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Emerging Technologies in Subsurface Monitoring of Petroleum Reservoirs

- a keynote lecture -

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تقنيات مستقبلية للمراقبة التحتسطحية للمكامن النفطية

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إن أغلب الحقول النفطية لا تنتج أكثر من 45% من مخزونها الكلي حتى بعد إجراء عمليات الاسترداد الإضافي. كما أن أغلب الزيت غير المنتج يعتبر مفقوداً وذلك لأن التقنيات المستخدمة لاستخراج الزيت أثناء الإنتاج تهمل كميات كبيرة من المخزون الأصلي. وإن إسترداد هذا الزيت المفقود سيؤدي إلى مردود إقتصادي هام حيث أن البنية التحتية اللازمة لاسترداد الزيت الإضافي موجودة أصلاً بالمكان ولم يبقى إلا كلفة الإنتاج التي سوف تكون بسيطة.

لقد تم في هذه الورقة مراجعة جميع التقننيات المتوفرة للمراقبة بما في ذلك استخدام المجسات السيزمية ذات الأربع أبعاد والمجسات داخل البئر بالإضافة إلى مراجعة شاملة لجميع التقنيات المستقبلية للمراقبة التحتسطحية. تتضمن هذه التقنيات تطبيق الموجات السيزمية والرسم الطيفي للمقاومة الكهربائية وصور الموجات الصوتية وفوق الصوتية والكهرومغناطيسية والألياف البصرية بآبار متعددة، بالإضافة إلى الليزرية/فوق الحمراء وذلك للنظر في المنطقة القريبة من جدار البئر.

Abstract: *Most oil fields do not produce more than 45% of the oil-in-place, even after enhanced oil recovery schemes have been applied. Most of this unproduced oil is missing because most displacement techniques by-pass significant portion of the original reserve. Finding this missing oil can lead to significant economic windfalls because the infrastructure for additional oil recovery is already in place and the cost of production is likely to be minimal. In this paper, all existing monitoring techniques, including 4D seismic and downhole seismic sensors, are reviewed. This is followed by a comprehensive review of emerging technologies in subsurface monitoring. These techniques include multi-well seismic, electrical resistivity tomography, electromagnetic and ultrasonic imaging, acoustic and fibre-optic imaging, as well as laser/infrared or MRI/NMR visualization near the wellbore region.*

INTRODUCTION

A detailed analysis indicates that for an accurate reservoir engineering analysis, geostatistical models should have information of 1m scale. This is the only scale that would satisfy the representative elemental volume (REV) requirement of an enhanced oil recovery (EOR) system. This scale length is orders of magnitude higher than that of core samples and at least an order of magnitude lower than the conventional seismic data. This data gap constitutes the weakest link between geophysical information and

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reservoir engineering. Any attempt to reconstitute the reservoir without information regarding petrophysical properties and fluid saturations in the 1m level, one would risk falling into the trap of multiple solutions – a typical problem of history matching through reservoir simulation. To obtain a resolution of 1m scale, one must investigate the possibility of using 50-2000 Hz seismic frequency range. While this seismic range cannot be used with vertical seismic profiles (VSP) because of the travelling distance constraints, multi-well imaging can be used with multi-component receivers. This system, in combination with borehole seismic sources, can provide one with the desired resolution. The same system can be used in combination with resistivity tomography, a method that has recently given satisfactory results for tracking ground-water contamination. The images can be further refined with acoustic and fibre-optic imaging techniques. These techniques can provide satisfactory details to track viscous fingering, wormholes, and other time-dependent properties of an active reservoir. Finally, infrared/laser or MRI/NMR imaging of a wellbore is still in its nascent state of development, but holds great promises for the future applications of real-time monitoring and eventual dynamic reservoir management.

4-D SEISMIC

The fourth dimension is time. This time is measured in months and years for any reservoir application. This is in contrast with measurements in millisecond as commonly used in seismology. Typically, new survey results are compared with original and previous survey results, in order to monitor changes in fluid content or even rock characteristics.

Reservoir Characterization

Improving reservoir performance and enhancing hydrocarbon recovery while reducing environmental impact are critical to the survival of the petroleum industry[1]. Proper reservoir characterization has been directly linked with growing reserve[2]. In order to achieve these objectives, one must start with characterization of reservoir parameters[3], including fluid properties and their changes with time[4-6]. This constitutes the essence of dynamic reservoir characterization. Recently, there has been a surge of three-dimensional (3D), three-component (3C) seismic survey activities[7]. Past experiences have shown that the time-lapse survey is necessary only when the reservoir is under some enhanced oil recovery scheme. Only recently, it has been recognized that time-lapse 3D can also be a reservoir characterization tool. If base-line data are already available, introducing time as the fourth dimension, new time-lapse (4D), 3C seismology can become an effective tool for monitoring production processes and to determine reservoir property variation under changing conditions[8]. The introduction of 4D seismic is equivalent to adding many new points to the production history (when one makes an analogy to the history matching process). Using 4D, 3C seismic monitoring as an integral part of dynamic reservoir characterization, refinements can be made to production processes to improve hydrocarbon recovery. Refinements made to reservoir characterization techniques and their applications, dynamically with 4D seismic, are important new areas of research. Benefits of this method include better reservoir characterization, increased hydrocarbon recovery and lower operating costs due to improved reservoir management[9]. Recently, guided seismic waves have been introduced as a tool for continuity logging – to be used by geologists[10]. This, in turn, can help predict the continuity of shale markers between gas wells that are significantly apart. This method holds promise for gas reservoirs. In addition, innovative reservoir characterization must be performed in order to predict accurately the reservoir potential as well as to develop the optimal production scheme. In this regard, the use of artificial intelligence and expert system is worth mentioning[11].

