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Fluid Selection Using Formation Damage Laboratory Testing - Key Parameters, Pitfalls and Potential

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اختيار السوائل باستخدام معايرة معملية لتشوه التكاوين الجيولوجية أهم المتغيرات والمخاطر الكامنة والاحتمالات

ايان باتي وميخائيل بايرني

تتم اختبارات تشوه االتكاوين بصفة متكررة لاختيار سوائل الحفر المناسبة قبل استخدامها بالآبار. وتعتمد القرارات الرئيسة التي تؤثرعلى إنتاجية وحقن الآبار على هذه الاختبارات ا لمعملية.

تصبو هذه الورقة لحل بعض من الجدل والاختلاف حول طرق اختبارات تشوه التكاوين وتقدم دليلا واضحا لدعم الآراء التي تم طرحها حول مميزات بعض من أنواع الاختبارات. وتصف هذه الورقة وبصورة مفصلة بعض الطرق التي يجب أن تؤخذ في الاعتبار أثناء إجراء أو طلب اختبار تشوه التكوين معمليا. كما تمت مناقشة الاختلافات في طرق الاختبار عند تحضير عينات لب البئر وعند محاكاة الإنتاج وقد عبر المؤلفان وبآراء واضحة على ما يعتقدانه أفضل الخيارات.

تم عرض أهم المشاكل التي تواجهه عملية تصميم التجارب المعملية وكذلك تقديم خطوط إرشادية مدعومة بأدلة واضحة باتجاه اختيار طرق معينة عن غيرها. كما تم تقديم أحدث التطورات عند تصميم الاختبار وتفسير نتائجه ونوقشت الاستعمالات الحالية والمتوقعة للنتائج المعملية، وقدم الباحثان آرائهما حول التقدم المحتمل واتجاهات البحث العلمي مستقبلا في هذا المجال الحساس.

خلصت المقالة إلى أن اختبار تشوه التكوين معمليا جدير بالمحاولة، ولكنه يتطلب تخطيطا وتصميما دقيقين. إن طرق الاختبارات المختلفة يجب أن يؤخذ بها بعناية حتى تكون النتائج قادرة على التنبؤ أو تعكس الواقع الفعلي لأداء البئر والمكمن.

Abstract. *Formation Damage laboratory testing is routinely performed to select optimum drilling, completion and other fluids prior to their deployment in wells. Major decisions which impact the productivity or injectivity of wells and fields are often based on laboratory tests. This paper aims to resolve some of the arguments and diversity in the procedures for laboratory formation damage tests and present clear evidence to support opinions expressed on the merits of particular tests.*

This paper describes in detail some of the procedures which need to be considered when conducting or ordering formation damage laboratory tests. From core preparation through to simulation of production, the differences between test methods are discussed and the authors express clear opinions on what they consider as the best approach.

Some of the biggest pitfalls which are encountered when designing laboratory tests are explained and guidelines are presented, backed by clear evidence which point towards particular methods and away from others.

The latest advances in test design and test result interpretation are presented. The current and potential use of laboratory data is discussed and the authors present their opinions on likely future

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advances and the direction of future research in this critical area.

The paper concludes that laboratory formation damage testing is worthwhile but it must be carefully planned and designed. The various test methodologies must be carefully considered in order for the results to predict or reflect real well and reservoir performance.

INTRODUCTION

Over the past 18 years various laboratory projects have been designed and conducted by the authors to improve well productivity and injectivity by understanding and mitigating formation damage. One of the most important factors in design of laboratory testing for formation damage is to decide if the test objective is to compare fluids procedures or to attempt to simulate real well behavior or both. The majority of formation damage testing referred to in this paper should be viewed as a combination of simulation and comparative testing. Another critical factor in testing is that all tests are conducted at reservoir conditions in suitable equipment. All reservoir conditions wetted parts must be composed of corrosion resistant materials such as Hastelloy and Teflon. Testing in inferior quality equipment will be prone to artifacts and will generate erroneous results.

Samples for testing must be carefully selected and prepared in order to obtain results that are relevant for the reservoir under investigation. Laboratory testing, if performed carefully and with due consideration to sample selection and test design, can accurately measure potential reduction in permeability. In order to use this information and enhance productivity it is often necessary to determine the precise cause or causes of Formation Damage. Identifying damage and interpreting the results of advanced core flood tests usually requires a combination of engineering and geological skills. Geological techniques such as Scanning Electron Microscopy (SEM) and Thin Section analysis can be used to identify solid damaging mechanisms such as solids invasion, residual mud cakes, precipitates, fines migration or bacterial growth. Cryogenic SEM involves preparing part of the sample after the flood test down to liquid nitrogen temperature and analysis of this frozen specimen. This technique allows the identification of fluid damaging mechanisms such as wettability alteration, water blocks and micro-emulsion formation. By combining engineering and geological skills, it is not only possible to examine and simulate Formation Damage problems but diagnose those problems and help to prescribe the best treatment or the least damaging procedure.

