3d). Temperature gelation is not observed. Effect of temperature is same both at high and low γ values such that τ readings decrease with increasing temperature.

The results obtained for filtration test were similar to that obtained for other rheological properties. Sample 1, 2 and 6 had lower filtration volumes than samples 3, 4 and 5 (Table 2). Increase in temperature causes a considerable increase in filtration loss for all drilling fluid samples. On the average, 60% increase in filtration loss was observed when temperature was increased from 40 °C up to 100 °C (being lowest, 52% for sample 2, highest, 69% for sample 3) (Fig. 4). This result is consistent with the previously found results [9].

Filtrate volumes obtained for different pressures showed that it was increased by about 25% with increasing the differential pressure from 100 psi up to 750 psi (Fig. 5). Although the pressure effect is considerable, comparison of the temperature effect with pressure indicates that the main controlling factor on the volume of filtration loss is temperature.

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Rock Mechanics Applications in Petroleum Engineering Practices

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ABSTRACT

Several rock deformation mechanisms are involved in the oil and gas reservoir formations and the overlaying strata. These deformations may occur during drilling, production, fracturing, stimulation, or enhanced recovery (secondary and tertiary). For example, during the drilling phase, wellbore instability may occur due to formation rock failure either in tension or in compression mode. This failure could be due to the application of low or excessive weight of a drilling fluid or due to formation swelling in case of shales. During production, rock mechanics can be used to select the proper perforations locations, optimum fracturing fluid and proppant concentrations and types, magnitude of fluid drawdown, etc. When calculating the hydrocarbon reserve, or applying secondary or tertiary oil recovery methods, rock mechanics principles must be implemented otherwise unusual recommendations will be taken and a huge drop in profits can be the result. Therefore, rock mechanics principles can be used as a tool to properly understand the reservoir-stress relationship and hence to avoid or solve the many problems facing the oil industry. The problems in which rock mechanics can be applied in are outlined and the management methods and data required to solve such problems are presented in this article.

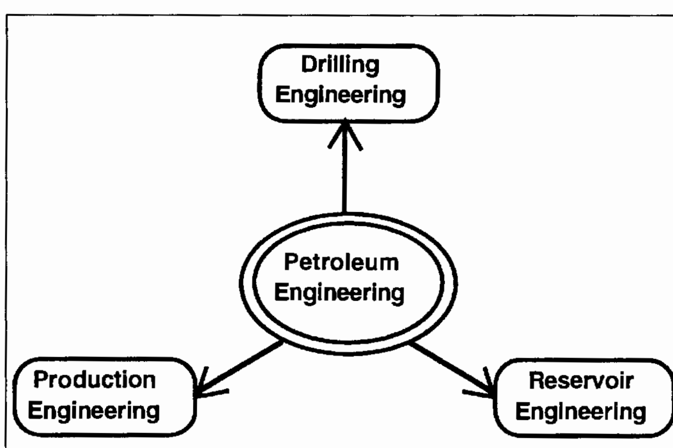

Fig. 1 Main branches of petroleum engineering science

INTRODUCTION

Rock mechanics is the science dealing with the theoretical and applied behaviour of rock due to either external natural or man made stresses [1]. Rock mechanics are widely used by civil as well as mining engineers long time ago. Recently, rock mechanics has been applied to solve problems in many aspects of petroleum engineering such as drilling, reservoir and production engineering [2 – 24]. In the following sections, light will be shed on the involvement of rock mechanics on solving the many problems that may encountered during the various petroleum engineering activities such as drilling, reservoir, and production engineering (Fig. 1).

ASSESSMENT OF ROCK PROPERTIES

Various rock properties are required as an input in any attempt to solve various engineering problems. It is obvious that rock mechanical testing of cores must be designed according to the purpose of the investigation. If the objective is to predict borehole instability, then the testing procedures may not be the same as for example in reservoir compaction. Rock cores preparation and testing procedures have been clearly outlined by the international society of rock mechanics (ISRM). These outlined testing procedures was set to minimize human errors. Rock mechanical data are obtained either by testing representative rock samples in laboratory or by analyzing field records. Triaxial testing of rock samples provides important data such as failure criteria, frictional properties (ap-