Industry Attitude

The fundamental objective of 4D seismic is to monitor changes in a reservoir. It is necessary, therefore, to conduct 3D seismic surveys at a given location many times over the course of months or years. This would enable one to compare surveys to the original or previous surveys. It is easily understood that such an extended effort must come with a price tag – something oil companies might not be willing to pay unless the prospect of payback is clear. In this regard, some of the world's largest oil companies are not yet convinced, especially when they have yet to realize the benefits of conventional 3D seismic. For instance, Saudi Aramco, with its reserve of 260 billion barrels of oil and 500 Sun workstations in its E&P center in Dhahran, still considers 3D seismic as its forte[12]. For the moment, Saudi Aramco is preoccupied with first 3D's in over 25,000 km over a productive area of 20,000 sq. km. This is not to mention that the benefits are less than spectacular. In fact, only in 1994, soon after some of the first series of 3D seismic surveys were finished, 2.9 billion barrels of reserve was added to the existing 250 bbl of Saudi Aramco. Saudi Aramco currently produces 8 million barrels of oil daily and has an ability to increase production to 10 million b/d within 60 days.

Shell has realized the value of 4D seismic. They have invested a great deal in improving the quality of 1st time 3D surveys. This is because, unless the state-of-the-art technique is applied to the original (baseline), it will be difficult to make use of new surveys that continue to see experimental growth in technical advances[13]. This view has been supported by BP Exploration[14] who admitted that many of the differences between old and new 3D surveys were not yet fully understood. Chevron, Amoco, Conoco, and Exxon developed a consortium with support from the US Department of Energy (US DoE) and the Gas Research Institute (GRI) to use seismology at higher frequency bands than the conventional ones. This really opened up the opportunity for using 4D seismic as a monitoring tool. It is true that ambient noise levels are much lower in the downhole than at the surface. For example, cross well surveying from deep in one well to receivers at corresponding depth in a nearby well should yield seismic data with measurable signals at frequencies approaching 1000 Hz. The resolution can be better than 10 ft[15-16].

Sceptics are critical of the fast pace in applying 4D seismic, comparing it to letting loose a novice to a Pandora's box. While the scepticism continues[17], the advancement in the last decade can assure one that the on-line monitoring of reservoirs is not an unrealistic dream[18]. Strenedes[19] reported that the average recovery factor from all the fields in the Norwegian sector has increased from 34-39% over 2-3 years, due to enhanced monitoring. He emphasized that North Sea production being on a decline, the needs for an improved technique is very important.

REMOTE SENSING AND RESERVOIR MONITORING

Reservoir and Tubulars

There is a need to improve the ability to depict phenomena occurring at three levels, namely, reservoir, wellbore, and wellhead. The conventional seismic technology has a resolution of 20 m for the reservoir region. While this resolution is sufficient for exploration purposes, it falls short of providing meaningful results for petroleum field development, for which 1 m resolution is necessary to monitor changes (with 4D seismic) in a reservoir. For the wellbore, a resolution of 1 mm is necessary. This can also help detecting fractures near the wellbore[13]. The current technology does not allow one to depict the wellbore with this resolution, especially when two or three phases are present in the wellbore[20]. A recent research study shows that resolution should be 1 meter in the reservoir, 1 cm near the wellbore, and 1 mm inside the tubulars[21].

Reservoir Permeability and Relationship to In-situ Conditions

Evaluation of sandstone permeability from recovered drill cores is done routinely as part of any hydrocarbon reservoir characterization program. These laboratory measurements usually involve mounting the prepared core specimens in a pressure chamber to enable permeability and acoustic measurements at simulated *in-situ* pressure conditions. However, current industry practice normally involves tests done under simulated overburden or hydrostatic pressures only, and recent works indicate that permeability under constant overburden pressure can vary significantly as lateral stress is varied[22-25]. Such lateral stress variations would be expected as a function of orientation in an anisotropic stress field and in response to production or stimulation procedures. As well, changes in reservoir gas pressure will alter effective overburden and lateral stresses by different relative amounts, a scenario which cannot be simulated using tests at hydrostatic pressures. Therefore, complete characterization of the permeability and acoustic properties of recovered cores as functions of independently applied overburden and lateral pressures is required to estimate:

- Permeability and preferred flow paths in an anisotropic stress field;
- changes in *in-situ* permeability resulting from changes in lateral pressures due to production, stimulation operations, and others;
- changes in *in situ* permeability due to reservoir gas pressure variations;
- remote identification of any of the above reservoir properties from acoustic and seismic data.

