Reservoir Monitoring Consortium (RMC)

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October 14, 2011

Reservoir Monitoring Consortium (RMC)

Executive Summary

The objective of Reservoir Monitoring Consortium (RMC) is to develop new methods for dynamic reservoir monitoring. We will carry out a number of focused applied research projects in reservoir monitoring that are directly pertinent to the current and future needs of our industry sponsors. We will develop specific workflows for different types of reservoirs. This will include the conventional reservoirs (e.g. carbonate, clastic, deep waters) and the unconventional reservoirs (shales, tight sands, heavy oils, and geothermal). This will be preceded by the identification of the key technology gaps with input from the project sponsors. We will then focus on major issues such as integration of disciplines, data, information, and expertise. We will maintain a balance between short and long term, high impact research goals and the immediate and foreseen industry needs. One key distinguishing edge of RMC compared to other academic consortia is its focus on multi—disciplinary aspect of reservoir monitoring.

Introduction

Optimum reservoir management requires up-to-date information about different reservoir properties throughout the entire reservoir volume. Access to the latest data on fluid distribution in a reservoir, and knowledge of how that distribution is changing with time, allows us to develop cost-effective strategies to get the most out of every field at the lowest possible risk. In the past, the type of data used for reservoir monitoring and production optimization was limited to production data and other well data. This included reservoir pressure and temperature as well as oil water ratio. When significant drop in reservoir pressure or oil production occurred, various enhance oil recovery scheme were implemented. These methods however relied primarily on the production data which provided little information on the three dimensional distribution of the fluids inside the reservoir, making it difficult to devise the optimum strategy for the injection and production wells.

Dvnamic characterization reservoir and effective more reservoir monitoring processes become even more important with major production declines in very large reservoirs of mature oil fields. Other important monitoring areas for reliable include techniques deep water reservoirs with expensive production platform and wells, shale oil and shale gas reservoirs, CO₂ injection process (both for EOR and sequestration) and monitoring hydrofracking and well stimulation processes, revitalizing old and abandoned wells and heavy oil insitu combustion and upgrading. Figure 1 shows a set of important practical problems and many tools that offer promise to address those challenges.



Figure 1- The Reservoir Monitoring Consortium Structure

In addition we expect to have more direct industry sponsor involvement in different stages of the work. Every year, we will propose our Project Portfolio comprised of a set of well-defined applied technology programs. The Project Portfolio Parts (PPP) will go through internal reviews, revisions, integration and ranking process. We will then ask the sponsors, represented at the strategic and technical advisory boards to further fine tune the ranking of different projects. If a particular sponsor or a small group of them have a keen interest in particular PPPs that are not selected for immediate funding by the entire RMC membership, they may consider funding them independently on an exclusive basis.

The main themes of our research plan are correlated with the technical expertise of our faculty and our ongoing general R&D focus areas. The following list is some of the main topics that we expect to focus on:

Main consortium themes:

- 4D volumetric inversion for pressure, saturation, and permeability changes.
- Integrated reservoir model updating and history matching.
- Passive seismic monitoring with a focus on shale.
- Seismic acquisition, processing and analysis for CO₂ sequestration & monitoring.
- Special issues for reservoir monitoring of mature oil fields, carbonate reservoirs or heavy oil.

When certain technical capability is deemed to be important to address specific practical challenges but we don't have adequate expertise at USC, we will join forces with others to supplement what we have internally at USC. This may include involving our adjunct professors or other experts in a complementary fashion. We will also seek opportunities to collaborate with other universities, national laboratories as well as the oil and gas and service companies to explore opportunities for technical cooperation. This would also include the possibility of a arrangement for visiting scientists or visiting scholars from both the academia and the industry. Recent advances in new sensor development and introduction of new data types as well as new data processing, analysis and integration methods have paved the way for a more effective reservoir monitoring. This includes use of time lapse geophysical data (e.g. 4D seismic), passive seismic and borehole to borehole data.

Geophysical technique	Physical property measured	Reservoir property inferred
Time lapse or 4D surface seismic,vsp, X-well seismic	Changes in amplitude, arrival time, seismic waveform	Fluid saturation, pressure changes
Microseismic continuous monitoring	Passive seismic waves from rock shear failure w/ stress perturbations	Fluid flow pathways Flow anisotropy
EM borehole and surface measurements	Electrical resistivity changes	Saturation 4D changes
ElectroSeismic (ES)	Seismic from electro-kinetic coupling changes Resistivity changes	Saturation 4D changes
Micro-gravity surface & borehole	Density differences Minute gravitational field change w/ fluid phase	Saturation 4D changes

Table 1- Different sensor measureme	ents with sens	sitivity to sp	pecific physical	properties
correlated v	<i>with reservoir</i>	properties		

Table 1 shows the list of different geophysical techniques, including time lapse or 4D seismic data, microseismic data, electromagnetic, electro-seismic, and micro-gravity data. In addition, Table 1 shows what type of data is most sensitive to specific physical properties and which reservoir properties could be inferred from the measurement of different physical properties through different sensing methods. For effective reservoir monitoring, or observing changes in the fluid and pressure, it will be important to integrate different types of data on Table 1 with other data such as petro-physical and production data. Different Project Portfolio Parts (PPPs) that will be described below will elaborate further on how we will go through the process of data fusion to quantify changes in reservoirs on different practical settings and how the results will help us with better reservoir management.

