IBP 1129_06

IMPROVED ASSET DEVELOPMENT PLANNING AND PERFORMANCE THROUGH GEOMECHANICS APPLICATION

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Resumo

A importância do estudo de geomecânica para um eficiente desenvolvimento de campo tem sido constantemente negligenciada por especialistas dos ativos, apesar de todos os benefícios que esta tecnologia pode trazer. Através de análises de geomecânica é possível projetar poços que tenham alto desempenho durante toda a vida útil do campo. Isto é obtido principalmente através do planejamento de trajetórias ótimas para os poços. Além disso, os poços podem ser projetados para manter alta produtividade mesmo sob severas mudanças nas condições do reservatório, tais como, migração induzida de sedimentos finos, compactação do reservatório, re-ativamento de falhas e mudanças de fase dos fluidos contidos no reservatório.

Este artigo discutirá como o uso de geomecânica pode ser incluído em um fluxo de trabalho que inclui simulações de reservatório e análises econômicas para determinar posições ótimas dos alvos de produção e injeção, com o intuito de melhorar o desempenho e o valor do reservatório. Será mostrado que os benefícios começam no processo de encontrar a posição ótima dos alvos, onde uma grande quantidade de simulações de possíveis cenários é considerada. Entretanto, considerando o uso de geomecânica, muitos destes cenários podem ser descartados antecipadamente uma vez que não representam situações ótimas sob as perspectivas de perfuração e completação. Assim, uma considerável quantidade de tempo gasto em computação poderá ser evitada mesmo antes das locações iniciais serem propostas, economizando um tempo precioso dos especialistas do ativo envolvido no projeto.

Abstract

The importance of geomechanics for optimizing field development and value has been consistently overlooked by asset teams despite all the benefits that this technology can bring. Geomechanics provides a means to optimize the well for the life of the field, by optimizing well trajectories for the completion design. Optimally designed wells help maintain productivity under changing reservoir conditions, such as shear induced fines migration, reservoir compaction, fault re-activation, and changing phase behavior.

This paper will discuss how to consider geomechanics in a workflow to improve reservoir performance and value that includes reservoir simulations and economic analysis for determining optimal subsurface locations for producing and injecting wells in a field. We will show that the benefits start in the field planning optimization phase where a great amount of simulation scenarios are often taken into account. However, in the light of geomechanics, many of these scenarios should be early discarded because they are not optimal from the drilling and completions perspectives. Thus, considerable computer time will be saved even before the initial well locations are proposed, saving precious time of the asset team.

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1. Introduction

Due to field uncertainties, it is time consuming to estimate the optimal number, type, subsurface location, and design parameters for new wells. Optimal estimation is a highly combinatorial, non-linear optimization problem and involves a great number of variables. It is therefore necessary to use innovative technology and processes to speed up the proper identification of the best results. In this work, we discuss an optimized field plan and execution workflow that includes geomechanics, reservoir simulations, and economic analysis. We also discuss an optimizer for determining optimal well target locations as well as optimization from the drilling and completions perspectives. The proposed optimized field plan workflow and execution is depicted in figure 1 and includes five major steps as described as follows:

i. Geomechanical model: A geomechanical study should be performed to make sure that the drilling and completions strategies are optimal, allowing better reservoir management;
ii. Preliminary field plan: A set of wells targeting on a static reservoir model is created according to the conclusions of the geomechanical model and a review of the static properties of the reservoir model, while honoring spacing constraints. Well plan geometries that honor drilling constraints, including geomechanical considerations, are then created by connecting one or multiple targets to a surface platform or tieback location;
iii. Field plan optimization: The preliminary field plan suggested in the previous step is then simultaneously optimized with dynamic flow simulation and economic analyses to model the dynamic behavior of production and achieve higher recovery;
iv. Well engineering analysis: Rigorous well engineering analyses are performed on the optimized wells from step three to avoid or minimize drilling and completions problems. In this step, the wells that resulted from the optimization process may be validated against the geomechanical model since the optimization involves moving the wells within the reservoir. If the well trajectories do not pass the geomechanical test validation, they have to be modified until they are acceptable. Note that this procedure is an iterative process that includes a directional path planning application and the geomechanical model;
v. Real-time drilling operations: Real-time drilling monitoring of surface and down-hole data may be used to enable proactive decision making during drilling. The geomechanical model can be updated in real-time, with what can be shown to add additional value.