One of the most important influences on Formation Damage is the geology of the reservoir. In order to apply the data produced from a laboratory test, it is essential to understand the relevance of the rock material tested. Samples for laboratory testing must be selected to represent the major production or injection intervals. If there are significant differences in permeability or clay type, for example, these differences must be adequately represented in the material for testing. All available geological and relevant production data should be used in order to select the most suitable core material. Samples preserved with reservoir fluids in the pore space are preferred but old, dried out core may be restored to very close to the reservoir conditions using careful handling techniques. Special cleaning and drying procedures should be employed to ensure that samples selected are prepared without altering delicate structures in the pore space. The laboratory tests are designed to incorporate all pressure changes in the near wellbore area. For example, if the well under investigation is to be returned to production by gradually decreasing the pressure in the wellbore (drawdown), then this-step should be incorporated in the laboratory test.

As technological advances are made and environmental concerns increase, new challenges confront those involved in dealing with Formation Damage problems. New environmentally friendly drilling fluids may not be particularly reservoir friendly, and need to be carefully selected for each application. Extended reach drilling can often lead to increased Formation Damage problems that can be expensive or impossible to remove. High temperature reservoirs may be damaged by breakdown of normal fluids under the intense conditions. H_2S production from microbial activity may cause problems that need to be minimized with environmentally friendly solutions. New sand control completion techniques should be thoroughly assessed for their impact on productivity. Old or marginal fields may benefit enormously from a reassessment of historical Formation Damage that can now be avoided. The list goes on but the key to resolving all of these problems is thorough laboratory simulation combined with full sample evaluation to identify problems and solutions.

Laboratory testing cannot recover all of these losses caused by Formation Damage but it can go a long way towards recovering significant amounts. By definition, properly constructed tests increase our understanding of the performance of each reservoir and can make a real difference to production, injection and profit.

Previous papers have suggested at the relative values obtained from one laboratory to another for the same tests can vary significantly[1,2]. This paper aims to dispel some of the misconceptions which surround laboratory testing and stimulate discussion and thought about the design, implementation and use of future laboratory tests. Based on collective authors' experience of more than 1,500 reservoir specific laboratory core flood tests some of the key parameters will be discussed and a recommended approach will be outlined. Potential pitfalls and errors during testing, some alluded to in previous publications will be presented and discussed. Evidence of the effects of corrosion in poor quality equipment, damage to samples prior to testing and the induced damage that can be measured due to poor laboratory procedures will be presented for the first time.

The case for particular laboratory test procedures will be made with the objective of increasing the reliability and relevance of laboratory formation damage testing. With an elevation of standards and thorough interpretation, laboratory testing can increasingly be used to predict and optimize well performance.

Finally the way forward for laboratory testing and the potential improved use of results obtained will be explored.

KEY PARAMETERS AND PITFALLS

The tests should be viewed as laboratory simulations. The criteria for test selection are therefore dependent on the well or field information to be simulated. Some of the basic categories are as follows:

Sample Selection

It is critical to select appropriate samples for all reservoir specific formation damage testing. In the tests, the objective is to simulate a reservoir or a well. If there are several different lithologies or rock types which contribute to production or will take injection, then all of these variations must be represented. If there are significant variations in permeability or lithology then additional samples will be required to represent the reservoir. Of course, the number of samples selected is a financial as well as scientific choice. Each additional lithology will increase the number of tests required and the cost of any project. Core samples from the well being studied or from adjacent or equivalent wells must be selected, the first selection criteria is that the core samples are representative. Then, the samples must be "in a good condition". In a good condition means that it is possible to obtain core plug samples which are representative of the key lithologies. Preserved samples have the advantage that the core is complete and it is therefore possible to take more or longer plug samples. Preserved samples may also have the advantage that the pore fluids are still in place and they do not require cleaning and restoration. Experience has shown us that many preserved samples have desaturated to some extent and so must be cleaned and restored. As illustrated in Figure 1, some preserved samples are contaminated with bacteria and should not be used. Normally, many plug samples are taken and prepared for testing. Sub-selection of samples is then performed to ensure that duplicates are used for the flood tests.