Potential invited sponsors:

A broad base of organizations including major and large independent oil companies, national oil companies, and service companies are the key expected project sponsors. We will also encourage participation from companies who have strong technical ties with the oil and gas companies. This includes companies who develop computer hardware and software or develop sensors and networks for different reservoir related problems. Our sponsors will have the flexibility to support our efforts through different methods. This includes unrestricted gift contribution and fellowship sponsoring specific students. To fully benefit from the ongoing technical developments in small software and service companies who may not be in a position to fully support RMC, we will encourage their participation on a mutually agreeable way. This might include a voluntary payment, in kind contribution or providing hardware, software or manpower that are deemed important to carry out some of our research projects.

Benefits to sponsors:

In what follows we describe some of the benefits the sponsors and project participants will receive.

- Access to low-cost, leading-edge research in an area of interest to sponsor.
- A mechanism to leverage contributions from multidisciplinary research that would otherwise be unavailable to some sponsors due to lack of internal expertise or infrastructure
- Staff Training for manpower capabilities.

- Recruiting opportunities and access to potential hires with expertise in reservoir characterization and real time reservoir monitoring.

Consortium membership year: November 1st - October 31th

Sponsorship Fee- The annual fee to sponsor RMC is set at \$50,000. The sponsorship fee can be paid in the form gift contribution (preferred to reduce the university overhead charge) or contract research. The delivered results in both cases will be the same. For smaller oil and service companies alternative arrangements will be made to have part of the fees paid in the form of in kind contribution, direct student support or fellowship. All companies will have the option to pay the sponsorship fee in 2-3 installments with the last installment due before March 31, 2012.

For those companies who choose the gift contribution route, an email stating they pledge to provide USC with an restricted gift for the amount to be paid according to a given payment schedule. They also should express preference the funds to be used for the RMC related research under Prof. Aminzadeh and the other CO-PIs. Those who choose to support the project under contract research should state their preference and we will send out the contract to be finalized.

Meetings: The inaugural meeting was held at the campus of the University of Southern California during September 14-15, 2011. We expect to hold annual meetings in September of each year at USC. Starting in 2012, we will also hold brief overview meetings at the annual SEG and SPE meeting locations.

Advisory Board: Strategic and Technical Advisory Boards (SAB and TAB) will provide general directions and priorities on problems to be addressed and the tools to be considered. We expect majority of our SAB will be comprise of the high level management from our sponsoring companies who are visionaries and can help guide RMC strategically. The TAB members are expected to be mostly from the technical staff of the sponsoring companies (in many cases the main contact person from each company to RMC) and USC Co-Principal Investigators. We may invite to our SAB and TAB participation of selected people who can contribute to RMC and its leadership both from strategic and technical viewpoints. All the RMC sponsors are requested to provide us with one candidate each for inclusion in our SAB and TAB

Project Portfolio

In what follows we will highlight different components of our R&D project. We will refer to each as the Project Portfolio Part. To simplify referring to each, we will name them as PPP(n)(x) where n refers to the project number and x refers to the first principal investigator named in the project. Based on the feedback from both physical and remote participants in our inaugural meeting we selected 6 out of the 17 projects for funding through the consortium. Other projects may be considered in the future and/or funded exclusively by some of the members of consortium or others.

The projects to be funded through "Base Membership" in the project are as follows. The projects are listed in the order of the combined ranking from the project evaluation. Some of the companies who have expressed the desire to support the projects not included in the list below through "Individual Company" support. They should express their wishes for follow up communication to make the necessary arrangements.

Base Membership Project Portfolio

- 1. **PPP10BJ- Optimization of Hydraulic Fracturing in Unconventional Reservoirs:** Numerical optimization algorithms will be developed that can be combined with flow simulation to improve the design and implementation of hydraulic fracturing to increase the productivity and net present value of unconventional assets. acterization and dynamic history matching.
- 2. **PPP7FA-** Integration of Microseimic Data for Fracture Characterization: Low permeability unconventional resources are typically produced through injection-induced stimulation (hydraulic fracturing). In this project, we plan to develop novel methodologies for integration of microseismic data into reservoir and fracture models for improved characterization and long-term production from unconventional reservoirs.
- 3. **PPP5CS- Using Microseismicity to Map Reservoir Structure:** The locations and magnitudes of small events will be used to determine the structure of the fracture network from which geothermal fluids are being produced. The observed structure and

magnitude distribution also indicates whether the microsesmicity is triggered or induced. This project will be combined with the previous project PPP8MS: Development of Dynamic Models of Fractured Reservoirs based on Unstructured Grid and Discrete Fractures, and Their Up-scaling: attempting to develop flexible, accurate, and efficient models of fractured reservoirs in order to set aside double-porosity and similar models, incorporate recent advances in multi resolution computations in the model, and take into account the evolving nature of the models of fractured reservoirs that is based on 4D seismic char

- 4. PPP12SW- Understanding impact of reservoir fluid on seismic response using physical modeling- Here, we conduct physical modeling experiments with the aim of predicting the impact of the reservoir fluid changes on the seismic response. Such physical modeling examines the effectiveness of time lapse seismic data in monitoring changes in reservoir fluid distribution in different geologic settings.
- 5. PPP15DH- Time Lapse Petrophysical Reservoir Monitoring and Evaluation of Reservoir Characterization Sensitivity- Using MWD, LWD and SWD, we would evaluate the sensitivity of various existing and potential reservoir petrophysical monitoring and characterization protocols to meet the reservoir monitoring needs of existing and future conventional and unconventional reservoirs.
- 6. PPP16AO- Reservoir Modeling using Tomography based on Field Operation Data-We propose to use novel injection (water, steam, etc) schedules and to monitor gross fluid production in order to actively measure the response time between well-pairs without altering the average daily operations. With the well-pair response time, we develop object-based algorithms to identify the heterogeneous structures. These objectbased algorithms are designed specifically to provide robust performance when high contrast structures have to be detected (e.g., high permeability channels).

