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WATER SENSITIVITY OF DARNEY, DUNHOUSE

AND CATCASTLE SANDSTONES

1. INTRODUCTION

Total rock characterisation of Darney, Dunhouse and Catcastle sandstones, which is summarised in File Note CAM/4 revealed that each of these rocks contain authigenic clay minerals, predominantly of the kaolinite family. As authigenic clays are a major control on reservoir quality and as permeability is particularly sensitive to the relative abundance of clays flooding tests were carried out to determine the interaction between the clays and the permeating fluids and in particular the water sensitivity of the three sandstone types. In addition, and to form the basis of a more detailed research programme, tests were carried out to determine whether oven drying has an effect on the permeability and sensitivity of clay-bearing sandstones.

2. WATER SENSITIVITY OF CLAY MINERALS

Water sensitivity has been defined by Hewitt⁽¹⁾ as the reduction in permeability which occurs when a rock containing clay minerals is exposed to fluids of differing ionic concentrations. The chemical and physical environments of the clay particles are altered and various equilibrium changes in the clay mineral structures can take place.

The basic building blocks of clay minerals are made of the silica tetrahedral sheet and the alumina octahedron sheet, and the arrangement of these sheets in the crystal lattice generally produces a platy or rod like mineral structure. Consequently, clays have a considerably greater surface area than the crystals of quartz and felspar, the most common rock-forming minerals in sandstones.

Substitution of Si^{4+} by Al^{3+} in the silica tetrahedron sheet and replacement of Al^{3+} with Mg^{2+} or Fe^{2+} in the alumina octahedron sheet produce a net negative charge on the clay. This negative charge is balanced by cations in the fluid surrounding the clay mineral which are attracted to the surface of each clay platelet. The cations on the clays are termed exchangeable since they are readily removed by other cations in their immediate environment.

The replacement of one cation by another is governed by the cation exchange capacity of the clay, the law of mass action and the valence of the cation. Generally where mono- and di-valent cations are present in the same concentration in an ionic fluid, the di-valent cation will be preferentially attracted to the clay. If a fluid containing only one cation is contacted with the clay it will tend to replace another cation on the clay surface regardless of its valence. The large surface area of clay minerals also imbues upon the clay a tendency to react more readily and rapidly with ionic fluids of different concentrations than any other mineral.

Clay minerals can be classified into four main groups or families: the kaolinite group, the smectite group, the illite group and the chlorite group. Each group contains several different members which can vary amongst themselves, particularly in terms of their respective morphologies. Different members of each group may also show differences in chemical composition. Thus the rate of reaction (or cation exchange) between clays and ionic fluids may vary significantly within a single family. However in general terms clay minerals can be classified as: (a) "expandable" or (b) "non-expandable".

(a) "Expandable" Clays

"Expandable" clays are those which are considered to belong to the smectite group, including montmorillonite, and which expand or swell by adsorbing water layers between the clay platelets. This absorption is brought about by hydration of the cation attracted to the clay. The degree of water absorption depends on the cation associated with the clay and the concentration of dissolved salts in contact with the clay. If the water in contact with the clay is diluted with less saline water, cation reactions cause additional water to be adsorbed and the clay swells. Smectites rich in sodium can expand by 600% to 1000% of their original volume. This expansion can result in a sealing-off of pore throats and a resultant loss in permeability. This type of permeability reduction is often termed dynamic permeability reduction.

(b) "Non-expandable" Clays

These include the kaolinite, illite and chlorite groups. Whilst these clays do in fact adsorb water to some degree when their equilibrium is disturbed, the volume changes of the minerals are insignificant when compared with the smectite group. However

when "non-expandable" clays are introduced to less saline water, cation exchange reactions take place, the cations on the clay dissociate and a positive ion swarm is established on the solution near the surface of the clay, and a negative charge is induced within the particle. This is referred to by Reed⁽²⁾ as an electrical double layer. Particles with such double layers repel each other in a less concentrated cationic environment and hence they tend to disperse. Since many "non-expandable" clays, particularly kaolinite, are only loosely adhered to pore walls or rock grains, the shear forces introduced by flowing liquid can detach individual dispersed clay platelets or aggregations of clay platelets and cause them to migrate. These migrating fines can be trapped in pore throats, acting as a check valve and can cause a blocking of permeability. This type of permeability damage is often referred to as a dynamic permeability reduction. If the fluid flow direction is reversed, these migrated clays can be removed from their trapped positions in pore throats thereby improving permeability. This improvement is only temporary, however, as most released particles are re-trapped in downstream pore throats.