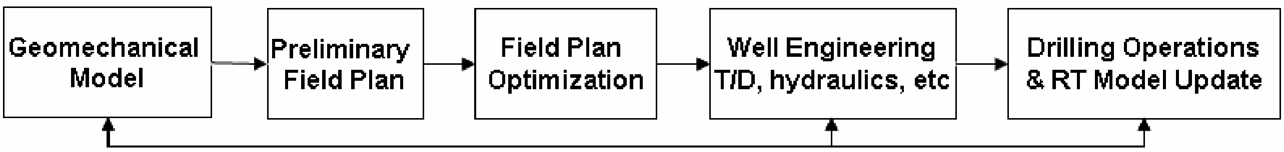

Figure 1: Optimized field plan & execution workflow

Note that the preliminary field plan already takes into account geomechanics. Such accounting helps to discard undesired well trajectories from the drilling and completion perspectives. Taking geomechanics into account will save precious time for the asset team during the field plan optimization phase.

In addition to the factors considered in the above workflow, proposed well locations must also consider other factors such as processing considerations, gathering center locations, alternative depletion strategies, and facility sizing and configuration. However, it is beyond the scope of this work to discuss these factors.

The successful implementation of the proposed field development workflow needs changes in the way individuals in the organization do their business. However, it is flexible enough to involve team members experimenting, exploring, and innovating within its capability (Dudley et al., 2006).

Detailed discussion of all steps of the proposed field plan and execution workflow is provided in the following sections of this work.

2. Geomechanical Modeling

Geomechanics can add a lot of value to costly and high-risk field development projects by reducing operations and engineering uncertainties and ultimately increasing Net Present Value (NPV). Geomechanics is a multidisciplinary approach that includes geology, geophysics, and rock mechanics. Its applications include the following:

- Drilling issues comprised of well bore stability analysis for the development well program;
- Completion issues relating to prediction of sand production and completion strategies;

- Reservoir management issues consisting of pore volume compressibility determination for various pay sands;
- Wider utilization of the study by mapping the mechanical characteristics of the reservoir, overburden, and other relevant information, to assist with subsidence prediction.

The description of a geomechanical model for a field involves detailed knowledge of in-situ stress orientations and magnitudes, pore pressure, and rock mechanical properties (Brehm et al., 2006). In addition, consideration of mud chemistry, fractures, and thermal effects are also relevant (figure 2).

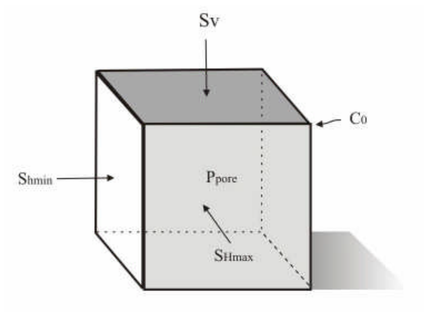

Figure 2. Building a geomechanical model involves knowledge of in-situ stress, pore pressure and rock mechanical properties. S_v is the overburden or vertical stress, S_{hmin} and S_{HMAX} are the least and maximum principal stresses, respectively. Note that the three stresses are mutually perpendicular.

A great amount of good quality data is required to perform a reliable geomechanical study. Data include seismic, drilling, logging, core and reservoir data from existing offset wells in the field, formation mechanical behavior and mechanisms of potential borehole instability. A summary of the sources for pertinent data is provided as follows (Bloch et al., 2005; Chhajlani et al., 2002):

- Overburden or vertical stress (Sv): integrated bulk density log;
- Pore pressure: Measurements (RFT, DST, PWD), log-based (sonic, resistivity), seismic (ITT, velocity cubes);
- Least principal stress (S_{hmin}): Extended LOT, LOT, minifrac, lost circulation, ballooning;
- S_{HMAX} magnitude and orientation: analysis of well bore failure (image logs), active geological structures;
- Rock strength: core tests, logs, cuttings, analysis of well bore failure.

The typical technical approach taken for building a geomechanical model starts with a detailed review of drilling experience performed on all offset wells (exploration and delineation wells).