Fig. 1. Microbial contamination of preserved sample. A rock chip from a preserved sample which has been immersed in solvent. A stream of biopolymer can be seen eluting from the pore space. This sample was ruled unsuitable for formation damage testing due to bacterial contamination.

Core Preparation

Computer Axial Tomography (CAT) Scanning of the whole core samples is performed in order to determine correct orientation and selection of plugging sites for duplicate core plug samples. Samples are usually taken parallel to principal flow direction in reservoir *i.e.* horizontal core plugs cut parallel to bedding. Either 1.5 or 1 inch diameter samples are used and length is limited to approximately 2 inches due to constraints of ultracentrifuge. Core plug samples should be cut using an inert mineral oil as bit lubricant to avoid damage.

Cleaning and Drying

The majority of reservoir rock samples available for testing are either poorly preserved or not preserved. To proceed for testing, they need to be cleaned of residual solids and fluids. There are many different methods for cleaning samples and the selection of the optimum method can have a profound effect on all results obtained from subsequent tests.

One popular method for cleaning is to flow fluids or combinations of fluids through the plug samples in a core holder. Amongst the potential problems with this method are: potential for fines migration to occur prior to the real laboratory testing; poor cleaning efficiency-inefficient sweep of all pores; difficulty in achieving required saturation with subsequent fluids.

Hot soxhlet solvent extraction can also be used to rapidly clean samples. This technique is now largely discredited due to severe alteration to delicate minerals which can occur. The photographs presented in Figures 2 and 3 are adequate evidence to condemn this technique where important decisions are made on the basis of the core flood testing.

We believe that the best methods for cleaning of samples are cold static cleaning and warm constant immersion cleaning. Cold static cleaning is normally prohibitively time consuming but warm constant immersion achieves good results in reasonable time

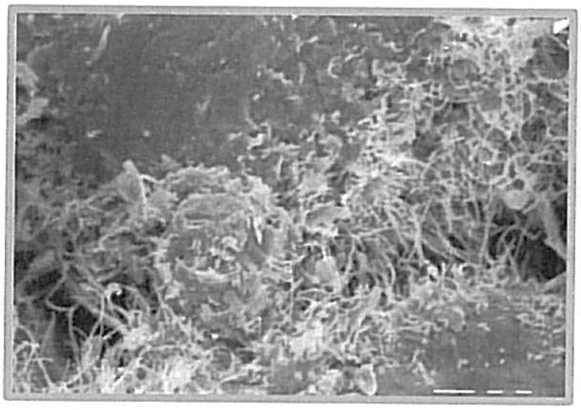

Fig. 2. Sample preparation - successful. The SEM photograph shows a pore in a sandstone reservoir filled with delicate illite fibres. Continuous immersion soxhlet cleaning and careful drying has preserved delicate structures maintaining the sample in a suitable state for core flood testing.

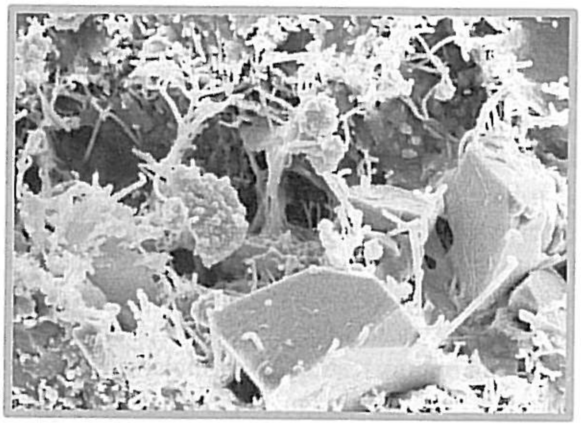

Fig. 3. Sample preparation – failed. As a contrast of figure 2, this sample from an identical continuous rock sample shows severe destruction of natural illite clay. The aggressive cleaning and drying used has destroyed the delicate illite fibres and rendered the sample unsuitable for core flood testing.

Samples are dried by low temperature oven drying to retain the intrinsic structures within the pore space.

Preparation to Fluid Saturation

For oil or gas leg simulation, the sample is saturated 100% to the formation water (pH adjusted), then prepared to irreducible formation water saturation using production phase (to eliminate relative permeability effects). Normally, this preparation to irreducible is achieved using an ultracentrifuge. There are three options-1 Ultracentrifuge, 2 dynamic (flooding), 3 porous plate. Ultracentrifuge rapidly achieves an irreducible saturation which is repeatable and consistent. Drawbacks such as variable saturation profile are outweighed by the benefits of this method and so it is the preferred technique for suitable core.