Appendix1- Detailed Project Descriptions

<u>1- PPP10BJ</u>

Key People: Behnam Jafarpour and Ph.D. Student (TBD)

Project Name: Optimization of Hydraulic Fracturing in Unconventional Reservoirs

Core Technical or Practical Problem(s) we are addressing

Production from low permeability unconventional reservoirs is accomplished through engineered hydraulic fracturing to generate pathways for gas flow from rock matrix to the production wells. While hydraulic fracturing technology has progressed considerably in the last thirty years, current practice in designing the fracture systems primarily involves subjective engineering decisions. We plan to develop numerical optimization algorithms that can be combined with flow simulation to improve the design and implementation of hydraulic fracturing to increase the productivity and net present value of unconventional assets.

Long term vision of how this impacts the industry

The ultimate goal of the project is to develop practical optimization tools to enhance production from unconventional gas resources. The significance of the proposed developments for optimization of unconventional reservoirs can be readily appreciated by observing the latest trends and emerging technologies in developing conventional reservoirs (e.g., smart fields, closed-loop reservoir management) and the limitations and challenges of the current practice in producing unconventional reservoirs. The main outcome of this project will be the development of a systematic approach to implement simultaneous optimization strategies for well trajectory and hydraulic fracture design in unconventional reservoirs in order to maximize production and realize better economic decisions.

Recent related activities in the industry/academia

During the past two decades, significant progress has been made in optimizing recovery from conventional resources. Model-based optimization strategies have been shown to outperform reactive control methods (opening and shutting wells) and improve on the recovery factor even when uncertain reservoir models are used. In addition, well placement decision has been largely facilitated by numerical optimization tools. Similar optimization developments can be developed to guide hydraulic fracturing by controlling the location and intensity of stimulation used to create fracture networks.

Brief Project Description

In this project, we will develop algorithms for fracture placement and optimization to facilitate the design of hydraulic fracturing systems. The main optimization problems are related to planning the best well trajectory for fracturing, designing the fracturing intervals for a selected trajectory, scheduling the fracturing sequence and adjusting the fracturing intensity at different locations, all based on an estimate of recovery potential in different regions of the reservoir as implied by flow and volumetric properties. As depicted in Figure 1, we will consider a hierarchical optimization deals with finding the best trajectory for drilling wells based on reservoir properties. The optimization will include constraints to ensure drilling feasibility of the well trajectory as well as geologic considerations including pay zones and spatial variability in reservoir properties. Each iteration to optimize fracture interval and intensity (see Figure 1). The sequence of outer and inner loop optimizations continue until no significant improvement

in the objective function (i.e., project NPV) is observed or a stopping criterion such as

maximum number of iterations is reached. The proposed optimization workflow described in this proposal is based on reliable knowledge of spatial distribution of reservoir properties such as porosity, geo-mechanical permeability. and properties. Reservoir property descriptions are, however, highly uncertain. Two important sources of information that can be used to improve reservoir property description are static data (such as well logs, core data and cross-well seismic) and dynamic data such as production and microseismic. The static data is often incorporated through geostatistical techniques while the dynamic data can be incorporated using nonlinear inversion methods. While, these components are not within the scope of the current project, they can in general be used to provide information about reservoir property distribution.

Immediate plans and goals for 2011-2012

The following tasks will be carried out in the first two years of the project.

- Development of fracturing well trajectory optimization algorithm (outer loop).
- Development of fracture optimization algorithms to identify fracture intervals and intensity for a fixed well trajectory (inner loop).
- Integration of fracture well trajectory optimization and fracture interval/intensity optimization to develop a hierarchical optimization algorithm.
- Fine-tuning and sensitivity analysis to evaluate the performance of the developed algorithms under geologic uncertainty.
- Preliminary test cases to evaluate the suitability of developed methodology before application to benchmark models and field data.

Deployment and testing plans

The developed framework will be validated using stimulation data from synthetic models as well as realistic field datasets provided by sponsor members.

Desired interactions with the sponsors

1. Technical interactions with sponsor members are essential for achieving planned milestones and ensuring satisfactory progress and completion of the project. We will work together with sponsor members to address specific issues encountered in their common practices and in benchmarking the developed strategies with realistic field data.



Figure 1. Demonstration of the proposed optimization workflow using a porosity map: (a) uniform fracturing; (b) inner loop optimization of fracture locations and intensity; (c) combined optimization of well trajectory and fracture design.

2. Sponsor members are welcome to provide field data to USC for our test cases. The case studies can be conducted either exclusively with each individual sponsor (to honor confidentiality) or with involvement of other sponsors. Depending on the sponsors' requirements, appropriate mechanisms will be designed for funding and other related logistics.