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parent cohesion and angle of internal friction), and elastic properties (Young's modulus, bulk modulus, Poisson's ratio, etc.). Many other properties can be measured based on rock testing such as, pore and bulk compressibility, permeability stress sensitivity, crushing resistance, P & S velocities, swelling, etc. Details of these tests can be found in any professional rock mechanics reference [1 – 5]. Field data may provide us with formation lithology, continuous record of formation porosity (as in indication of the rock strength), formation fluids analysis, reservoir geology, etc. (Table 1). Well logs provide continuous data versus depth, but do not measure directly the parameters that are needed for a rock mechanical analysis [6 – 7]. Rock mechanics have been used to investigate and solve several problems in the oil industry. Table 2 summarizes these problems management techniques and data required.

Table 2 **Implementation of rock mechanics in solving petroleum engineering problems**

Petroleum engineering phase	Problem	Potential solutions	Data required
Drilling	Borehole instability	– changing mud weight. – selecting mud type. – controlling mud cake efficiency. – managing well orientation.	– rock elastic properties. – rock failure criteria. – in-situ stress state. – rock swelling characteristics. – well orientation. – well inclination. – drilling fluid properties. – mud cake efficiency.
Production	Sand production and perforation stability	– selecting perforation location. – selecting completion type. – controlling fluid drawdown. – controlling production rate.	– rock elastic properties. – rock failure criteria. – in-situ stress state. – rock swelling characteristics. – well orientation. – well inclination. – reservoir description.
	Fracturing height and orientation	– managing proppant crushing resistance. – selecting proppant type. – selecting fracturing fluid type. – measuring rock compressibility. – controlling injection rate.	
	Water injection	– controlling water temperature. – testing water-rock compatibility. – controlling injection rate.	
Reservoir	reserve calculation	– selecting well location. – controlling production rate. – controlling injection rate.	– rock elastic properties. – rock failure criteria. – in-situ stress state. – rock swelling characteristics. – well orientation. – well inclination. – reservoir description. – permeability sensitivity to stress.
	Compaction		
	Subsidence		
	reservoir stress sensitivity		

DRILLING ENGINEERING

Several problems occur repeatedly during oil and gas well drilling. Normally, the first attempt to solve such problems is based on experience. If all methods are failed to solve such problems, a rock mechanics study is considered to be the last hope. At this stage, rock mechanics analysis will be difficult due to the lack of data, and rock samples, therefore, back analysis is the only solution. Thus, rock mechanics principals must be considered from the beginning and rock and reservoir mechanical data base must be established to speed up solving any new coming problems. In average, drilling problems due to borehole instability are responsible for about 10 to 20 % of the drilling cost of a well. 80 to 90 % of these instabilities occur when drilling through shale sections [8]. These instabilities cost the industry around $ 40 – 500 millions per year [9]. Problems generally build-up with time, starting with the fragmentation of borehole wall, followed by the transfer of the fragmentation to the annulus and finally creating in problems such as sticky hole, hole fill, stuck pipe, lost circulation, etc. A Borehole can be kept open and stable if special care is given to insure good mud sealing capability (i. e. mud cake efficiency) [10]. Controlling the drilling mud water activity is crucial to stop shale swelling. Water activity is the property which controls the magnitude and the direction of the filtrate invasion. The water activity of a 100 % water saturated rock equals to unity [11]. Therefore, water activity of the drilling fluid must be always kept lower than that of the formation being drilled. Water invasion into shale formations cause them to swell and loose a large portion of their strength and therefore fail into the borehole and lead to borehole instability. In sandstone formations, water invasion leads to pore pressure build-up. The build-up in the formation pore pressure will change the magnitude of the effective in-situ principal stresses responsible for formation stability. Upon change in the effective in-situ stresses, shear failure could be the result which can shifts the borehole laterally causing tight hole, and abnormal torque and overpull. Drilling fluid weight provides a radial support to the sides of the borehole. The magnitude of the radial support is highly dependent of the mud cake efficiency. Therefore, the radial support provided by the drilling mud is not effective if the mud cake efficiency (quality) is very low [12]. A high mud cake quality allows no filtration. The magnitude of the mud weight required to keep a borehole open, can be predicted using rock mechanics principles [13]. Borehole orientation with respect to the maximum horizontal in-situ principle stress is very important form the point view of borehole instability analysis. For example, horizontal boreholes drilled parallel to the minimum horizontal in-situ principal stress are the most stable among those drilled suing other horizontal orientations [14]. Therefore, rock mechanics must be used to asses the risks associated with vertical, high angle, and horizontal oil and gas wells drilling.