Dynamic flooding is the best option for samples which cannot withstand the physical forces of the ultracentrifuge. The technique suffers from incomplete sweep and from the fact that the flowing phases can induce fine migration. The porous plate is reliable and produces a consistent saturation profile but in most cases it is prohibitively slow and there can be contact material artifacts introduced to the plug sample.

Test fluids

It is the properties of reservoir fluids in the near wellbore that dictate the test fluids. For production wells, gas and oil are the most common test fluids. Convention is to use inert humidified nitrogen gas to represent producing gas phase. The majority of damage mechanisms are not dependent on the use of live gas in the tests. For oil wells, convention is to use dead crude oil to represent producing oil phase. Tests with live crude oil can be conducted but are generally considered to be prohibitively expensive. Experience with dead crude oil has led to the development of special laboratory procedures which are important to observe in order to avoid artifacts. The oil must be completely dewatered and must be maintained at all times above the wax appearance temperature. The oil must be filtered at reservoir conditions to very fine specifications to avoid introducing particles to the test. If insufficient crude oil is available (approximately five liters for each test) or if the crude oil is unstable (*e.g.* due to asphaltene deposition), inert mineral oil of similar viscosity to the crude oil can be substituted.

The appropriate fluid phase should be used for any simulation. Oil should not be used to represent gas as the relative clean-up of any damage with oil and gas may differ.

Flow Direction

The direction of flow of fluids through a core plug sample during testing should reflect real wellbore flow directions at all times. Terms such as "forward, reverse, inlet, outlet, upstream and downstream" should not be used during formation damage simulations for production or injection wells. These can lead to confusion in test procedures and interpretation. For example, during simulation of drilling a water injection well, the permeability we are most interested in is from the well to the reservoir with injection water. This could be described as forward flow, upstream to downstream or inlet to outlet. If the well is back flowed prior to injection then flow is from outlet to inlet in the reverse direction and downstream to upstream! A more sensible approach is to allocate a formation and wellbore end to the plug sample and describe any flow in terms of formation to wellbore (production) or wellbore to formation (injection). This nomenclature has stood the test of time and more than 1,500 tests and avoids ambiguity in flow direction.

In-situ Permeability Measurement

It is essential that all testing can be conducted in the same apparatus. Needless offloading of plug samples and transferring to other equipment set-ups should be avoided. Permeability measurements should be made in-situ at reservoir conditions if possible. Measurements made at room conditions can be subject to artifacts and produce misleading results.

Base Permeability

Base permeability must be established in order to have a value with which to compare any after test or final permeability. The base permeability must not cause any damage in itself and so must be measured with least possible disturbance to the rock matrix. Some procedures advocate measurement of base permeability at a series of increasing rates or differential pressures across the sample. In theory, this yields a calculated permeability which is independent of the actual rate used. This is potentially damaging to the sample, as fines migration can be induced as the rate is increased. The value of all subsequent testing can be lost if damage is induced. The multiple rate or pressure measurement suggests that rates above the minimum are employed and we believe that for "return permeability" base permeability measurement this is wrong. Instead, we advocate, as outlined in SPE 38154, that for each lithology, rock type or permeability range, a base non-damaging flow rate below the critical velocity, (the flow rate which causes the onset of fines migration) for the appropriate fluid is established and permeability determined. The lowest possible rate at which meaningful data can be generated is the safest. Clearly, this rate will differ from one rock type to another. In the absence of information on critical velocity, the lowest possible rate should be used. After the simulation part of the test, return permeability is measured and provided that this measurement is made at equivalent rate or pressure to the base permeability then the data is comparable. If fines migration has occurred during drawdown or any other part of the simulation then this is a real effect and the result is valid.

Corrosion Free Hastelloy Equipment

In order to properly evaluate potential Formation Damage, it is important to incorporate all reservoirs and introduced fluids. It is essential to eliminate artifacts such as corrosion from the test as this may lead to erroneous results, conclusions and recommendations. Traditional stainless steel testing apparatus will corrode in the presence of reservoir fluids, not to mention aggressive clean up or stimulation fluids at reservoir conditions. Equipment which is contacted by fluids at reservoir conditions should be composed entirely of corrosion resistant materials such as Hastelloy and Teflon. This eliminates any possibility of corrosion interfering with the test results.

Completion Type Planned or Options

If the completion strategy has been selected prior to the core flood tests, the design of the core flood tests must include consideration of the completion. Alternatively, core flood tests can be used to help select the optimum completion design, hardware and fluids. Normally, two sets of tests are conducted for drilling/completion operations. The first is used to screen drilling fluid options regardless of the completion fluids and hardware and the second is used to test the entire sequence from drilling through completion to production or injection.