Key references

- 1. Brouwer D.R., Jansen J.D. (2004): Dynamic optimization of water flooding with smart wells using optimal control theory, SPE J. **9** (4), 391–402.
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<u>2- PPP7FA</u>

Key People: Fred Aminzadeh, Tayeb Tafti, and Debotyam Maity

Project Name: Integration of Microseismic Data for Reservoir Characterization

Core Technical or Practical Problem(s) we are addressing

We will study the use of microseismic data for monitoring changes in unconventional reservoirs. The aim is to better understand the complexity of the fracture networks in the subsurface and how they change with the hydrofracing. Thorough understanding of the fracture network helps optimize the stimulation process and is of high importance to reservoir engineers. There are many useful tools which can be used for better understanding of the fractures created in the subsurface by injection induced stimulation. In addition to performing the traditional studies, we will look into relatively new approaches including:

- 1. Shear wave splitting (SWS) studies to determine fracture density/ orientations.
- 2. Multiplets analysis and fractal analysis to detect fracture patterns and movements which may differ from overall event distribution.
- 3. Integration of microseismic with conventional seismic data and other geophysical data types in an integrated interpretation approach.
- 4. Creating accurate fracture and property models from microseismic events to characterize time lapse anomalies.

These studies should reveal additional properties of the reservoir or enhance the resolution/ coverage of estimates being made. Our goal is to provide additional information to the reservoir engineer to allow for optimized field development especially in shale oil and gas reservoirs where sufficient microseismic activity is present during the hydraulic fracturing process for useful analysis. More importantly, monitoring changes in the velocity model and induced microseismicity over multiple stimulation stages along with establishing the cause and effect relationship between stimulation and observations can provide us a method for assessing the effectiveness of different stimulation methods and allow improved understanding of the stimulated area. Enhanced fracture network models should allow for better reservoir simulations studies and better field management over the long term.

Long term vision of how this impacts the industry

The proposed method should allow for *better reservoir property estimations* including *better fracture network modeling* which will help in improving reservoir management. It should enable reliable fracture network characterization including time lapse propagation and *improved long term production estimates*.

Recent related activities in the industry/academia

Passive seismic monitoring is a heavily used and necessary tool in most unconventional reservoir developments involving hydraulic fracturing or injection schemes. Because of the importance of unconventional resources in the US, this topic is receiving significant attention from both industry as well as academia. In the past, passive seismic data has been used extensively for fracture growth detection, fracture properties and stimulated zone estimation as well as rock property estimates. It has also been used for monitoring of injection processes over time. Most studies have used MEQ cloud location/ distribution to obtain useful fracture property estimates. Some also involve integrating conventional seismic data and advanced algorithms such as ant tracking schemes for better fracture characterization. Work has been done on 4D reservoir characterization using passive seismic data as part of hydraulic fracturing process. Passive seismic tomographic inversion is a well understood technique and has been used for multiple property estimates. Microseismic data have also been combined with available fracture models using different concepts (see Figure 1 as an example) leading to improvements. Over the last few years, rapid progress has been made to better understand the reservoir and monitor for any divergent conditions or to take advantage of any additional information/ analysis in production optimization.

While full utilization of many capabilities is still limited, a holistic integrated approach is also



Figure 1: Example showing the workflow for integration of microseismic data into fracture model using fracture probability map concept: (a) prior fracture model; (b) rock criticality map showing the distribution of rock strength (a well is located on bottom left corner of the field, shown with red circle); (c) simulated microseismic data after hydraulic fracturing; (d) quantified fracture probability map generated from the microseismic data in (c); (e) updated fracture model after integration of microseismic data through fracture probability map. Notice that the updated fracture model is more consistent with the microseismic events indicating the location of high fracture density.

missing in the way passive seismic data is being used today. Major issues include associated high costs, evaluation time as well as the approaches/ techniques used.

Brief Project Description

We discuss the project activities in the context of proposed workflow (Figure 2).

- 1. Advanced autopickers under development at USC are able to pick both compressional (p) and shear (s) wave arrivals with high accuracy. We will use these arrival times to generate event locations using tomographic inversion.
- 2. We will find the spatial structure and frequency-magnitude (Gutenberg-Richter) distribution of microseismicity to obtain additional information about the fracture network. Since events usually occur on the existing fracture network, fractal analysis can illuminate its underlying structure.

- 3. Compressional and shear wave velocity models will be generated from microseismic events and these will be integrated with other data such as borehole logs and core data to constrain models and to reveal properties of the reservoir such as porosity and fracture density.
- 4. We will ascertain fracture orientation, density maps and clusters using shear wave splitting phenomenon and multiplets analysis.
- 5. We will use seismic attribute analysis along with conventional seismic data to map fractures/ faults in an integrated fashion with MEQ's and reservoir properties derived from passive seismic data.
- 6. We will develop a fracture characterization framework for improved characterization of unconventional reservoirs. This will be accomplished by integrating microseismic data with production measurements into fracture model descriptions using advanced inverse modeling techniques.
- **7.** We have the tools and the capability to tie the well logs with corresponding reservoir properties (e.g.: fracture density) and also to implement AI interpretation techniques (such as FL-ANN integrated learning schemes) to develop constrained reservoir property models.