Another important aspect of building a geomechanical model is the determination of the fault regime (figure 3). The fault regime can be normal ($S_v \geq S_{Hmax} \geq S_{hmin}$), strike-slip ($S_{Hmax} \geq S_V \geq S_{hmin}$), and reverse ($S_{Hmax} \geq S_{Hmin} \geq S_V$). Fault regimes can be determined by investigating fault orientations on structure maps for various formations (Awal et al., 2001). In a simple, normally faulted environment, the maximum horizontal stress should parallel the strike of faulting.

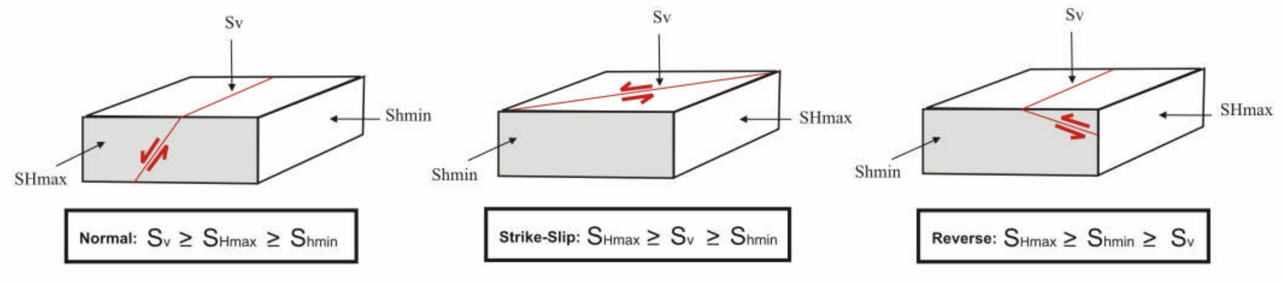

Figure 3. Distinct fault regimes: normal, strike-slip, and reverse.

Ideally, a single geomechanical model is required to represent an entire field. However, in fields with high geological complexity, two or more different geomechanical models may be necessary to accurately represent the entire field.

Once the geomechanical model has been completed and calibrated with the occurrences on the offset wells, it can be applied on the upcoming development wells. One of its major applications, as previously mentioned, is in well bore stability analysis, mainly in extended reach drilling (Cheatham, 1984). Maintaining a stable well bore is of primary importance during well drilling and production (figure 4). The shape and direction of the hole must be controlled during drilling, and hole collapse and solid particle influx must be prevented during production. Well bore stability requires a proper balance between the uncontrollable factors of earth stresses, rock strength, and pore pressure and the controllable factors of well bore fluid pressure and mud chemical composition. Therefore, a well bore stability analysis consists of mud weight window prediction and optimal well trajectory analysis.

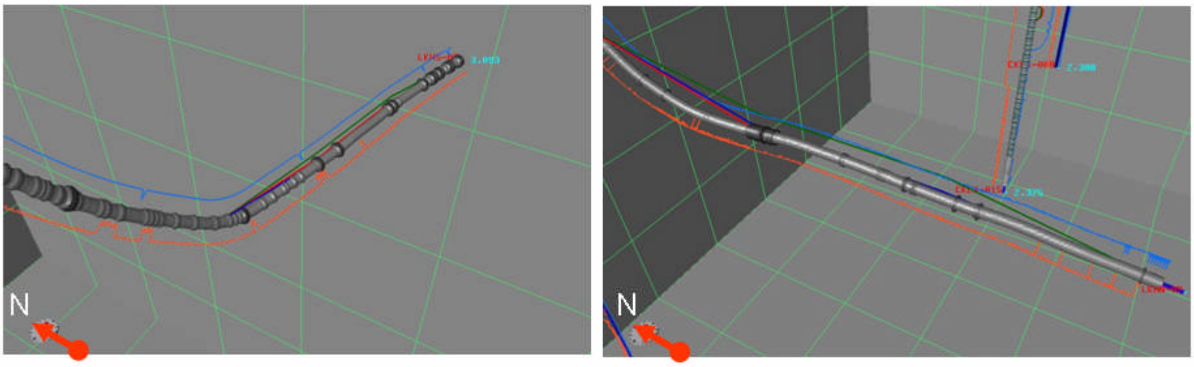

Figure 4. Example of a field where wells drilled along the N-S direction are more stable than wells drilled along the E-W direction. Central caliper logs are shown along the well trajectories. Note the difference in numbers and sizes of breakouts.

