Direct Reservoir Imaging: The Need for Innovative Advancement in Exploration and Production*

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Abstract

The seismic methods being used today for imaging reservoirs rely on the propagation of seismic waves through earth and mapping the reflected signals from the interfaces of the sub-surface rocks. The current science of seismic imaging is based on the assumption that the earth behaves as an elastically linear medium. This assumption over-simplifies the behavior of the fluid-saturated reservoir rock and avoids the complexity of dealing with the dynamic physical properties of the oil and gas fluids stored in the porous reservoir rocks. What is needed is the development of a new methodology that will provide a new seismic approach that will allow us to map the reservoir porosity profile, permeable flow units, location and orientation of fractures, and the distribution of different viscosity pore fluids.

Criteria for the future technology should be such that it has to directly indicate the subsurface accumulations of the hydrocarbons. This new technology needs to be sophisticated enough to satisfy the requirements of the large companies with budgets of tens of billions of dollars for mapping the inter-well geologic profile of the reservoir rocks and their flow characteristics (including porosity, permeability, pockets of oil left behind) to achieve more efficient secondary and tertiary recovery, and at the same time be simple enough that it can be effectively used by a small-size independent explorationist, whose budget may be limited to finding small pockets of oil reserves in his or her local area of operation. Ideally, it is not going to be capital-intensive and the current hardware/software can be used, so that the rewards will be directly related to the exploration efforts of the oil companies.

Using current extraction capabilities, hydrocarbon reserves can be economically produced if a seismic imaging technology is introduced to provide unique and unambiguous results for identifying and locating the hydrocarbons in the reservoirs. The introduction of a new technology, which can make direct measurements of the reservoir pore fluids and the relevant reservoir characteristics, will open a new world of possibilities for oil and gas exploration and production.

For oil and gas, Nonlinear Seismic Imaging is considered a breakthrough technology that will solve many of the complex challenges we will face in the next few decades as the easy oil has been extracted. Using Nonlinear Seismic Imaging, we do not lose anything that the existing

imaging provides. Nonlinear Seismic is additional information, which gives us a better understanding of the reservoir rocks and their pore fluids that are of the primary interest in exploration for oil and gas.

The topic covers this technology for direct reservoir imaging, which is based upon mapping the changes in the reflection and propagation characteristics of the seismic waves according to the physical properties of the reservoir fluids and the pore space. The work so far has resulted in a portfolio of U.S. Patents that describe new seismic imaging methods to directly map the porosity, permeability, fractures, and reservoir fluids. The most recent invention is Direct Reservoir Signature using the Drag Wave™.

NONLINEAR SEISMIC IMAGING, INC.

Direct Reservoir Imaging

The Need for Innovative Advancement in Exploration and Production

Permian and Midland Basin New Technologies
An AAPG Research Exchange (RX) September
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Houston, Texas USA

A New Seismic Approach

- Addresses a change of the fundamentals being used in subsurface imaging methods to explore for oil and gas
- We cannot ignore the effects of nonlinearity
- Use new seismic attributes
- Upgrade the physical model of the reservoir rocks
- Simplify interpretation and reduce ambiguity

Dynamic Elastic Nonlinearity of the Reservoir Rocks

- Responsible Mechanism
- Grain to Grain Contacts
- Low Aspect Ratio Cracks
- Pore Fluids
- Micro-Heterogeneities

Sensitivity of Nonlinear Response to the Grain Structure and Fluid Content is Greater than the Linear Measurements of Wave Speed, Modulus and Attenuation.

Nonlinear Response of Earth Materials is Pervasive.

(Los Alamos National Laboratory, USA

Three Main Attributes of the Nonlinearity Component

- Harmonics of all the primary frequencies that are present in the seismic signal
- When there are more than one seismic signals propagating through the reservoir formation simultaneously, the sum and difference frequencies of the two primary waves are created
- Another seismic wave is created which is identified as the Slow Wave or Drag Wave™. This Slow Wave travels at a lower velocity than the velocity of the compressional wave. This phenomenon creates a very low frequency wave that will only be present in the reservoir

Processing

- Pre-planning is critical
- Proper data acquisition
- Define the specific problems
- Cannot use a generalized approach and partial knowledge to find solutions to the complex challenge

How do we map the unique signals that are being generated in the reservoir rock when the compressional wave propagates through it?

Illustrative Examples using Empirical Results

- Crosswell Seismic Showing Direct Relationship between
- Porosity, Pore Fluids and Nonlinearity – an early study
- Land data showing Conventional and Nonlinearity
- Component images – trying out a new technique
- Land data showing Conventional/Nonlinearity components, and Drag Wave – Zhukov confirmed
- Lower frequencies highlight the reservoir rocks that conventional seismic fail to image
- Marine data Low and High frequency comparison for verification of the reservoir anomaly

In order to understand the flow patterns between the wells and between the reservoir facies for accurate reservoir simulation in secondary and tertiary recovery and CO2 injection, how can we measure the permeable continuity which will define the permeable units in the interwell space?

To eliminate the cost of drilling dry wells, how can we map the porosity profile of an existing or potential reservoir?

If there's a deeper zone, can both zones be mapped simultaneously?

Will the presence of the Slow Wave generate a unique and independent signal that will identify the reservoir?

If there is no acoustic impedance contrast between the reservoir and other non-reservoir sedimentary rocks, can this technology be used to identify and map those formations?

How do we certify and ensure that we have highlighted the seismic anomaly which is porous and fluid-saturated?