Figures 1 and 2 show some of the experimental setup that can be used for collecting above data in a laboratory. Figure 3 shows an example set of data on permeability variation as a function of overburden pressure. Figure 4 shows changes in acoustic response due to overburden pressure changes. These data provide valuable information regarding monitoring of a reservoir that is currently under production.

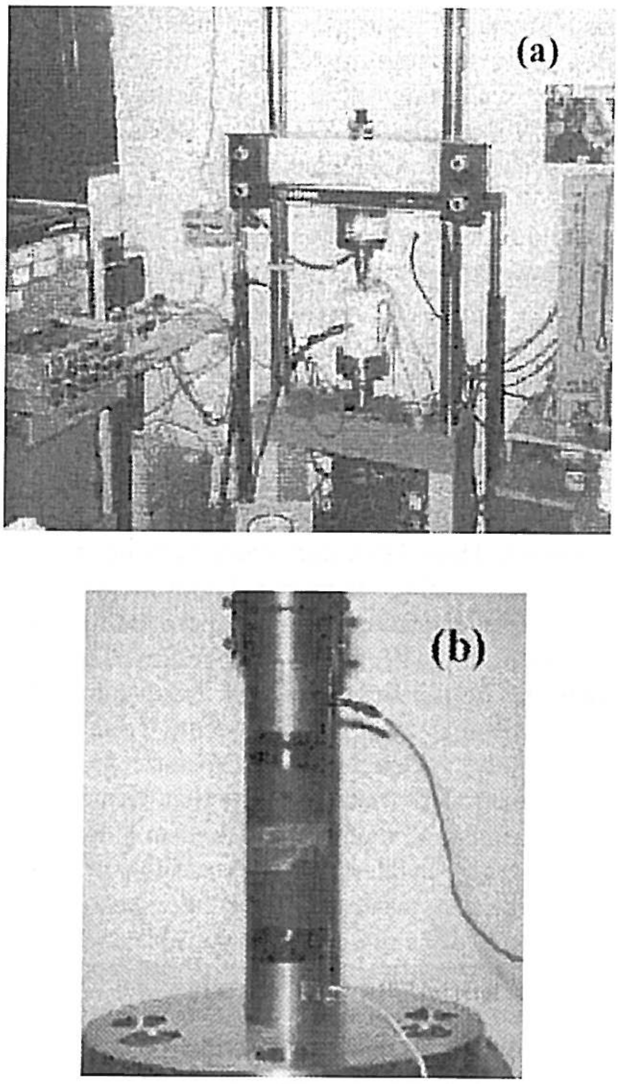

Fig. 1. Photograph of stress flow acoustic (a) and uniaxial (b) test facilities.

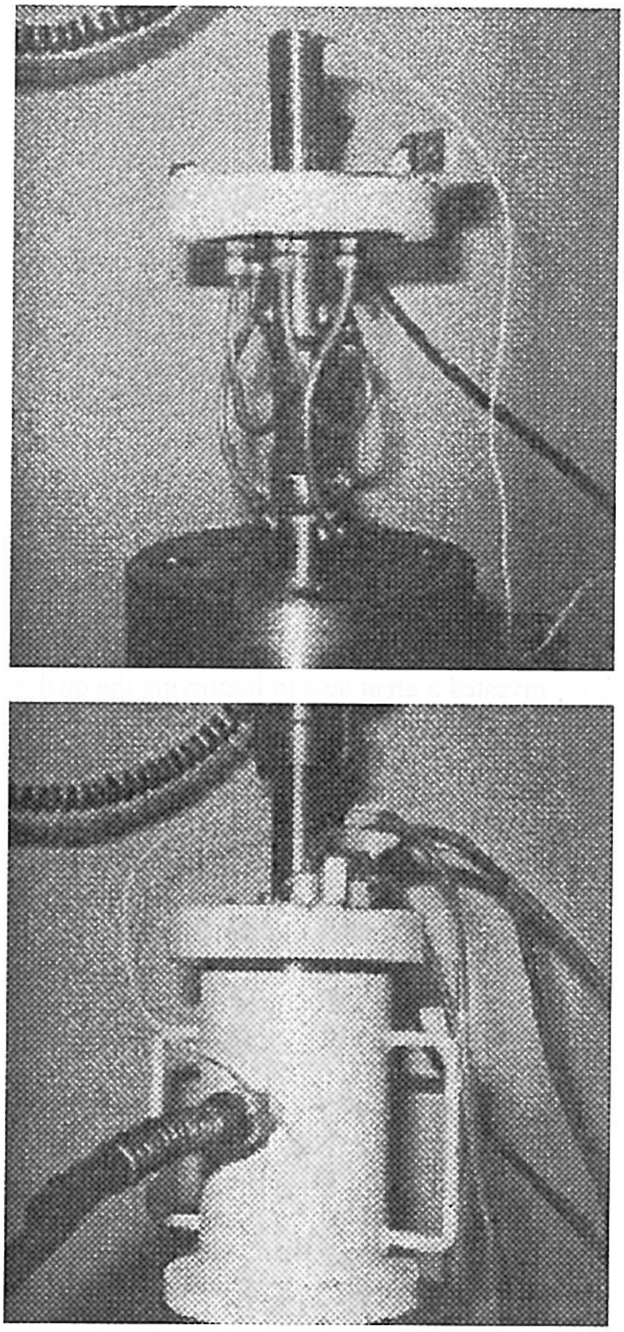

Fig. 2. Photograph of triaxial test facilities.