Drilling Fluid Options

Laboratory core flood tests are often used by operating companies to help with the selection of drilling and completion fluids and hardware service providers. It is important to test any options available and to compare like with like. Fluids provided by different vendors should be designed for field use (not just laboratory test fluids) and should meet any operational requirements such as rheology, cost *etc.* Fluid properties should be fully understood in order to avoid anomalous results which can be obtained due to poor handling and preparation procedures [3].

Completion Hardware

In wells where completion hardware is deployed, this hardware must also be considered in laboratory tests. The well must be produced or injected through the composite of reservoir rock, residual mud and completion hardware in to the open well annulus. This composite must be reflected in at least some of the laboratory testing. A drilling mud may exhibit good clean-up properties when fluid alone is considered, however following gravel packing for example, the same mud or mud body may cause significant impairment and damage. The tests conducted in the laboratory must include the option to insert the completion hardware at the appropriate time in the well operations sequence.

Clean-up Options

Some tests may be conducted on the drilling fluids alone or on completion fluids alone, however, any clean-up options should be incorporated into at least some of the testing. The data presented in Table 1 is extracted from a technical paper on the Neptune development and illustrates this point clearly. Without clean-up fluids, the drilling and completion options generated significant damage. Laboratory testing showed that with appropriate clean-up fluids this damage could be significantly reduced. Test 1 shows a reduction of over 99% in permeability when no clean-up was employed. Test 2 shows a decrease of 35.6% in permeability at an equivalent point in the test when full clean-up was designed and implemented.

It is important that the clean-up fluids, and indeed any other fluid sequences, reflect real operations. Two distinct cases exist. The first is a sequence clean-up where clean-up fluids follow immediately any other introduced wellbore fluids (drilling, completion fluids). The well is then produced or injected. The second case is a remedial clean-up where the well is produced (or injected) prior to clean-up fluids application.

Although the fluids may be similar for the two different operation, the results in the field and the laboratory can be different. It is therefore essential to reflect the real operational sequence of events in the laboratory tests.

Table 1. Impact of clean-up on return permeability testing.

TEST	Fluids applied	Gravel pack1	Change in permeability after fluid application and drawdown	Change in permeability after gravel pack and mud removed	Change in permeability after spin down in ultracentrifuge
1	Base mud only	16.30	.998%	-99.3%	66.1%
2	Base Mud brine, Enzyme treatment acid treatment	16.30	356%	103%	294%

Likely Exposure Time of Formation to Any Introduced Fluids

Many field developments plans are optimized by batch drilling or batch completion of wells prior to production or injection. This process often includes long term exposure of the reservoir to introduced fluids at overbalance or balance. Introduced fluids may degrade or alter with time at reservoir conditions of temperature and pressure. Chemical or biological alteration of fluids and any changes in reservoir damage or sensitivity should be examined with long term exposure tests. Tests of increasing duration are conducted to reflect long term exposure and establish any trends in formation damage with time. Typically tests of 7, 14 and 28 days are conducted. The proposed suspension fluid or fluids should be tested.

Fluid Application

All introduced fluids such as drilling fluids and completion fluids should be applied to the wellbore face of the sample by flowing across the face at appropriate overbalance or under balance pressure and at an appropriate rate.

Drawdown

It is generally agreed that one of the key parameters in well performance and in laboratory return permeability is the progression of the well onto production (or injection). In the laboratory, two distinct methods which aim to simulate this process have been developed[5]. These are rate controlled and pressure controlled drawdown. The debate within the industry over which is the best to use will no doubt continue, we believe the answer lies in the degree to which an attempt to simulate real wellbore conditions is being made. If the testing limits its ambition to comparing the behaviour of different fluids or procedures in a laboratory test then rate controlled drawdown is acceptable. If however, we are a little bit more ambitious and are attempting to simulate real well conditions and the initial productivity or injectivity of a well, then pressure control seems to be the better method.

Rate Controlled Drawdown

After the fluid application in a coreflood test, return permeability must be measured. In order to measure a permeability comparable to the base permeability, the sample is flooded with oil, water or gas at a constant rate and pressure build-up is measured. Eventually, stable pressure is recorded, the test has reached it's end point and permeability is measured. Some authors have attributed various classifications to the pressure profiles generated and have described mud-off, lift-off and other data generated[6]. Some tests attempt to apply a rate or flux which is equivalent to real rates anticipated per unit area of wellbore. This method fails scientific scrutiny in a number of ways.

