1° divergent slit, a 0.2 mm receiving slit, and a fixed 1° scatter slit at instrument settings of 45 kV and 40 mA. The specific analytical methods used in this paper are listed below.

Bulk Analysis

Some core samples were only hand ground in a mortar and pestle to form a powder before XRD analysis. Later in the study, all bulk core samples were briefly disaggregated and lightly crushed in a mortar and pestle, and then 3-4 grams of sample were pulverized for 40 seconds in a SPEX 8510 shatterbox using tungsten carbide grinding vessels. The powdered samples were back loaded by hand into sample holders and analyzed from $4-60^\circ 2\theta$, using a step size of 0.02° and a count time of 1 second/step.

The height of the most intense peak of each phase was used for quantification, and results were normalized to equal 100% or [100% - % of clay minerals present from the separate clay analysis which is added into the bulk results]. The larger of the clay mineral values determined from the bulk analysis or the separate clay-size mineral analysis was used to express the amount of "actual" clay. This is because some clay minerals may be larger than clay size (bulk XRD has shown as much as 10% kaolinite present whereas the clay fraction has shown only 1% kaolinite).

The solubility of all samples in hot 15% hydrochloric acid was also measured. If there was good agreement between this solubility and the XRD-determined percentages of acid soluble minerals (carbonates, chlorite, iron oxides, halite, anhydrite), then the analysis was assumed to be good. If there were differences, or if any peak was seen to have a significantly different width, then peak area was used instead of peak height to determine mineral percentages. Clay mineral peaks in the bulk analysis always need to be corrected for peak width. Such procedures are accurate if no amorphous or poorly crystalline minerals are present.

Clay-size Fraction

The clay-size material (<2 micron equivalent spherical diameter) was separated from the larger size particles by sedimentation techniques. The sample was disaggregated and ground minimally in a mortar and pestle. 1-2 grams of this material was accurately weighed and dispersed in distilled water containing a few drops of sodium hexametaphosphate using a sonic probe for 4 minutes. The particle suspension was then centrifuged for an appropriate time to remove all particles >2 microns. The suspended clay in the top water was transferred to another centrifuge tube, a few drops of 15% hydrochloric acid were added to flocculate the clay, and the tube was centrifuged to remove the clay from suspension. The top water was discarded, a small amount of distilled water and a fluorite powder internal standard were added, and the clay was resuspended using the sonifier for a brief time. The clay slurry was poured onto a glass slide and allowed to sediment and dry over night at room conditions. This procedure gives a clay sample with a high degree of preferred orientation of the basal clay planes.

The bottom sediments from the original separation were resuspended in distilled water, centrifuged, and the top water discarded. This process was repeated until the top water was clear with no suspended clay. The centrifuge tube containing the bottom sediments was dried over night in an oven at 105°C . The sample weight of the coarse size material was then determined. The weight of clay-size material in the sample is the difference between the original sample weight and the weight of the coarse-size material.

$$\text{wt. \% clay fraction} = 100 \times \text{wt. clay-size fraction} / \text{original sample wt.}$$

The weight percent of clay-size material was corrected for the presence of water soluble salts (NaCl, KCl) which are another possible source of the sample's weight loss. Water soluble salts were determined from the bulk XRD analysis.

The clay slides were analyzed between $4-32^\circ 2\theta$, using 0.04° step sizes and 0.6 second/step count times. The samples were run in both an air-dried and a glycolated state (exposure to ethylene glycol vapors for 3+ hours at 60°C). Experience has shown that these are the only two XRD scans that are usually needed to completely characterize the clay minerals. Areas of deconvoluted peaks were used for quantification, and the phases were normalized to equal 100%.

The glycolated peak areas of illite/smectite were used to proportion the amount of these minerals in the air-dried diffractogram. Peak d-spacing measurements were corrected by use of the fluorite internal standard. The smectite content of randomly interstratified illite/smectite was determined by Mering's method (Reynolds, 1984). Kaolinite and chlorite were quantified based on their 7\AA peak. The amount of each mineral was apportioned from their 3.5\AA peaks [kaolinite (002), chlorite (004)] which are clearly resolved in almost all diffractograms. The presence of chlorite's (001) and (003) peaks also aided in the recognition of these two phases. In rare instances, an acid treatment was used to attack the chlorite to better ascertain the content of kaolinite and chlorite.

The percent of each clay mineral in the entire core sample was determined by multiplying its normalized percentage in the clay-size fraction by the weight percent of the clay-size fraction. This value was then used for the value of each clay mineral in the bulk analysis (see bulk analysis section).

Clay Volumetrics

Clay-size material was separated from the core samples by the techniques mentioned above. A sufficiently large amount of core was used to give measurable volumes of clay in the centrifuge tubes. After the initial separation of the clay-size suspended material, it was placed in a graduated centrifuge tube. Distilled water was added along with a few drops of 15% HCl to cause the clay to flocculate. The sample was then repeatedly centrifuged in a manner similar to the normal clay analysis, with cycles of the same duration. Volumes were measured after every centrifuge cycle and plotted versus cycle number. The first few cycle points give a straight line that can be projected back to the Y-axis to determine the original clay volume before compaction by centrifugation. This volume was then divided by the weight of clay-size material (see clay analysis) to give the volume of clay and associated water per gram of clay-size material in the sample.

To determine the volumetric factor of each individual clay mineral, simultaneous equations were solved using the percentages of clay minerals determined in the XRD clay analysis. This formula is:

$$a \cdot V_a + b \cdot V_b + c \cdot V_c + d \cdot V_d + \dots = V_T$$

where a, b, c, d, ... = fraction of clay-size material composed by constituents A, B, C, D, ... and $a + b + c + d + \dots = 1$

$$V_a, V_b, V_c, V_d, \dots = \text{volumetric factor (cc/g) for constituents A, B, C, D, ...}$$

$$V_T = \text{volume/weight (cc/g) of all clay-size material from the sample.}$$

The values of a, b, c, d, ... are experimentally known as well as that of V_T . A sufficient number of simultaneous equations must be solved to determine the volumetric factors of all clay components. In actual practice, care must be taken that the samples used for the calculations contain equal amounts of smectite in the random I/S and also in the ordered I/S.

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