3. EFFECT OF DRYING ON PERMEABILITY

Land⁽³⁾ and Atwood⁽⁴⁾ discovered that the permeability of cores damaged by fresh water can be restored by drying. They found that dispersed sodium-montmorillonite forms brush heap structures which recede to the pore walls on drying thereby increasing the pore throat diameters and improving permeability. However, the sensitivity to water remains the same if the core is wetted again. Gray⁽⁵⁾ states that the dynamic permeability reduction caused by migrated clays cannot be improved on drying as the pores themselves have been rearranged.

Pallat⁽⁶⁾ considers that drying of clay bearing sandstone cores, even in a humidity controlled oven, can effect their measured brine permeabilities by apparently improving permeability over their non-dried state. Whilst the precise mechanism for such apparent permeability improvement is unknown, it has been suggested that the high surface tension forces, developed at the fluid/air interface as the fluid meniscus recedes through the rock during drying can be of sufficient magnitude to physically alter the clay mineral structure. By implication this alteration may render the clays physically passive and make them less sensitive to changes in their ionic environment.

4. WATER SENSITIVITY TESTS

The water sensitivity tests were carried out in the clay sensitivity rig which is designed to flow either brine or fresh (distilled) water through a 1-inch diameter by 1-inch long test plug. Details of the flow scheme of the rig are given by Gilbert⁽⁷⁾.

The permeating fluids were prepared using reagent grade chemicals and distilled water, and were filtered down through an 0.22 micron filter before use in the rig. Any bacterial growth, or reprecipitation of the salts used to make up the fluids, which may have occurred during storage, was subsequently filtered out by 0.8 micron and 0.22 micron filters placed in line in the rig.

Three cores of each of Darney, Catcastle and Dunhouse sandstones were cut from the same 6-inch by 6-inch by 1-inch blocks used for the rock characterisation analyses. The cores were cut and trimmed to size using 20.6 g/l sodium chloride brine as the coolant. In order to assess the effects of oven drying on the permeability and water sensitivity of each rock type, two separate test procedures were carried out:

(i) Procedure 'A'

One core plug of each of the three rock types was dried in a humidity controlled oven for 12 hours at 60°C and 40% relative humidity, then allowed to cool in a vacuum dessicator. The porosities of each core were then determined using a helium gas expansion porosimeter and a mercury pycnometer. Their permeabilities to gas were measured using a nitrogen permeameter and the apparent "liquid" permeabilities corrected for the Klinkenberg gas slippage effect were calculated. This enabled comparison of their poroperm properties with those determined in the initial rock characterisation.

Each core was then placed in turn in the coreholder of the clay sensitivity rig and hydraulically confined under a pressure of 450 psig. The core was evacuated for 1½ hours to 2 hours using a high powered vacuum pump to allow complete and efficient saturation of the pore spaces in the rock by the 20.6 g/l sodium chloride brine.

The brine solution was then pumped from a Cornelius vessel by a constant flow rate metering pump, and, after being bled of air, the brine was diverted through the core. The brine was flowed sequentially in the forward and reverse directions until the pressure differential across the core was the same in both directions. At this point brine was flowed in the forward direction and the permeability against volume throughout was monitored. Permeability was calculated from the formula:

$$k = \frac{1000 \times \mu \times L \times 14.7 \times Q}{\Delta p \times A}$$

where k = permeability, millidarcies

μ = viscosity of liquid at test temperature, centipoise

L = length of core, cm

Q = flow rate through core, $\text{cm}^3 \text{s}^{-1}$

A = cross-sectional area of core, cm^2

Δp = pressure differential across core, psig

All the flow tests were carried out at 25°C to eliminate temperature as a variable.

Permeability measurements were continued until steady state conditions were reached (i.e. constant flow rate and constant pressure differential). At this point brine flow was discontinued and the core was then flowed with fresh water. The permeability against volume throughput of fresh water was measured until steady state conditions were reached. The flow of fresh water was then reversed and the permeability again monitored. Once steady state conditions were re-established the core was removed, dried in the humidity oven for 12 hours and their porosities and gas permeabilities redetermined.