3-- PPP5CS (combined with PPP8MS)

Key People: Charles Sammis, Muhammad Sahimi, and Fred Aminzadeh

Project Name: Dynamic Mapping of Fractured Reservoirs

Core Technical or Practical Problem(s) we are addressing

We use the locations and magnitudes of small events to determine the structure of the fracture network from which geothermal fluids are being produced. The observed structure and magnitude distribution also indicates whether the microsesmicity is triggered or induced. Despite decades of research, modeling of fractured reservoirs is still mostly based on the double-porosity model, even though its inadequacy for modeling of most of such reservoirs is well-documented. Some progress has been made, but the problem is still largely unsolved. At the same time, even if the geological model of a fractured reservoir can be adequately developed, its up-scaling for use in reservoir simulation is still a major problem. Finally, with the advent of dynamic reservoir characterization, the development of a flexible model that can incorporate rapidly the newly arrived data and information and upscale the model has become paramount. Some of the major problems that one must address are:

- 1. How to adequately represent the widely disparate relevant length scales in a single model: Oil and gas reservoirs are highly heterogeneous at several distinct and widely separated length scales. Every relevant length scale may contain certain information that are useful, and even crucial, to the overall accuracy of the model.
- 2. How to represent the fracture and the matrix accurately, given the heterogeneous distribution of the former: As is well-known, fractures are not distributed as in the double-porosity model, which assumes a well-connected fracture network in the form of a cubic network, or some perturbations of it. They are distributed non-uniformly with the fractures' orientations and lengths following statistical distribution. If there are only a few dominating fractures that control most of the fluid flow, the problem is even more difficult.

- 3. How to model the interaction between the matrix and the fractures, given the large differences between the permeabilities of the two: A uniform grid cannot represent the interface between the two.
- 4. Even if an accurate geological model of a fractured reservoir is developed, the question of its up-scaling to a coarse, yet accurate level, is still a major challenge: Practically, all the current up-scaling methods are inadequate when it comes to fractured reservoirs. Thus, one must resort to empirical, semi-empirical, and curve fitting in order to develop the up-scaled model.
- 5. Given the advances in dynamic reservoir characterization, and in particular dynamic history matching, any model must be flexible enough to be able to handle new incoming information and data, incorporate them in the model, and up-scale it quickly, in order to maintain the model up to date.

Long-term vision of how this impacts the industry

A detailed map of the fracture network can be used in formulating extraction strategies, as it is an improvement on the dual-porosity models commonly used to model fracture dominated reservoirs. A determination of whether the microseimicity is induced (event energy comes from the injection itself through pressure or thermal contraction) or triggered (energy comes from the release of stored tectonic stress) is important in assessing the risk of causing a large destructive earthquake. This risk is low for induced seismicity and higher for triggered seismicity.

Recent related activities in the industry/academia

It has long been known that tectonically driven fault networks are self-similar (fractal) with a fractal dimension near $D_{r=2}$ in 3 dimensions. It is also known that the *b*-value (the slope of the Gutenberg-Richter frequency-magnitude relation) is near b=1 in tectonic regimes. Theoretical analysis of seismicity on a fractal network shows that the fractal dimension and b-value should be related as $b=2D_{f}$, which matches observation. It is also known that the b-value in volcanic and geothermal areas is significantly higher than b=1 as is the fractal dimension of the seismicity (if it is fractal, which is not always observed).

Brief Project Description

We are currently mapping microseismicity in The Geysers geothermal reservoir and measuring the fractal (correlation) dimension and *b*-value for selected clusters of activity. Our preliminary results find high b-values approaching b=1.3 and correspondingly high fractal dimension approaching $D_{r}=2.6$. The implication is that we are observing induced seismicity and the risk of triggering a large tectonic earthquake is low. Our working hypothesis is that tectonic seismicity is limited to the near-vertical faults in the network since they have lower normal stress and hence less frictional resistance to shear. Induced seismicity involves volume change and is not necessarily favored on vertical fractures. Since the entire fracture network is active, the observe dimension is near $D_{r}=3$ and the corresponding b-approaches b=1.5.





- 1. To address the problem of incorporating all the relevant length scales in a single model, we have developed use of multiresolution wavelet transformation that is capable of addressing the multiscale nature of the problem.
- 2. To address the problem of incorporating a non-uniform spatial distribution of fractures, we have been working on the development of discrete fracture network models that are totally flexible and can represent practically any spatial distribution of fractures.
- 3. To address the problem of how to represent the interactions between the matrix and the fractures, we have been developing a method that combines three essential ingredients: (i) Use of a totally unstructured grid; (ii) representing the fracture as merely the high permeability paths, and (iii) use of multiresolution wavelet transformation to determine the density of the grid not just the in the matrix, but also around the interface between the matrix and the fractures. Two-dimensional models have been developed, and we have begun the development of 3D model based on advancing front technique and the aforementioned three ingredients.
- 4. To address the problem of up-scaling of the geological model of fractured reservoirs, we have been developing a method based on the use of wavelet transformation. The method has already been developed for the unfractured reservoirs and, in addition to its high precision, has been shown to be computationally more efficient than the best alternative by at least three orders of magnitude. Due to the nature of the wavelet transformations, its use for fractured reservoirs is natural, and the model
- 5. Due to its flexibility and extremely high efficiency, incorporation of new data that may become available dynamically poses no major problem with the models and methods that are developing.