Infrastructures

In order to remain competitive in today's global economic environment, owners of civil structures

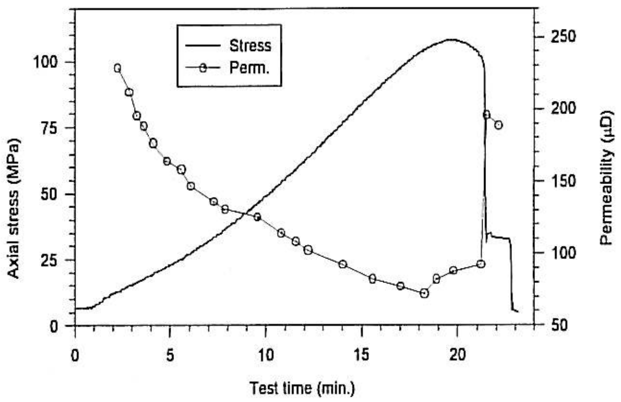

Fig. 3. Permeability variation with overburden pressure (vertical permeability as a function of varying overburden pressure – c.p. = 5 Mpa).

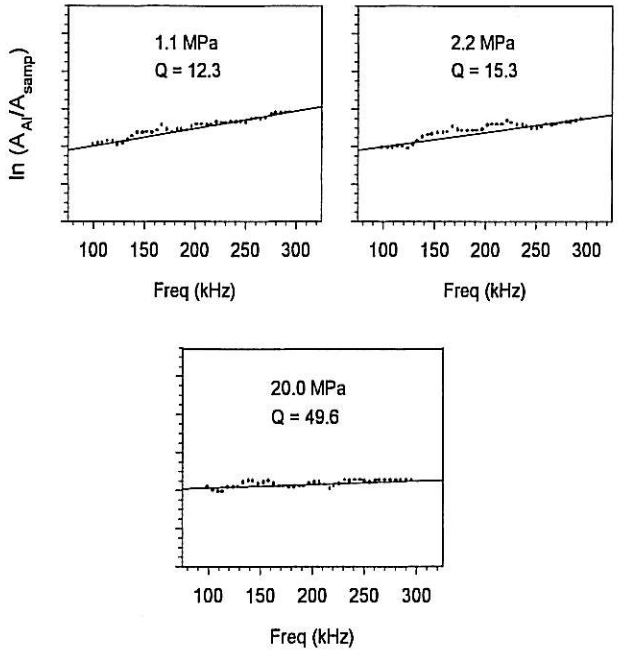

Fig. 4. Acoustic response for various overburden pressures (P-wave attenuation parameter Q as a function of overburden pressure (using spectral ratios method).

such as buildings, bridges, offshore platforms and reservoirs need to minimize the number of days their facilities are out of service owing to maintenance, rehabilitation or even replacement.. That is, they need to maximize the output of their system. Indicators of structural system performance, such as serviceability, reliability and durability are needed for the owner to allocate resources toward repair, replacement or rehabilitation of their structures. To quantify these system performance measures requires a structural monitoring system to monitor and evaluate the integrity of large civil structures while in service[26, 27]. The same applies to petroleum structures. Offshore structures are of particular significance in this regard for both structural monitoring and stress corrosion measurements.

FUTURE RESEARCH ACTIVITIES

Reservoir Characterization

The following steps should be taken in a 4D seismic research. 1) repeated acquisition of 3D, 3C seismic survey. Initial works have been done by Mari and Wicquart[28], who used acoustic log data obtained by dipole source imaging tool. 2) demonstrate the correlation between 4D, 3C seismology and rock/fluid property change associated with a production process. Past permeability-porosity correlations in this regard have used core data[29]. This offers a major drawback. Scaling criteria for upscaling core data to reservoir scale (resolution of meter) should be developed, using artificial intelligence. Initial efforts have made in this regard for upscaling well log data[30]; 3) incorporate geological, petrophysical, reservoir engineering, and other geophysical studies. Cross-well seismic should also be included. This can improve the resolution of reservoir petrophysical data [26-31]; 4) refine the reservoir models and recommend procedure for scaling; 5) link bulk rock/ fluid property variation monitored by 4D, 3C seismic surveying to permeability, fluid saturations, flow characterization, and other dynamic attributes. The ratios of the P (pressure) and S (shear) velocities, Vp/Vs for both the fast and slow shear components can provide a tool for separating bulk rock changes due to fluid property variations from bulk rock changes due to effective stress variation. Also, changes in shear wave anisotropy may reflect varying concentrations of open fractures and low aspect ratio pore structures in both spatial and temporal sense across the reservoir. The permeability of a formation, or the connectivity of the pore space, will be the target for the 4D,3C seismology. This should be done in the following sequence: 1) Develop a technique that will be able to generate real time data that are compatible with the computer data acquisition system. Geological data should be used in reservoir characterization using factorial krigging analysis (FKA). This technique was first introduced by Matheron in 1982 and was successfully applied in integrating reservoir data with geophysical data[32]; 2) Develop mathematical models, suitable for characterizing fractured and geologically complex reservoirs, using the theory of chaos, fractals, and solitons. An effective way of handling heterogeneity is to use multifractal statistics with some success[33]. 3) Couple these models with a compositional, integrated (with geomechanics and flexible wellbore model) simulator; 4) Develop an expert system for geological, geophysical, and reservoir engineering characterization. This integration of conventional reservoir engineering analysis with real-time monitoring, environmental impact and economic constraints has not been conducted in the past[10]. Even though expert systems (ES) and artificial intelligence (AI) did not live up to the expectations once touted a decade ago, they still offer an excellent tool for reservoir characterization[11,34-36]. The above reservoir characterization should be backed by fundamental studies of gas and gas condensate flow in porous media. Studies in this regard are still in their nascent state[37]. Several aspects of these need to be addressed with fresh approach. Conventional approach lacks depth in science and understanding of the fundamental. For the reservoir, new flow equations need to be developed for the following cases: 1) thermodynamics of gas condensates coupled with models capable of mimicking phenomena, such as condensate blockage; 2) geomechanics of fractured formations under thermal as well as mechanical stress; and 3) solid deposits (e.g. wax, asphaltene, hydrate) during gas production and its impact on wellbore blockage. Each of these factors can affect gas (or gas condensate) production significantly and should be predicted accurately in order to mitigate problems and optimize production strategies. However, to-date, coupled thermodynamic/ reservoir models have not been developed.