The selection of the appropriate well completion strategy depends on several factors, but one of primary importance is the occurrence of sand production from the wells (Cerasi et al., 2005). During the actual production from a cased and perforated hole, failure of the formation around the perforation can cause sand production, which in turn could hinder production or completely sand-up a well. It could also cause erosion and sand handling problems on the surface. To avoid such problems, it is necessary to determine the maximum drawdown pressure (the difference between the reservoir and flowing bottom-hole pressures) beyond which sand production will occur. Thus a geomechanical analysis considering the stress field and the fluid and drag forces around the perforations at various stages of reservoir depletion are important to evaluate the completion and production strategies.

Another problem where a geomechanical model can be applied with success is in the determination of pore volume compressibility (Settari et al., 2005; Thomas et al., 2002). It is defined as the relative change in pore volume of rock with changes in pore pressure. It is an important parameter input during material balance calculations of reservoir estimates, especially in compaction-drive reservoirs. Compaction of the reservoir rock, which depends on the pore volume compressibility, has important implications on reserve estimations and performance, production casing integrity and subsidence evaluations. The adequate evaluation of these parameters is essential in deep water projects due to the high project risks and costs.

Although unstimulated horizontal wells are usually very successful in naturally fractured reservoirs and in reservoirs with gas or water coning problems, there are situations where fracturing a horizontal well is necessary. An example is with restricted vertical flow caused by low vertical permeability or the presence of shales streaks. Due to the dependence of the orientation of a hydraulic fracture on well direction with respect to the stress field, fracturing a horizontal well must be carefully planned to allow the proper well bore orientation. For that purpose, a geomechanical model can be used.

Improved reservoir management and oil recovery can also be obtained by incorporating geomechanics. There is an intimate role of geomechanics in secondary recovery schemes, including flooding directionalities associated with the orientations of the stress state.

3. Preliminary Field Plan

Once a geomechanical model has been completed and calibrated, the preliminary field plan can begin. For this purpose, an application that allows users to automatically create targets on a reservoir model or seismic volume (figure 5) should be used. The application should provide the ability to target on filtered attributes (porosity, permeability, etc.) within the reservoir models used. It should also offer modes for automated path planning, allowing the user to specify the type of trajectories to be generated (vertical, deviated, horizontal, or multi-lateral designs) using engineering constraints such as dogleg severity, build rates, walk rates, etc.

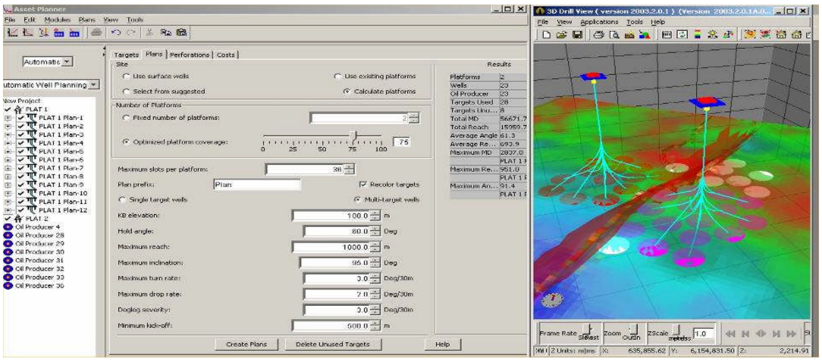

Figure 5. Example of automated target and directional well planning, showing required input data and preliminary well plan with targets and well trajectories (Landmark's Asset Planner^{TM} software application).

In this phase, rigorous well engineering analyses are not required because some of the production and injection wells proposed may be discarded during the optimization process that will be described in the next section. However, the suggested well trajectories should, as much as possible, be planned along the preferred directions indicated by the geomechanical model. Such planning is required to make sure that the well paths are optimal from the drilling and completions perspectives. By doing so, precious time of the asset team can be saved since analyses of non-optimal geomechanical scenarios are discarded.

In a normally faulted environment (figure 3), well trajectories along the horizontal stress are desired in terms of geomechanics. They will require lower mud weights to prevent hole collapse compared to holes drilled in the direction of the maximum horizontal stress (Hemphill, 2005).