(ii) Procedure 'B'

Following cutting and trimming two cores of each of the three sandstone types were stored in the de-aerated sodium chloride brine until required. Each core was then placed in the rig core-holder and immediately flushed with brine to prohibit the core from drying out. A confining pressure of 450 psig was then applied and the cores were flowed with brine in the forward and reverse directions until equilibrium was achieved.

An identical sequence of brine and then fresh water flow to that of Procedure 'A' was carried out, the permeability against volume throughput of each fluid being constantly monitored.

Following the flow tests, the cores were removed, dried in the humidity oven for 12 hours and their porosities and gas permeabilities determined. In the case of one of the cores, Catcastle CTL1, it was not possible to determine the gas permeability as the plug was too friable to fit the permeameter core sleeve.

5. RESULTS AND DISCUSSION

The two plugs of each of the Darney, Dunhouse and Catcastle sandstones, which were not allowed to dry out following cutting were denoted DAL1 and DAL2, DUL1 and DUL2, and CTL1 and CTL2 respectively. The single core plugs cut from each of the sandstones which were oven dried were denoted DAD1, DUD1 and CTD1 respectively.

The results of the flow tests and the porosities and apparent "liquid" permeabilities from the gas permeameter before and after the flow tests are given in Table 1. As the determination of initial porosities and gas permeabilities involves drying the cores completely, the initial poroperm properties for the non dried cores, given in Table 1, are the averages of the values measured on the blocks during the previous rock characterisation analyses.

It is apparent from a study of the results that each rock type suffers permeability damage when exposed to fresh water following brine. The water sensitivity ratio (i.e. the ratio of fresh water permeability to that of brine) which serves as a measure of permeability damage, was found to be between 0.10 to 0.55

for Catcastle (all cores), between 0 and 0.32 for Dunhouse (all cores) and 0.07 and 0.09 for Darney (non dried cores). The oven dried Darney core DAD1, proved not to be damaged by fresh water (sensitivity ratio = 1.00). Reversal of the flow direction during fresh water flow in each sensitive core caused an immediate, though extremely short lived, permeability improvement followed by a gradual decline. The porosities of the cores after damage were generally lower than their initial values. Both these phenomena indicate that a dynamic permeability reduction has occurred with the migration of dispersed fines (presumably kaolinite) causing them to be trapped in the pore throats and resulting in a re-arrangement of the pores themselves.

With the possible spurious exception of Darney sandstone, which was found to be insensitive, there is no clear evidence that the effects of oven drying mask the water sensitivity. There is however some evidence that drying may have some effect on the measured brine permeability. It is apparent that the measured brine permeability (k_b) of the dried cores is much closer to the initial Klinkenberg-corrected gas permeability (k_{gf}) than the non-dried cores. Whilst this suggests that drying does appear to have some effect on the measured brine permeability it is also apparent that, even in the non-dried cores, there must be some interaction between the brine and the rock medium. It is difficult to visualise a chemical or physico-chemical effect which causes this apparent anomaly and therefore it is likely that there could be some mechanical reaction between the flowing brine and the pore lining clay minerals. It is possible that viscous shear forces are set up during brine flow which are not developed during flow of the considerably less viscous nitrogen gas. These shear forces alone could be sufficient to dislodge individual clay platelets from the clay mineral structure thereby releasing migratory fines.

The ratio of corrected gas permeabilities (k_{gf}/k_{gi}) before and after damage is generally greater than the water sensitivity ratio. This is particularly true of the more sensitive cores. Again this provides some, albeit limited, evidence that drying the cores affects liquid permeability and may even help to restore permeability damage. It is possible that interlayer water⁽³⁾ between the clay minerals is removed during drying. Whereas Land proved this to be a temporary effect with montmorillonite perhaps with kaolinite the effect is more permanent. It should also be borne in mind, however, that deficiencies in the experimental techniques on the non-dried cores may have led to the results that are considered to have been produced by drying, and that conclusions based on this series of tests are possibly erroneous. The non-dried cores were not evacuated prior to testing and whilst every effort was made to ensure they were completely saturated with brine, it is possible that the cores were at irreducible air saturation and that the permeability measured is not an absolute permeability but rather a brine permeability relative to air. Furthermore, there may have been slight, though possibly significant, differences between the initial average gas permeability assumed for each core and the actual initial gas permeability.