Effect of Dimensionality

Recent investigations have shown that dimensionality plays a role in modelling of complex rock/fluid interactions[38] or even during water flooding[39]. Figure 5 shows a schematic of the effect of dimensionality within a 3D system. It is conceivable that within a 3D system, dependence on grid size would be evident. Figure 6 shows how the grid size for 3-D cases would affect the prediction of oil recovery. Because no exact solution is available for multiphase flow, it is impossible at this point to tell which ones are closer to the real solution. Experimental (both laboratory and field) observations are equally difficult to make under controlled and fully known conditions. Note that figure 6 pertains to uniform petrophysical properties. When heterogeneity dominates, the profile of Figure 6 becomes more complicated. It is well known that accurate knowledge of porosity is necessary for predicting fluid capacity of a reservoir. However, far more sensitivity is expected if prediction of a dynamic system with heterogeneity has to be made. Taking a simple case of known heterogeneity (Fig. 7), for which the permeability distribution (either shale streaks or higher-permeability zones) is known, one can show that the recovery prediction will be extremely sensitive to the grid size. For even this simple case, physical phenomena (related to Representative Elemental Volume, REV) overshadow the numerical problems, as shown in figure 8. Of course, one desires to operate in the stable region for which both physics and the numerical method are captured properly. This region is likely to be 1-10 m in the reservoir region, 1-10 cm in the near wellbore region, and 1mm-

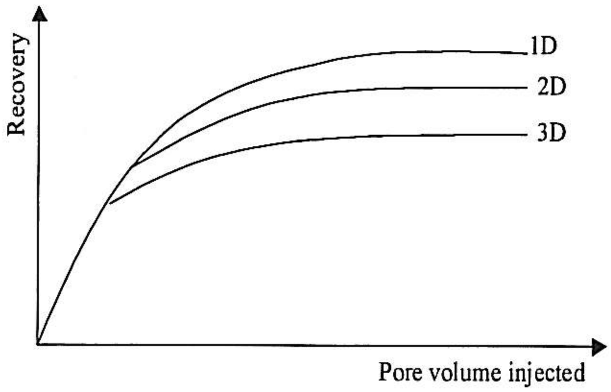

Fig. 5. Typical effect of dimensionality on predictions of recovery performance.

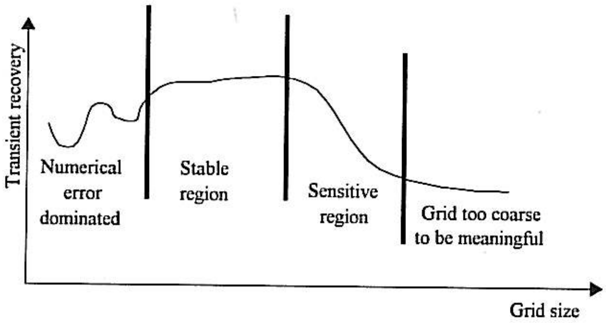

Fig. 6. Transient recovery (e.g. breakthrough recovery) for various grid sizes.

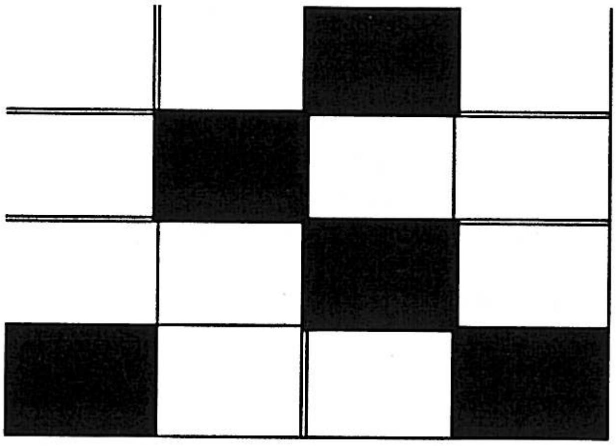

Fig. 7. A simple heterogeneity model.