4. Field Plan Optimization

After the conclusion of the preliminary field plan, the optimization can initiate. The multiple target placement optimizations problem can be resolved by considering many location combinations with nonlinear effects of fluid drive, water injection, physical constraints, and economics. An innovative solution for this problem is well explained by Narayanan et al (2003) and Cullick et al. (2005). They used a software system that includes a reservoir simulator, an economics analysis package, and an optimizer. The flow simulator handles the nonlinear physical model production flow and constraints. The optimizer uses a global, evolutionary approach that progressively improves the objective function by finding better solutions as the procedure progresses (figure 6). The uncertainty calculations are executed with Monte Carlo or quasi-Monte Carlo simulation, such as Latin Hypercube. The optimization process stops when a specified number of iterations or some improvements in objective are met.

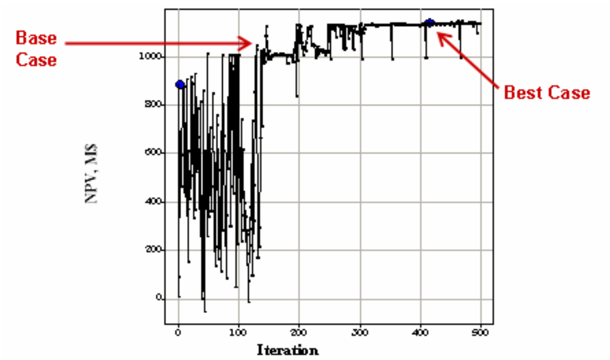

Figure 6. Example of net present values vs. optimizer iteration
(Cullick et al., 2005)

The optimization decision variables are the locations in the x, y, and z grid-unit space in the reservoir model. Wells are allowed to move horizontally and vertically along the major grid axes from their initial locations. Typical allowed well movements are five grid units (approximately 2,500 feet) and one grid unit (approximately 50 feet) along the horizontal and vertical directions, respectively. The optimization process does not change the overall well geometry as compared with the original geometry because the grid is fairly regular and the same x, y, or z movements are applied to all intervals of the well.

Cullick et al. (2005) show examples of the optimization of multiple target placements for production and water injection wells. The uncertainties considered in the examples are earth model realization, fault transmissibility, rock compressibility, water oil contact, ratio of vertical and horizontal permeabilities, and well skin. Discrete, uniform, and normal probability functions were used for the uncertainties. For the twenty-one wells considered in their work, there were sixty-three decision variables, which lead to approximately 10^{26} possible target locations. The optimization process identified a plan for significant increase in net present value and rate of return by a choice of a set of wells that increased cumulative produced oil and reduced cumulative produced and injected water. The optimization was reached with just 500 iterations.

Note that although the above optimizer does not alter the overall well geometry, it actually moves wells within the reservoir. Therefore, it is advisable to re-validate the optimized wells against the geomechanical model developed for the field. In the present example, it has to be done manually. However, in the future, the optimization process should be enhanced to automatically include geomechanical aspects, which is not a trivial thing.

5. Well Engineering Analysis

There should be rigorous review of the wells that were selected as optimum in the previous section. The review should address issues such as anti-collision, torque and drag, and cost. In addition, to ensure that the results of the geomechanical study, including the well bore stability analysis, are efficiently used to minimize drilling problems and increase safety, casing seating depth, Equivalent Circulating Density (ECD), hole cleaning, surge and swab, torque and drag, and drill string vibration analyses should be performed (Oort et al., 2001). Mud type, density (obtained from the safe mud window indicated by the geomechanical model), and rheology have great influence on these analyses. Figure 7 displays an example of hole cleaning analysis using the Landmark's WellPlan™ application.

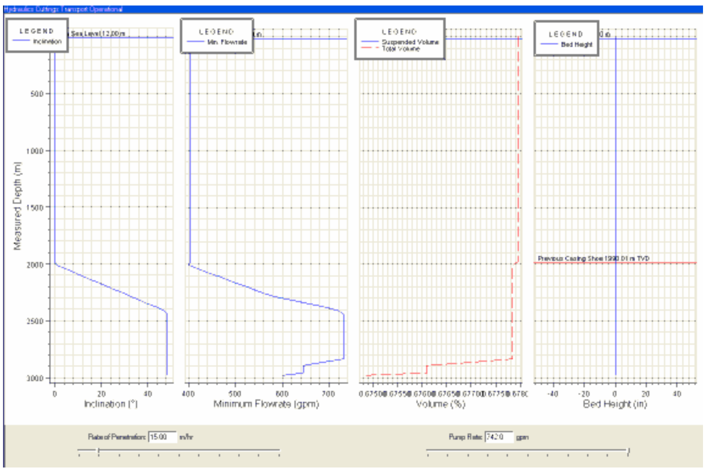

Figure 7. Example of hole cleaning analysis, showing hole inclination, fluid flow rate in the annulus, percentage of cuttings suspended volume, and cuttings bed height.