It is undeniable that a mud, mud cake or mud body which lifted or popped off the formation in large chunks would satisfy many of our well clean-up requirements. In fact, the pressure build-up and drop often described as lift-off or pop-off has many other sources including relative permeability, pump back pressure and release of filtrate. It is rare for a mud cake or mud body to lift or pop off in a laboratory test, or more importantly, in a real well.

The differential pressure profile measured across the core in flood tests by rate controlled drawdown is strongly rate dependent. A high rate will tend to produce an immediate pressure spike and then a surge as fluids break through. This process can cause rates and pressures which exceed those ever likely in the well. At a lower rate, pumped fluid will tend to percolate through the sample/mud body and without rate increase, it is unlikely that a representative saturation profile will be achieved.

When the rate is calculated for a well, it is impossible to predict the rate for each lithology. The rate will be controlled by damage which is, after all what we are trying to predict with the test!

Pressure Controlled Drawdown

In real well, the well is produced or injected by changing the well bore pressure and allowing flow to occur. This is precisely what the pressure controlled drawdown or injection test achieves. A pressure or range of pressures are selected to reflect real drawdown pressures in the well. The formation end of the sample is maintained with a large reservoir of fluid supplied at reservoir pore pressure. By dropping the pressure in the wellbore annulus of the core holder set-up, flow can be initiated through the sample if the rock and the damage allow. Normally, the rate of flow increases with time until a plateau is reached, at which point permeability to production phase can be measured. The method is much more representative of well bore clean-up than the rate controlled method described above. It is the permeability of the rock and the extent of damage that determines flow-rate or production rate. One area of ambiguity however, is the selection of drawdown pressure or pressures. The maximum drawdown pressure once the well production will be dissipated for a great depth in to the reservoir. The length of any core plug is limited, often to about 5 cm. Once the well is flowing, only a small proportion of the drawdown pressure will be lost in the near wellbore unless there is a region of damage. At the onset of production, the majority of the pressure is likely to be taken by the very near well bore. Slowly, as the well begins to flow, the actual pressure in the near well bore area will decrease and the rate will increase. To reflect the initial period, it seems sensible to select a pressure close to the full initial drawdown to represent the pressure drop which helps to initiate flow and clean-up damage. This will give "best case" for clean-up and "worst case" for rate sensitive effects such as fines migration. Maximum drawdown pressure must never be exceeded.

INTERPRETATION

Some of the laboratory analytical procedures which can be undertaken in order to determine which mechanisms have taken place during core flood testing and their relative contribution to damage is as follows:

Pre and Post - Test Sample Evaluation

Each core plug sample at the end of the flood test is fractured lengthways into two halves, one of which is immediately cryogenically frozen under liquid nitrogen and the other half cleaned and dried by non-damaging techniques.

Untreated SEM/EDS Analysis

The trim of the core plug sample is cleaned and dried by non-damaging techniques to represent the initial state of the rock prior to the flood test, *i.e.* untreated SEM/EDS samples. This is used to determine the natural cements and clay mineralogy before analysis for comparison purposes with final dry treated samples. An example of untreated SEM analysis is presented in Figure 4.

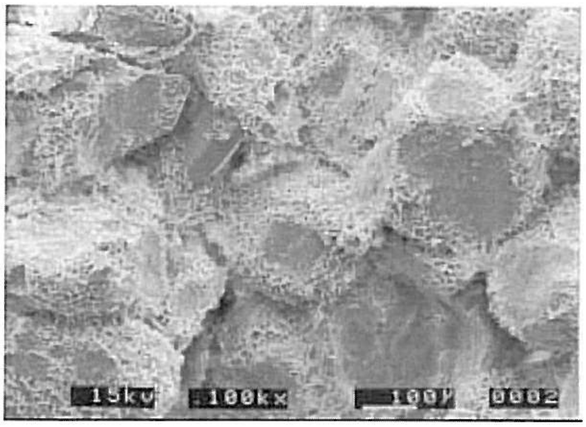

Fig. 4. Untreated SEM. The photograph shows a sample before formation damage testing. The rock grains, cements, clays and pore system can be seen and compared with the "treated' or after test samples.

Untreated Cryogenic SEM Analysis

Another off cut sample, prepared to the same initial fluid saturation profile as the respective plug, before the flood test is cryogenically frozen in liquid nitrogen and prepared and run on a cryogenic SEM. Cryogenic SEM analyses can determine the original oil/gas/formation water fluid distributions and morphologies for comparison with final treated cryogenic samples.

Untreated Thin Section Analysis

Thin section analysis of an untreated core plug trim to determine by point count analysis the mineral percentages present prior to any flood test analysis being performed.