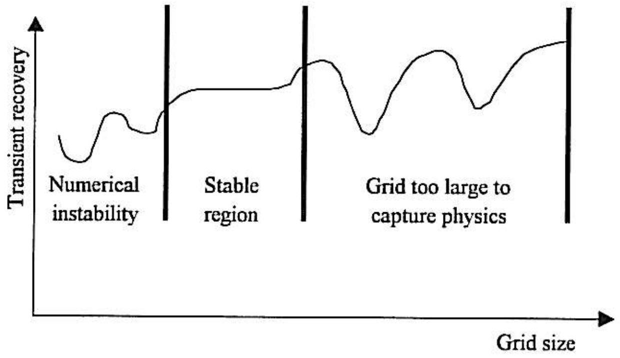

Fig. 8. Effect of grid size for heterogeneous formations.

1cm in the wellbore region, the latter two being significant only for reservoir simulators that are capable of modelling wellbore phenomena. A finer grid block would only increase numerical error, unless special techniques were used. For modelling viscous fingering in the reservoir, much smaller grid blocks are needed[40]. These sizes are so small that using such a grid distribution in the entire reservoir is unrealistic and calls for using dynamic refinement of the grid based on the location of the displacement front. Even though such an approach has been proposed in modeling in situ combustion, such method for modeling non-isothermal techniques has not been tested yet.

Another important factor is the fact that for refined grid blocks, petrophysical data are almost invariably absent for each block, owing to limitations in the data acquisition system. This problem is illustrated in figure 9. The upper part of this figure shows the number of faults resolvable per unit volume against the size of the fault that can be seen in meters. This figure clearly shows that a data gap of several orders of magnitude exists between the information provided by well logs or cores and information acquired through 3D seismic. With the currently available technique, the resolution of the data is limited by the highest frequency signal returning from the target that can be seen above the noise level. For a target depth of 2 or 3 km, the highest frequency is in the range of 50Hz which can yield a resolution of barely 20 m. If 1 m resolution in the reservoir is necessary, the current methods cannot provide one with this information. This problem is addressed by geostatistical methods that are used to generate required properties for each block of whatever size. Seismic data are downscaled while petrophysical data are upscaled. Seismic attributes analysis has been developed to obtain petrophysical parameters between wells. This method has some flaws. For instance, petrophysical properties (measured at cm scale) on a core are measured on the same core samples but with 1MHz frequency – 4 orders of magnitude higher than the one used in seismic surveys.

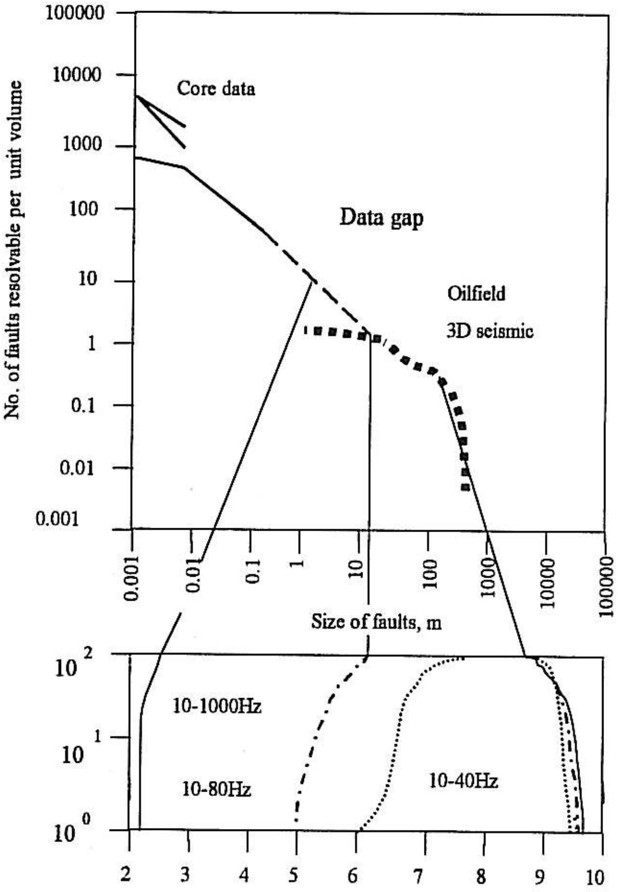

Fig. 9. Data gap in geophysical data acquisition

Seismic properties being frequency dependent, problems arise. The other problem is that the relationships, as derived in the laboratory, are assumed to be valid for seismic data, in which the smallest resolvable volume is six to nine orders of magnitude greater than the core samples. This latter aspect needs further investigation, as publications on the topic are rare.