6. Drilling Operations and Real Time Model Update

Upon the completion of the field plan optimization, the drilling campaign can start. Real-time drilling monitoring may be used to enable proactive decision making during drilling. By combining real-time surface and down-hole information (gamma ray, sonic, neutron, pressure-while-drilling, temperature, vibration, etc.), it is possible to continuously update the geomechanical model concerning rock strength, Poisson's ratio and pore pressure. In addition, it is possible to monitor ECD, torque and drag, and drill string vibration (Greenwood et al., 2005). Figure 8 is an example of hydraulic real-time data monitoring using the Landmark's WellPlan™ software.

ECD monitoring using pressure-while-drilling measurements (PWD) is of particular importance to manage the safe operating mud window between formation collapse and fracture gradient while drilling. A critical situation where PWD can be used with great success is when the circulating temperatures in the well bore are higher than expected due to friction effects and the safe mud window is narrow, such as in deep water situations. In this case, the thermal expansion of the fluid can mask compressibility effects. The net result is a reduction in down-hole fluid density compared to that measured at the surface. Although the reduction may appear small, say 0.13lbm/gal, it may be enough to reduce the down-hole fluid density to a level below the predicted density for well bore stability (Hemphill, 2005).

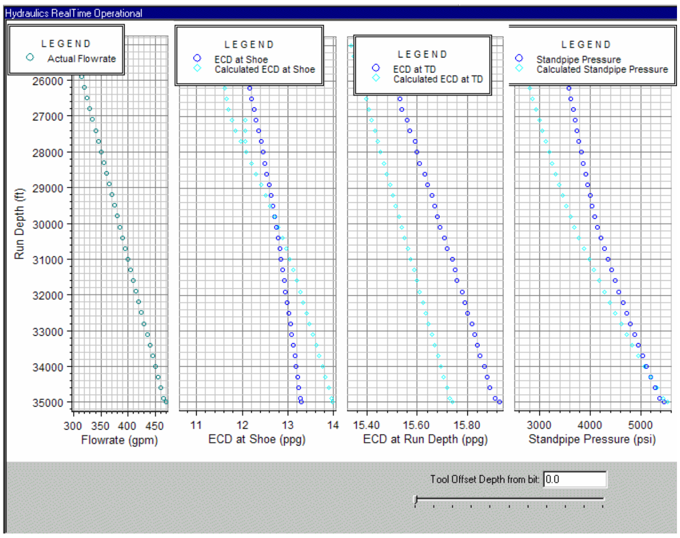

Figure 8. Example of hydraulic real-time data, showing actual flow rate, measured and calculated ECD at shoe and at bit depth, and measured and calculated stand pipe pressure. The real-time data can be used to rapidly undertake engineering studies.

7. Conclusions

The following conclusions can be drawn from this work:

i. Geomechanics study should be an integrated part of any costly and high-risk field development project. It is essential to the optimization of critical drilling, completion and reservoir issues. It also creates intense technical cooperation between the various groups involved with project development;

ii. After the geomechanical model is completed and validated, one of its major applications is in well bore stability analysis, mainly for extended reach drilling. A well bore stability analysis consists of mud weight window prediction and optimal well trajectory analysis;

iii. In the proposed workflow, the preliminary field plan already takes into account geomechanics, which helps to discard undesired well trajectories from the drilling and completion perspectives. Discarding undesired well trajectories saves precious time for the asset team during the field plan optimization phase;

iv. The multiple target placement optimization problems can be solved by considering many combinations of location with nonlinear effects of fluid drive, water injection, physical constraints, and economics. Differently from typical approaches that are serial in nature with little opportunity to make data changes throughout the workflow, the approach described in this paper is an iterative and flexible process that allows changes anytime throughout the workflow;

v. The successful implementation of the proposed field development workflow needs changes in the way individuals in the organization do their business. However, it is flexible enough to involve team members experimenting, exploring and innovating within its capability.