Table 1 **Types of rock mechanical tests.**

- Uniaxial tensile and compressive strength.
- Triaxial compressive strength and failure criteria.
- Cement-casing and Cement-formation bond strength.
- Direct and indirect shear strength.
- Permeability stress sensitivity.
- Elastic and Frictional properties.
- Matrix and pore compressibility.
- P & S velocities.
- Proppant crushing resistance.
- Swelling and wet/dry rock strength.

PRODUCTION ENGINEERING

When producing reservoir fluids over a long period, the reservoir will be depleted and compaction and subsidence may be the result. Subsidence of the productive formation and the overlying strata could mobilize (activate) stable faults or shear surfaces. Hence, an expensive oil well could be lost. Formation subsidence may damage cement sheath around cased wells and creates microannuli which allow abnormal pressured fluids either to damage or to corrode the casting string. Another rock mechanics related problem may be encountered during hydrocarbon production called sand production. Sand production is the production of small or huge amounts of solids along with the reservoir fluids down to the borehole and along to the surface. Sand grains forming the productive formation will produced along with the reservoir fluids if excessive production (drawdown) is implemented. Excessive drawdown, may lead to the failure of stabilized sand arches formed round the production perforations in case of unconsolidated sandstone formations or to the generation of localized shear failures near the wellbore in the productive formation in case of consolidated sandstones. The produced sand comes either from the failed sand arches or from the induced shear surfaces [15]. Numerous problems could be raised due to sand production such as, wear of downhole and surface production equipment, casting wear and collapse, unnecessary cost comes form dumping dirty sands, etc. Several rock mechanical solutions have been developed by many researchers and have been dramatically minimized the problem of sand production [16 – 17]. When designing hydraulic fracturing, the proppant to be used to keep the induced fracture open, must be tested. Upon relieving the injection pressure fracturing which is applied on the fracturing fluid, the fracture will close and the proppant will be stressed. Therefore, the proppant crushing resistance must be examined in order to keep the induced fracture open and not to close the generated flow paths by the debris of the crushed proppant [18]. The height and orientation of the hydraulically induced fractures are function of the in-situ stress state. Therefore, rock mechanics must be implemented in designing hydraulic fracturing to avoid gas migration and water coning.

RESERVOIR ENGINEERING

The accuracy of reservoir reserve calculations is highly dependent on the measured reservoir rock compressibility [19]. Rock compressibility is a function of the in-situ stress state and it can be accurately measured at the rock mechanics laboratories. Upon pressure drop in the oil and gas reservoir, secondary and tertiary recovery methods are applied to increase hydrocarbon recovery [20]. When water flooding or thermal recovery techniques is applied, thermal stresses may be generated due to the difference in temperature between the reservoir environment and the injected water [21]. These induced thermal stresses are responsible for activating stable faults and induced shear surfaces. Water is injected either to maintain the reservoir pressure or to displace the residual oil, if the injected water are incompatible, the cementing material bonding formation grains together may be damaged, and the result could be formation damage, sand production or borehole instability [22]. In low permeability reservoirs, water injection may increase the capillary forces and lead to pore collapse (i. e. mechanical permeability damage) [23]. When drilling adjacent wells from a single platform, borehole stability will be critical [24]. The ignorance of rock mechanics when investigating the above reservoir problems, may cause several problems at different occasions during the reservoir life, thus decreases the reservoir productivity and profits.

CONCLUSIONS

- Rock mechanics is a new active discipline available to the petroleum engineer.
- Understanding the reservoir rock behaviour is essential to avoid costly remedial works.
- Neglecting rock mechanics principles during reservoir planning may lead to unusual recommendations.
- Several drilling, production, and reservoir problems are directly related to rock mechanics, are still not fully understood such as sand production and borehole instability in shale formations.
- Further research are required regarding the measurement of the rock in-situ mechanical properties.
- Rock mechanics is an essential science for petroleum engineers, therefore, it is strongly recommonded to include it in the petroleum engineering programs in the petroleum schools.

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