Development of Technologies for In-situ Reservoir Monitoring

Current practice for monitoring reservoir performance is generally limited to pressure measurements and sampling at or near the well-head. Such well-head monitoring is limited because it provides little information regarding downhole conditions and for complex well systems (such as encountered routinely in off-shore fields) it is difficult to determine the relative production contribution from each well segment or production horizon. Further, when production problems are encountered, very little information regarding the location or nature of the difficulty is available, making remedial action difficult to plan and implement. To date, in situ monitoring has concentrated on high frequency seismic sensors to facilitate high resolution cross-well tomography and to monitor acoustic emissions from hydrofracturing and related enhancement procedures[41], but recent work has expanded to include high resolution imaging near the well bore using acoustic logging, ground probing radar, NMR, and even more traditional geophysical methods (*e.g.* electrical resistivity) calibrated for fine discrimination. However, limited battery lives, difficulties in maintaining communication/power cables, and harsh operating conditions often result in short operational lives of this instrumentation, and there is a need to expand the scope of downhole measurements to include fluid temperature/pressure, chemical analysis, flow rate, etc. to better characterize in situ conditions.

Some measure of remote monitoring is provided by time-lapse seismics (Ref. 42), which uses laboratory data correlating reservoir conditions and seismic properties to identify characteristic changes in rock/fluid properties over time, but even this type of work would benefit from in situ data for the purposes of applying corrections and calibrating seismic results against measured reservoir conditions. However, under current practice (despite the clear benefits of expanded in situ monitoring operations as discussed above), most reservoir characterization and diagnosis of production problems must be done using production interrupting (and therefore very expensive) down-hole logging operations.

Improvement in Remote Sensing Ability

The current technology does not allow one to depict the reservoir, the wellbore, or the tubulars with acceptable resolution[32,43]. New techniques, which have seen applications in space research, can be used to develop more accurate techniques for mapping wellbores[44,45]. This technique, if successful, will become the most environmentally benign technique of all logging methods. The remote sensing research should also develop technologies for transmitting both downhole and wellhead data (chemical analysis of oil, gas, water, and solid) for real-time access from any desired location. Finally, methods should be developed to remotely conduct real-time control of various operations, in all locations, such as, the wellbore, production string, and pipelines. Recently, the use of NMR has been gaining popularity[46]. In this regard, service companies (e.g. Baker Atlas, Shlumberger are quite active in research). The objective in this regard is to develop an effective technique for improving resolution of wellbore imaging. In the next phase of this task, resolutions in the reservoir should be increased by using cross-well tomography[32,47]. In order to improve resolution within a wellbore, acoustic response should be analyzed. Such method has been attempted in the past in the context of wellbore mapping using sonic logs[28]. However, the possibility of using the technique to determine multiphase flow within the wellbore needs to be investigated. In addition, fibre-optic detection of multiphase flow should be investigated[21].

Recently, resistivity tomography has been proposed by Lawrence Livermore National Laboratories for developed improved images of the subsurface. The technique is based on the automated measurement and computerized analysis of electrical resistivity changes caused by natural or man-made processes. The inversion of the raw data is accomplished using a finite-element scheme. The technique can be coupled with the

4D seismic technology to develop finer resolution for subsurface mapping.

Instrumental Research

Video Logging

Recently, strides have been made in downhole cameras that can now operate in temperatures as high as 300°F and pressures up to 10,000 psi. It has an integral light ring to illuminate the wellbore and can perform in wellbores from 4 to 20 inches in diameter at depths up to 20,000 ft[48]. Currently, advances have been made in fiber optical transmission as an alternative to coaxial cable transmission. Fiber optics allow a superior quality of video transmission from downhole, irrespective of the length of the wellbore. Besides, a 7/32 inch diameter is far more flexible than a coaxial cable. Difficulties are encountered owing to imperfect transmission at high temperature and irreversible damage in a severed cable.

Videologging should not be considered as a replacement logging tool. It should be used to augment conventional electric logging. For instance, caliper and corrosion log results can be visually verified through a video log to plan a remedial operation.

Acoustic Logging

Medlin and Schmitt[49] reported acoustic logging based on wellbore resonance. This relatively new modification of conventional acoustic log uses stimulated Model Acoustic Long (SMAL) that relies on driving an acoustic transmitter at a selected frequency that corresponds to wellbore resonance, which is demonstrated by means of excitation logs. Remarkable signal enhancement was reported using the SMAL method. Recently, there has been a surge in using ultrasonic for wellbore logging. This medical technology (Ultrasonic Doppler) appears to provide one with a visualization tool for both dynamic[50] and static[51] systems. For the dynamic system, an ultrasonic signal emitted from a transmitter is reflected by scatters in the path of the beam. The velocity difference between the scattered and the transmitted signals results in a frequency shift (Doppler shift) of the returned signal. This frequency shift is proportional to the scatterers' velocity. For downhole applications, ultrasound is scattered at phase boundaries, such as oil/water droplets, gas bubbles, sand grains, fines or fluid turbulence. Although theoretically there is no upper or lower limit for velocity measurements, the measurement range is limited by the mode of signal interpretation scheme, and the geometry of the instrument[52].

Logging in Harsh Conditions

In order to keep up with drilling in increasingly deeper formations, research is being done to increase maximum operating temperatures of downhole well logging tools. Research in this area is focussed on developing special electronic circuits and in using high-performance materials. High-temperature applications specific integrated circuits (HTASIC's) are being developed to replace conventional logging tool electronics. These electronics are ultra compact, often taking as little as 5% of the space conventional circuitry. In terms of new materials, fibre optics are being proposed for transmitting data. Also, diamond and other heat and chemical resistant materials are being investigated for use in harsh environments, such as at high temperatures, H_2S, *etc*[53].