8. Acknowledgments

We thank Halliburton/Landmark for permission to publish this work.

9. References

AWAL, M. R., KHAN, M. S., MOHIUDDIN, M. A., ABDULRAHEEM, A., AND AZEEMUDDIN, M. A new approach to borehole trajectory optimization for incresed hole stability. Paper SPE 68092 presented at the SPE Middle East Oil Show, Bahrain, 17 – 20 March 2001.

BLOCH, M., FREITAS, S.M.S., SOCORRO, M., SOARES, J.A., AND BACELAR, C.J.R. In-situ stress determination based upon borehole imaging and rock-sample analysis. A comparison among anelastic strain recovery (ASR), acoustic velocity, and acoustic tomography. Paper SPE 94919 presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, 20 – 23 June 2005.

BREHM, A., WARD, C., BRADFORD, D., AND RIDDLE, G. Optimizing a deepwater subsalt drilling program by evaluating anisotropic rock strength effects on wellbore stability and near-wellbore stress effects on the fracture gradient. Paper IADC/SPE 98227 presented at the IADC/SPE Drilling Conference, Miami, 21 – 23 February 2006.

CERASI, P., PAPAMICHOS, E., STENEBRATEN, J.F. Quantitative sand-production prediction: Friction-dominated flow model. Paper SPE 94791 presented at the SPE Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, 20 – 23 June 2005.

CHEATHAM, J. B. Wellbore stability. *Journal of Petroleum Technology*, p. 889-896, June 1984.

CHHAJLANI, R., ZHENG, Z., MAYFIELD, D., AND MACARTHUR, B. Utilization of geomechanics for Medusa field development, deepwater Gulf of Mexico. Paper SPE 77779 presented at the SPE Annual Technical conference and Exhibition, San Antonio, 29 Sep. – 2 Oct. 2002.

CULLICK, A. S., NARAYANAN, K., AND GORELL, S. Optimal field development planning of well locations with reservoir uncertainty. Paper SPE 96986 presented at the SPE Annual Technical Conference nd Exhibition, Dallas – TX, 9-12 October 2005.

DUDLEY, G., PERRY, J., GOODWIN, S., CRITCHLEY, C., HOCKING, P., SHAHLY, M., BARKVED, O. I., AND SAUL, D. The challenges of implementing at scale: Field of the future–technologies in the North Sea. Paper SPE 99829 presented at the 2008 SPE Intelligent Energy Conference and Exhibition, Amsterdam, 11-13 April 2006.

GREENWOOD, J. A., BREHM, A., VAN OORT, E., ALGU, D.R., AND VOLOKITIN, Y. E. Application of real-time wellbore stability monitoring on a deepwater ERD well. SPE/IADC paper 92588 presented at the SPE/IADC Drilling Conference, Amsterdam, 23 – 25 February 2005.

HEMPHILL, T. Integrated management of the safe operating window: wellbore stability is more than just fluid density. Paper SPE 94732 presented at the the SPE Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, 20 – 23 June 2005.

NARAYANAN, K., CULLICK, A. S., AND BENNETT, MATTHEW. Better field development decisions from multi-scenario, interdependent reservoir, well, and facility simulations. Paper SPE 79703 presented at the SPE Reservoir Simulation Symposium, Houston, 3 – 5 February 2003.

SETTARI, A. T., BACHMAN, R. C., AND WALTERS, D. A. How to approximate effects of geomechanics in conventional reservoir simulation. Paper SPE 97155 presented at the SPE Annual Technical Conference and Exhibition, Dallas, 9-12 October 2005.

THOMAS, L.K., CHIN, L.Y., PIERSON, R. G., AND SYLTE, J.E. Coupled Geomechnichs and Reservoir Simulation. Paper SPE 77723 preseneted at the SPE Annual Conference and Exhibition, San Antonio, 29 Sep. – 2 Oct. 2002.

VAN OORT, E., NICHOLSON, J., AND D'AGOSTINO, J. Integrated Borehole stability studies: Key to drilling at the technical limit and trouble cost reduction. Paper SPE/IADC 67763 presented at the SPE/IADC Drilling Conference, Amsterdam, 27 Feb. – 1st March 2001.