We have extensive experience in developing techniques for addressing all the major problems that may arise. For example, we have been developing novel techniques for the analysis of cross-correlations between various types of data, including well logs. In addition, we have been studying elastic wave propagation in heterogeneous media and the effect that large-scale heterogeneities and long-range correlations have on the wave propagation and its localization, which are completely relevant to the interpretation of seismic data.

Here, we propose to develop an integrated method that addresses the five major problems listed above, and develop a flexible, accurate, and highly efficient technique for the development of models of fractured reservoirs that is also flexible enough that can be used in conjunction with dynamic reservoir characterization.

The model may also be easily integrated with what other members of the RMC are doing, or plan to do, such as the groups led by Fred Aminzadeh, and by Cyrus Shahabi, since in order to update the upscaled model one needs fast processing of the new data and their incorporation in the geological model, in order to efficiently upscale the model.

Immediate plans and goals for 2011-2012

We plan to enhance the fractal analysis by using the magnitude information. The idea is that larger events involve a larger fracture (or fault plane) so we can incorporate this information into our ultimate fracture map. This has, to our knowledge, never been done.

Deployment and testing plans

We would like to apply this analysis to other reservoir seismicity data.

Desired interactions with the sponsors

- 1. We expect the sponsors who are members of SEAM facilitate USC access to the models and the corresponding 3D synthetic seismic volumes developed under SEAM
- 2. Sponsors can suggest which models should be considered for our tests.
- 3. Any sponsor who may wish to provide real data can work directly with USC to test the results using their data. This part of the work can be either exclusive with that sponsor (if the results to be kept confidential) or other sponsors can be involved in the tests. Accordingly, different funding mechanism for this part of the effort may be required.

Key references

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<u>4- PPP12KJ</u>

Key People: Shangxu Wang, Fred Aminzadeh, Flora Sun

Project Name: Understanding impact of reservoir fluid on seismic response using physical modeling

Core Technical or Practical Problem(s) we are addressing

We propose to develop and conduct physical modeling experiments with the aim of predicting the reservoir fluid content in complex geologic settings. Time lapse seismic data is a vital tool in understanding the reservoir fluid distribution. However, there is still considerable scope for improvement when it comes to delineating the subtle differences between zones containing oil and water. Experiments have shown that the reflection characteristics of the resulting seismic response may differ based on the type of fluid present and these differences can either be directly predicted or indirectly obtained due to

transmission effects. These differences should be useful in better interpretation of time lapse seismic data with a better delineation of different fluid zones of interest. We also plan on using these modeling experiments to develop and test fluid detection and inversion techniques for contemporary use. This project will allow us to demonstrate the effectiveness of different seismic attributes in observing fluid saturation impact as well as their diagnostics capability.

Long term vision of how this impacts the industry

Our proposed approach should allow for better physical models to be generated and should lead to more accurate fluid prediction in reservoirs. The tools developed should be useful in all those settings where multiple fluids are expected in the reservoir (water flooding and other multiphase flow scenarios) and should improve reservoir management in the long run. Moreover, if fluid properties can be deduced from seismic data, oil & gas exploration efficiency can be greatly improved.

Recent related activities in the industry/academia

Seismic modeling has been used extensively as a tool for exploration. Most of the efforts have been limited to numerical modeling. The main focus of such numerical modeling has been to test the impact of changes in the geologic structures on the seismic response. Till date, the applications have included examining the imaging approaches, analyzing the impact of reservoir fluid on the seismic response as well as many other reservoir property prediction problems such as pressure, porosity and permeability mapping. Physical modeling approaches has also been used to simulate both structural models and reservoirs with different properties. In the recent years, time-lapse seismic, AVO and prestack elastic inversion have been used extensively for hydrocarbon detection.

Brief Project Description

The project workflow can be summarized as follows:

- 1. First step will involve the preparation of reservoir model based on the geologic setting under investigation. An example of a typical model can involve overburden stratum and a series of thin reservoirs with interbedded shale layers (simulating shale setting). Design of such models is well understood and has been done in the past by the project team. Figure 1 shows this sample physical model setting in some detail.
- 2. The parameters of the designed model will be obtained through systematic examination of the same. At this point we will also devise the relation between the physical model and the actual geological setting in question.



Figure 1: Experimental setup

- 3. Experimentation and data acquisition phase will follow. The acquisition parameters will be kept as close to the real reservoir setting as possible and repeatability will be used to keep the necessary parameters identical in all experiments with different fluids under study.
- 4. Next stage will involve experimental data processing. This involves upscaling the acquisition system to field level followed by filtering, stacking and migration.
- 5. Cross-equalization technique will be used to keep the non-reservoir reflections consistent and to focus the differences in the reservoir response. Differencing techniques such as midpoint amplitude difference, etc will be then applied to analyze the attributes in a time lapse fashion.
- 6. Attributes other than amplitude will be tested including those associated with the spectra and the phase of the signals.
- 7. We will test for observable differences between different phases being present in the reservoir model. These reflection characteristics will be documented and developed further for possible use in real life scenarios to distinguish reservoir types, etc.
- 8. Results will be finally applied in a real test case reservoir setting and the designed attribute anomalies will be tested in the field case to monitor fluid changes in the reservoir (such as EOR processes using gas injection).

Immediate plans and goals for 2011-2012

The following tasks will be carried out in the first two years of the project.