Treated SEM Analysis

The cleaned and dried half of the core plug after the flood test is further split into wellbore and formation plug fragments. These two fragments are prepared such that the fractured surfaces are orientated perpendicular to the plug end faces. The wellbore end plug fragment can be used to check for the depth of Drilling Mud Solids invasion (see Figure 5) and together with the formation end plug fragment can be used to identify any possible fines migration and/or scale precipitates.

Treated Cryogenic SEM Analysis

The cryogenically frozen half of the core plug after the flood test is further split into wellbore and

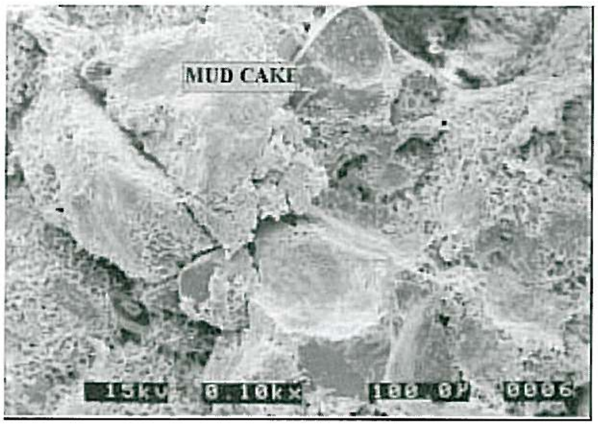

Fig. 5. Treated SEM. When comparing with the untreated sample shown in figure 4, damage mechanisms can be seen. This example shows drilling mud solids on the well bore end face towards the centre of the view.

formation plug fragments. These two fragments are prepared such that the fractured surfaces analysed are orientated perpendicular to the plug end faces. The wellbore end plug fragment can be used to check for the depth of Drilling Mud Solids/filtrate invasion and together with the formation end plug fragment is used to identify any possible soluble salt precipitation, micro-emulsion formation, fluid retention (see Figure 6) and any other immiscible fluid features.

Treated Thin Section Analysis

A longitudinal slice through the core plug sample is prepared for thin section analysis. This allows major scale precipitates, drilling mud solids invasion (see Figure 7) and fines migration to be observed. Dissolution of natural cements can also be observed.

POTENTIAL FOR USE OF LABORATORY TESTING

Most formation damage laboratory data is used for comparative purposes — Mud A versus Mud B *etc.* however, the majority of tests do attempt to reflect real well bore conditions and it should be possible to

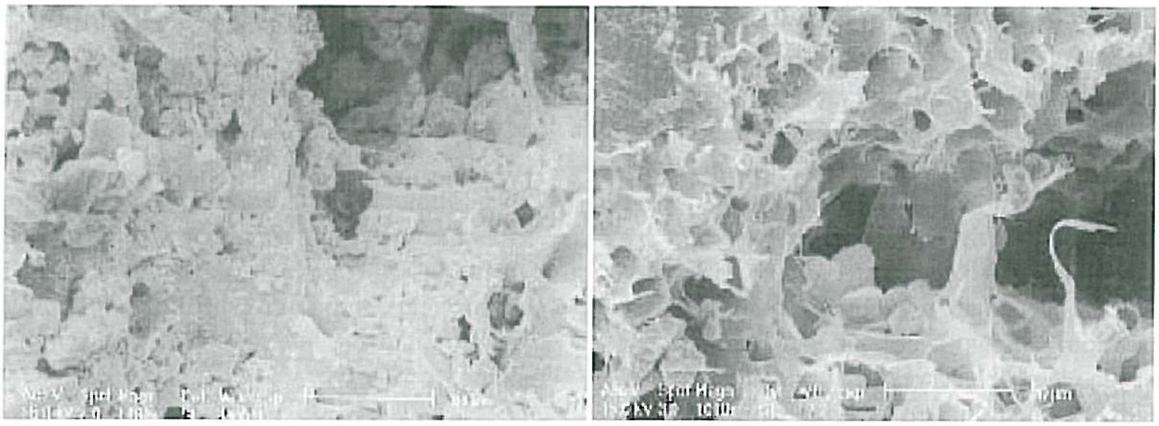

Fig. 6. Treated Cryogenic SEM. The two photographs show different levels of filtrate retention within the sample. On the left is the wellbore end / where filtrate has been retained during a core flood test, lining pores and reducing permeability. On the right the / formation end of the sample appears free of filtrate and no retention is visible.