Fibre Optics Sensors

In the past, fibre optic sensors used to be considered only for measuring temperatures. They are now being extended to sense a wide range of additional parameters, such as, pressure, vibration, flow, and acoustic fields. In this, a distributed-temperature sensor is used for temperature profiling, an optically excited resonant-pressure sensor, an interferometric point sensor for pressure monitoring, and Bragg-grating-based sensors for range of parameters. This technology that finds its root in medical (chemical probes) and military (e.g. underwater acoustic arrays), is now being applied in civil-strucutural monitoring, industrial applications sensing (distributed spectroscopy), and security monitoring (intrusion detection). The advantages of this technology in oil and gas sectors are considered to be[54]:

- electrically passive;
- intrinsically safe;
- immune to elecromotive interference;
- operable at high temperatures;

- can be multiplexed or operated in a distributed mode;
- small cross-section and operationally flexible.

The scientific and industrial benefits of this work fall within the general scope of benefits of improved reservoir characterization. More specifically, however, accurate characterization of *in-situ* permeability and its relationship to gas pressure, lateral stresses and acoustic velocity/ attenuation is important knowledge for reservoir engineers and geoscientists regarding many aspects of reservoir analysis. These include, but are not limited to:

- Prediction of reservoir production over time;
- Correlation between drill stem test results and core data;
- Interwell communication/correlation;
- Analysis of shut-in tests and more reliable reserve estimation;
- Planning and implementation of stimulation and enhanced recovery schemes.

The tangible benefits of this research to industry will improve reservoir characterization, more effective use of technical facilities and expertise, and ultimately the potential for extended production from hydrocarbon fields at reduced operating costs.

In addition to the task of calibrating measurements with reservoir conditions, the greatest challenges in developing technologies for *in situ* monitoring are harsh operating conditions (*e.g.* high temperatures, corrosive fluids, *etc.*), instrumentation size limitations, and long-term difficulties maintaining power and signal cables. In light of these challenges, research efforts will concentrate on evaluating:

- Corrosion resistant materials (e.g. high temperature ceramics) for instrument components;
- Long life batteries and/or low power drain electronics;
- Transmitting electric or acoustic signals between in situ sensors and near surface receivers using steel casing and tubing;
- Piezoelectric sensors which generate their own high voltage signals in response to mechanical stimuli;
- Mechanical devices which "ping" the casing at a rate which can be correlated with pressure, flow rate, temperature, *etc...*;
- Techniques for differentiating between signals originating from multiple down-hole sensors;
- Passive acoustic sensors to "listen" for casing leaks, ruptures, and related production problems;
- Improvements to power/signal cables for long-term installation.

The most promising of these research components will be deployed in the field for *in situ* evaluation.

Regarding scientific and industrial benefits, the ability to monitor a reservoir *in situ* is a powerful tool for oil and gas companies and can assist with, among other applications:

- determining production contributions from various regions or well segments within the reservoir;
- facilitating more accurate surface and downhole time-lapse seismic monitoring;
- evaluating and monitoring stimulation and enhancement procedures;
- calibrating reservoir models and facilitating more accurate predictions;
- providing advanced warning of impending production difficulties to enable preventative and remedial action.

Monitoring of Petroleum Structures

Research should be dedicated to developing a structural monitoring system that will integrate, fibre optic sensor system, remote monitoring communication system, intelligent data processing system, damage detection and modal analysis system and non destructive evaluation system[26-27]. A similar system of monitoring devices, which will be capable of detecting signs of stress corrosion cracking should be developed. A fibre optic-based sensor system, and remote monitoring communication system will allow the monitoring not only of the internal operating pressures, but also the residual stress levels, which are suspected for the initiation and growth of near-neutral pH Stress corrosion cracking[55].

Real-Time Control System

The ultimate objective of monitoring is real-time control of an oilfield. This can be achieved if one can integrate reservoir models with vertical and surface network and monitoring systems [56]. Therefore, progress must be made in advancing the technology of remote sensing with data processing and continuous feedback systems. This aspect can benefit greatly from using artificial intelligence. Artificial intelligence should be used for solving both reservoir and production problems and to develop strategies for production optimization as well as smart design of enhanced oil recovery schemes. These analyses are incomplete without a decision support system that minimizes economic risk. A decision support system should be developed by integrating technical constraints with economical constraints as well as environmental impact. A fully integrated system that takes environmental constraints under considerations is yet to be proposed in the petroleum industry. Finally, one needs to develop virtual time travel capability in and out of the reservoir and couple monitoring systems with production control schemes. This will give petroleum engineers the long-desired ability to go for a site visit, the site being the reservoir and inside of various tubulars.

CONCLUSIONS

The need to monitor reservoirs and petroleum production systems is well recognized. Only recently, efforts are being made to integrate monitoring systems with reservoir characterization tools. Despite much scepticism, improved reservoir monitoring systems can increase the proven reserve several times in many instances. In this paper, the research opportunities in petroleum reservoir monitoring are identified.

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