- Define reservoir setting as well as the attributes to be worked with.
- Design and develop physical models based on the actual reservoir under study.
- Design experimentation workflow based on defined project objectives.
- Design the acquisition scheme based on the actual reservoir and seismic data acquisition scheme being followed.
- Conduct necessary experiments in different settings as defined in the workflow.



Figure 2: Differences in RMS, maximum, minimum, average and mid-point amplitudes for gas/ oil (left figure) and water/ oil (right figure) indicating fluid variations detected within the reservoir for gas/ oil combination and below the reservoir for water/ oil combination.

Deployment and testing plans

Upon the availability of time lapse seismic data from the sponsors, we will test our results on the real data case.

Desired interactions with the sponsors

Any sponsor or group of sponsors can suggest a particular physical model to be built. The characteristics of such model can be chosen to mimic a particular type of reservoir to test the impact of different structural settings or reservoir properties on the seismic response. This part of the work can be either exclusive with that sponsor (if the results are to be kept confidential) or other sponsors can be involved in the tests.

Key references (own or others work)

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ppendix 15- PPP15DH

Key People: Donald G. Hill, Fred Aminzadeh and Arman Khodabakhshnejad

Project Name: Time Lapse Petrophysical Reservoir Monitoring and Evaluation of Reservoir Characterization Sensitivity

Core Technical or Practical Problem(s) we are addressing

We would evaluate the sensitivity of various existing and potential reservoir petrophysical monitoring and characterization protocols to meet the reservoir monitoring needs of existing and future conventional and unconventional reservoirs.

Long-term vision of how this impacts the industry

It has been said that while a theory can be right or wrong, a model can be right, wrong, or irrelevant. Successful reservoir monitoring requires reservoir models. If the reservoir is inadequately characterized, the resulting model will be inadequate or irrelevant. The petrophysical parameters of reservoirs under production will change, with time. As a result, even those reservoirs which were properly characterized, initially, need to have their characteristics monitored, over time, as they are produced.

Seismic data that is used to monitor changes in reservoir for both conventional and unconventional reservoirs needs to be calibrated using well logs. Inversion of seismic data could not be performed without building precise time-equivalent petrophysical properties.

Some companies required wireline vendors to shut down all non-correlation logs outside of previously identified pay zones. While this practice obviously save the operator a few U\$S/ft. in logging charges (depth charges would be unchanged), the incumbent and successor operators were left naked, once the primary drilling targets were depleted because this inadequate logging program offered no source rock and/or bypassed pay information.

Furthermore, many of the giant and super-giant Niger Delta fields were developed with a wireline program, which consisted of:

- Gamma Ray logs to differentiate between sands and shales.
- LateroLog 3, to determine if the sands were pay.
- Sidewall Cores to distinguish between gas and oil hydrocarbons.

While this logging program also saved on initial logging costs, it was totally inadequate for depletion planning and probably misidentified some high-energy Zircon rich beach sands as shales, because of the thorium content in the zircon.

Conventional wireline, Measurements while Drilling (MWD)/Logging While Drilling (LWD), and core analysis also appear to be inadequate for unconventional hydrocarbon resources, such as shale oil, Coal Bed Methane (CBM), Shale gas and complex reservoir rocks like the Monterey and Bakken Formations. If the reservoirs are inadequately characterized, to begin with, any monitoring program becomes problematic.

With the decline in major new hydrocarbon discoveries, the importance of increasing recovery from existing reservoirs is equivalent to locating new reserves. Improving the efficiency and safety of stimulation and enhanced oil recovery (EOR), as well as monitoring technologies for these technologies are essential for increasing recoverable hydrocarbon reserves. Achieving this goal is only possible through accurate evaluation of petrophysical properties of reservoir for current and future development plan.

The most common EOR technologies are Water and Steam flooding. New technologies, which can deal with thief zones and tight formations, as well as those, which do not involve introducing foreign substances into reservoirs need to be evaluated. While there have been some evaluations of monitoring EOR activities, this need to be expanded.

Recent related activities in the industry/academia

The solutions to the first problems, listed above, are obvious: make more measurements, but which ones? Wireline MWD/LWD and core measurement vendors are not going to recommend selective measurements, if it will result in fewer services, requested.

The unconventional reservoir characterization issue is even more complex. Recent unconventional reservoir workshops have moved from traditional Formation Evaluation (FE) volumetric (i.e., porosity and saturation) and flow (i.e., permeability) and Recoverability (i.e., capillary pressure) measurements, used to estimate total and recoverable reserves, to resource (i.e., Total Organic Content, or TOC) estimation with recovery based upon production decline curves.

Tilt-meter, and Microseismic monitoring have been utilized for monitoring stimulation and fluid flood EOR projects. Cross-well seismic and EM tomography have been utilized to monitor the advance of steam and water floods. These, and other, monitoring technologies need to be further evaluated and improved for monitoring stimulation and EOR projects, with time.

Brief Project Description

We will start by evaluating existing laboratory, wireline and MWD/LWD technologies for initial reservoir characterization and reservoir monitoring, with time, to identify which protocols appear to provide the most cost-effective benefits for reservoir monitoring and the situations where they work best. We will also look into integration of MWD and LWD with Seismic While Drilling (SWD), for further improvement in both drilling process and reservoir monitoring, Neill et al (1993).