6. FUTURE WORK

Whilst the tests show fairly conclusively that Darney, Dunhouse and Catcastle sandstones are water sensitive, the conclusions on the effects of drying on the permeabilities of the core are severely limited by virtue of the experimental procedure. It should be realised at the outset that the tests to investigate the effects of drying were designed only as an initial exploration of the subject.

A great deal more flooding tests on non-dried and dried cores are required before one can obtain statistically valid results. To overcome the problem of incomplete brine saturation of the quarried sandstones consideration should be given to prolonged high pressure saturation. It would also be relevant to compare the results of flooding tests on dried and non-dried cores with those carried out on cores which have been critically point dried. This method of drying, discussed in File Note CAM/3 has been suggested to be non-damaging to clay minerals and has produced results more comparable with permeabilities obtained during well tests. Critical point drying will also enable the actual porosities and initial gas permeabilities to be determined and will allow vacuum saturation with brine thereby eliminating deficiencies in the experimental techniques.

Further work is also required to determine the precise mechanism whereby oven drying affects the clay minerals. In this regard consideration may have to be given to the determination of the cation exchange capacity of the clay before and after drying and a measure of any surface area changes in the clay minerals before and after drying. X-ray diffraction techniques could also prove useful to investigate whether interlayer water between the clay platelets has been removed.

TABLE I

RESULTS OF WATER SENSITIVITY TESTS

Procedure 'A' - Dried Cores

Rock Type	Sample No.	Porosity (%)		Corrected Gas Permeability (md)		Brine Permeability (md) k_b	Fresh Water Permeability (md) k_f	Water Sensitivity Ratio (k_f/k_b)	k_{gf}/k_{g1}
		Initial	Final	Initial (k_{g1})	Final (k_{gf})				
Darney	DAD 1	18.1	18.0	140.2	129.3	72.4	72.9	1.00	0.92
Dunhouse	DUD 1	16.7	16.1	47.1	37.8	14.9	2.0	0.13	0.80
Catcastle	CTD 1	15.3	15.3	48.0	31.3	38.6	21.1	0.55	0.65

Procedure 'B' - Non-Dried Cores

Darney	DAL 1	18.0	17.5	164.6	66.3	31.8	2.3	0.07	0.40
	DAL 2	18.0	17.7	164.5	68.3	42.3	3.6	0.09	0.42
Dunhouse	DUL 1	16.8	16.4	65.3	51.1	10.8	0	0	0.78
	DUL 2	16.8	16.5	65.3	21.1	2.1	0.69	0.32	0.32
Catcastle	CTL 1	14.1	13.8	46.3	-*	9.1	4.3	0.47	-
	CTL 2	14.1	14.4	46.3	10.3	3.3	0.34	0.10	0.22

* Test plug too friable to fit permeameter

R E F E R E N C E S

1. Newitt, C.H. (1963) "Analytical Techniques for Recognising Water Sensitive Reservoir Rocks", J. Pet. Tech. (Aug), pp 813-818.
2. Reed, M.G. (1972) "Stabilisation of Formation Clays with Hydroxy-Aluminium Solutions", J. Pet. Tech., (July), pp 860-864.
3. Land, C.S. and Baptist, O.C. (1965) "Effect of Hydration of Montmorillonite on the Permeability to Gas of Water Sensitive Reservoir Rocks", J. Pet. Tech., (Oct), pp 1213-1218.
4. Atwood, D.K. (1964) "Restoration of Permeability to Water-Damaged Cores", J. Pet. Tech. (Dec), pp 1405-1410.
5. Gray, D.H. and Rex, R.W. (1966) "Formation Damage in Sandstones by Clay Dispersion and Migration", Nat. Conf. on Clays and Clay Mins., 14th, Berkeley, Calif., in Clays and Clay Mins., 26, pp 355-366.
6. Pallat, N., BP Research Centre, Sunbury-on-Thames Pers. Comm.
7. Gilbert, L.V. (1980) "Plugging of Berea and Elgin Sandstones due to In Situ Clay Minerals", unpubl File Note, LVG/22, Department of Petroleum Engineering, Heriot-Watt University.