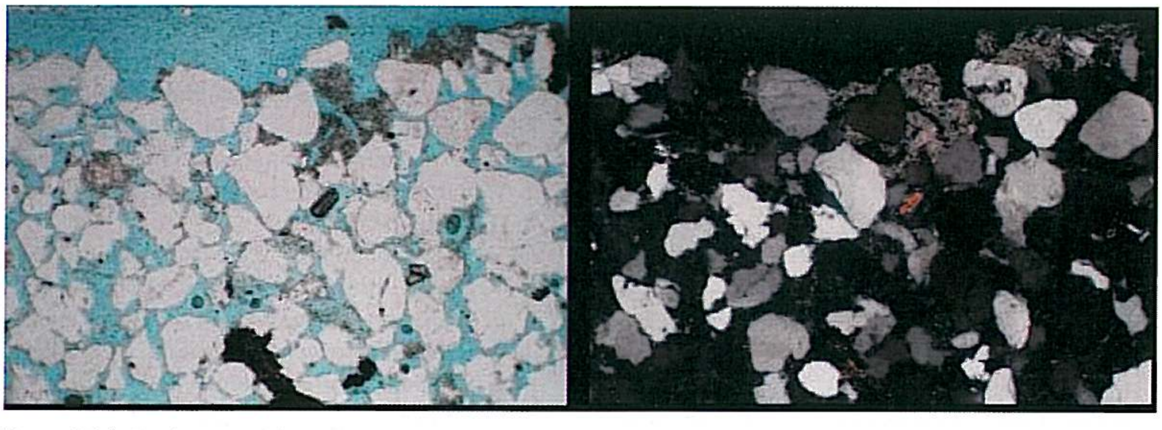

Fig. 7. Treated Thin Section. Two views of the sample sample region. The plane polarized light view on the left shows mud solids or remnant mud filter cake occluding pores at the well bore end face of the sample (towards the top right of view). A cross polarized light view on the right shows the distinctive birefringence of the calcium carbonate mud solids.

use the data to predict well performance. In theory, if all points in the well are represented and the quantity, depth and mechanisms of damage are understood, then accurate well performance prediction can be made. To achieve this objective would require analysis of test design and selection of tests to truly represent the entire wellbore. For long horizontal wells, consideration would need to be given to pressure variations along the length of the well. Overbalance will be higher and drawdown pressure higher at the heel compared to the toe. Points around the radial axis of the well should also be considered, Mud body buildup, clean-up and sand control can be different at different points in the wellbore. This variability is illustrated in Figure 8 and should be considered when laboratory tests to predict inflow performance are being designed.

Most testing is geared towards future developments of wells. Proper formation damage testing can also be used to study wells which have been drilled, completed, produced or injected. From a detailed laboratory analysis, damage mechanisms can be identified and quantified. This enables lessons to be learned and remedial treatments to be developed. In addition, old exploration well test results can be calibrated for damage based on laboratory tests and more accurate development planning can result. Many oil companies have realised that the best way to increase hydrocarbon reserves is not by exploration of new or untested acreage but by reassessment of current producing fields. Evaluation of Formation Damage problems can immediately increase recoverable reserves today and in the future, and quality testing designed to recreate the reservoir in the laboratory is a low cost solution to maximise production.

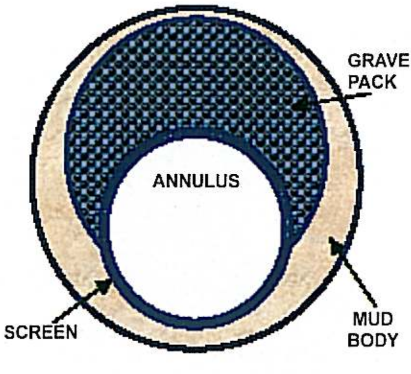

Fig. 8. Horizontal well bore schematic. Schematic diagram illustrating thicker mud body at base of horizontal. Screen sits towards the base of well and gravel fills void space. The diagram illustrates the difficulty in simulating the entire well circumference with a single linear core flood test.

CONCLUSIONS

Formation Damage laboratory tests, though simple in principle and design, are highly sensitive to the techniques and procedures employed. Careful attention to sample selection, preparation and test execution are required in order to generate data which is representative of real formation damage or stimulation mechanisms.

Through implementation of the procedures outlined in this paper, it is possible to simulate most formation damage mechanisms at reservoir conditions of temperature and pressure. Alternative procedures may be viable but those presented here give the least opportunity for anomalous results. Poor testing procedures or compromise for reasons of cost or time can lead to decisions based on incorrect results. Some of the choices and decisions made based on laboratory testing can have a significant impact on well productivity.

It is, therefore, worth the extra effort to undertake accurate tests rather than relying on tests which do not adequately simulate damage mechanisms.

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