Pulsed Neutron Capture (PNC) and Cased Hole Resistivity (CHR) techniques have both proven successful in some environments but not others. We will also evaluate potential new measurement technologies. which have not had sufficient time to develop any consistent "Track Record". We will also evaluate existing stimulation and EOR monitoring technologies in an effort to improve upon existing technologies or develop new technologies.



Immediate plans and goals for 2011-2012

The following tasks will be carried out in the first two years of the project.

- Evaluation of existing laboratory, wireline and MWD/LWD technologies for initial reservoir characterization and reservoir monitoring technologies.
- Evaluation of existing and mature experimental stimulation and EOR Technologies.
- Evaluation of surface-Borehole permanent monitoring arrays

Deployment and testing plans

Upon the availability of field data from the sponsors, we will test our results on such real data cases.

Desired interactions with the sponsors

- 1- We expect the sponsors who are members of USC RMC to facilitate USC access to existing reservoir characterization and monitoring studies
- 2- Sponsors can suggest which models should be considered for our tests.
- 3- Any sponsor who may wish to provide real data can work directly with USC to test the results using their data. This part of the work can be either exclusive with that sponsor (if the results to be kept confidential) or other sponsors can be involved in the tests. Accordingly, different funding mechanism for this part of the effort may be required.

Key references

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<u>6- PPP16AO</u>

Key People: Antonio Ortega Yenting Lin, and

Project Name: Reservoir Modeling using Tomography based on Field Operation Data

Core Technical or Practical Problem(s) we are addressing

Identifying high contrast heterogeneous structures within a reservoir is always a challenging problem for reservoir modeling. A major limitation of conventional methods (seismic, tracer test) is that they require additional equipment, cost and time, and so cannot be used on a routine. Our goal is to identify these heterogeneous structures by using field operation data that is routinely available, including for example injection/production rates in a waterflood. We propose to use novel injection (water, steam, etc) schedules and to monitor gross fluid production in order to actively measure the response time between well-pairs without altering the average daily operations. With the well-pair response time, we develop object-based algorithms to identify the heterogeneous structures. These object-based algorithms are designed specifically to provide robust performance when high contrast structures have to be detected (e.g., high permeability channels).

Long term vision of how this impacts the industry

Real-time monitoring and identifying the heterogeneity for reservoir flow property is critical for prediction and production optimization. With the seismic or tracer test methods, it is possible to provide a map of reservoir flow properties but normal operations need to be interrupted for measurements to be obtained. Our active injection method provides a monitoring tool that does not disrupt normal operations and can estimate dynamic reservoir behavior, enabling the observation of changes in heterogeneous structures as they occur. Our long term vision is for the tools we develop to provide real time monitoring of reservoir characteristics with no impact on daily operations.

Recent related activities in the industry/academia

There has been significant interest in understanding highly heterogeneous reservoirs, which contain high contrast permeability structures that are likely to give rise to very fast flow paths. Grid-based inversion methods have been proposed that make use of tracer test or seismic data. To the best of our knowledge, we are the first to propose using injection/production rates to identify high contrast heterogeneous objects. We are also leveraging an emerging body of work on signal sparsity in the signal processing literature, in order to improve the reconstruction quality we can achieve.

Brief Project Description

With decreases in cost, multiple types of sensors can be found in modern reservoirs. These sensors record actions taken, such as rates (e.g., injection, steaming) or events (e.g., hydraulic fracturing, maintenance), while also recording production rates with different levels of granularity (e.g., bi-weekly). Even though increasing amounts of data are available, *a key challenge remains in modeling reservoirs in real time at a level of detail consistent with the amount of data available.* We propose to develop techniques based on two emerging signal processing techniques, namely sparsity and graph based representations, to achieve the best possible models, with accuracy adaptive to the amount of observed data, which sometimes can be very limited.

We consider tools for building object-based models to present high contrast heterogeneous structure by using sparseness constraints. This makes it possible (as in compressed sensing applications in signal processing) to identify likely models even when insufficient data is available. Compared to grid-based methods, we will be able to achieve better accuracy with limited data. We also use graph representation to model the relationship between heterogeneous objects. This concept enables us to apply the prior information and connectivity of these objects. Examples of application include tomographic techniques to estimate permeability and shale discontinuity between layers.

The proposed techniques can also incorporate prior information in order to favor solutions that match known reservoir characteristics. For example, prior seismic studies could be used in order to favor solutions with high permeability channels in certain orientations. Because the complexity of these algorithms is modest, it is possible to generate multiple solutions under different prior assumptions and present the end user (e.g., a reservoir engineer) with different alternative interpretations of the reservoir characteristics

Immediate plans and goals for 2011-2012

The following tasks will be performed in the first two years.

- Estimation of orientation of hydraulic fractures at producers and of shale breaker between layers using tomography
- Experimental design injection schedule techniques for modeling the reservoir as large scale MIMO systems

Deployment and testing plans

After completion of the development phase, the viability of the proposed approach can be evaluated using field data or apply a field trial by the sponsors.

Key references

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Lin, Y. and Ortega, A. and Nejad, A. and Ershaghi, I. "Waterflood Tomography: Mapping High Contrast

Permeability Structures Using Injection/Production Data". In Proceedings of the 2010 SPE Western Regional Meeting(SPE WRM 2010), Anaheim, May 2010.



perm estimation: (a) Testing case in simulator; (b) Injection schedule; (c) Retrieved wellpair response; (d) Estimation result of high perms.