Differential Illumination

- Based on the field examples, we can identify how the oil and gas producing zones are highlighted and unproductive rocks obscured
- Conventional linear seismic images are retained to provide the structural information
- Additional nonlinearity component images are provided to display hydrocarbons

Direct Reservoir Signature using the Drag Wave™

- Deliver simple approach
- Information that is currently being ignored
- The lower frequency generated due to the Drag
- Wave is totally unique
- This lower frequency becomes a very reliable indicator of the presence of subsurface reservoir formations

Permian Basin and Midland Basin

- Reservoir Quality: The formations change laterally a great deal due to the depositional environment – it can be tricky to measure reservoir quality
- There are so many new shales that are now being considered prospective and need evaluation
- Before CO_2 flooding can be implemented, the flow model has to be understood to deploy such technologies in reservoirs with complex geology

Rigorous Solutions for the Complex Challenges

- Direct Reservoir Signature
- Imaging Reservoir Effective Porosity
- Imaging Reservoir Permeability
- Mapping Pore Fluids
- Imaging Reservoir Fractures

Compatible with State of the Art Technology

- In areas with vertical wells and horizontal drilling
- Anywhere the current seismic can be effectively used
- Nonlinear Seismic Imaging does not eliminate anything
- The end result produces the conventional seismic image and additionally provides images based on Nonlinear Seismic Imaging attributes.
- Data recorded from any seismic method can be used with this special application

Conclusion

- This technology as implemented will evolve to assist industry in recovering new accumulations of hydrocarbons and extracting more efficiently from existing reservoirs
- Direct Reservoir Imaging could help us in mapping the hydrocarbons in the reservoirs which cannot be mapped due to the shortcomings of the current technology, which maps structure in contrast to this new approach which will map the fluids of interest.
- Secondary and tertiary recovery – provide better understanding of the reservoir flow model – injection and recovery programs can be applied with greater efficiency

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The Importance of the Frequencies Generated in the Reservoir Itself

- Permeability is one of the most important factors in influencing the commercial viability of a hydrocarbon reservoir.
- Drag Wave™ cannot exist without the interconnected pores that contain fluid.
- Due to the presence of this Drag Wave™ in the permeable rock formation, the character and the amplitude of the reflected and refracted signals is affected and changed.
- Measurement of the Drag Wave™ frequency and its relative amplitude is directly related to the bulk tortuosity and bulk permeability of the reservoir formation, which affect the flow mechanism of the reservoir fluids.
- Understanding the Drag Wave™ behavior can be used to identify the prospective subsurface reservoir potential.
- During the propagation of the seismic wave in the reservoir rocks, a certain amount of spectral broadening takes place. This spectral broadening is caused by the elastic nonlinearity of the reservoir rocks.
- The presence of these newly created frequencies in a seismic reflection representing a subsurface reservoir formation is an indicator that the particular formation is porous and permeable.
- The lower frequencies of interest are generated due to summing and differencing of the discrete frequencies which are part of the input signal wavelet which have the broadening effect of the spectrum of the original input signal.
- These lower frequencies are not part of the input signal – they are generated in the reservoir itself and will not be present without a porous and permeable reservoir.
- A significant contribution of the lower frequencies is caused by the Drag Wave™
- These lower frequencies can be mapped
- In the case of fractures, the lower frequency anomaly will only be there when the source/receiver orientation is at right angles to the fractures.
- Without porosity and permeability, lower frequencies of importance will not be generated
- Mapping the lower frequencies using Nonlinear Seismic Imaging methodology is a very cost effective way of locating the reservoir formations.

Fractured Reservoirs

- NSII has three Patents that describe new methods of mapping fractures, joints, and conductive faults. U.S. Patent # 6,678,617 describes a surface seismic method designed to map the swarm of fractures and their orientation. Recording and processing procedures are similar to the standard 3D seismic. The processed end result is a conventional 3D image and two additional 3D images highlighting fracture sweet spots only. The orientation of the fractures can be determined by creating reservoir images using different azimuthal angles. This Patent addresses the industry need to map fractured sweet spots in low permeability reservoirs. Fractured low permeability reservoirs are common throughout the world and are prime targets for future hydrocarbon exploration.
- U.S. Patents # 6,597,632 and # 6,684,159 describe methods to map individual fractures, joints, and conductive fault locations and orientation with higher accuracy. Determining the exact location of fractures and faults has become increasingly important in reservoirs where water invasion is problematic. Some of the prolific carbonate reservoirs in the world have high permeability layers intersected with vertical fractures, joints, and conductive faults. When the reservoir had a full oil column, the combination of high permeability layers and conductive faults helped in producing large quantities of oil from each individual well. As the oil column gets reduced and as the water level in the reservoir comes up, new problems emerge. The fractures and faults become water carriers. The water production goes up. The direction of the water flood becomes unpredictable. In cases like these, which are common worldwide, it is important to know the exact location and orientation of the fractures, joints, and faults to design a production program that will maximize oil recovery with the lowest cost.
- Horizontal drilling has become more popular since the horizontal wellbore intersects more of the producing reservoir rock. Thus, horizontal drilling has increased the demand to map and characterize the fractures with greater accuracy. The ability to drill horizontally and stay in a selected reservoir formation, control the drilling directions and horizontal well lengths, provides a method to get higher productivity. To take full advantage of this capability, correct decisions have to be made for selecting the formations, directions, and lengths of the wellbore to optimize costs and production. These decisions can only be made if the location and orientation of the fractures are accurately mapped. U.S. Patents # 6,597,632 and # 6,684,159 describe the methods to achieve the desired accuracy. U.S. Patent # 6,597,632 uses a vibratory surface source and is more suited for land operations, while U.S. Patent #
- 6,684,159 uses an impulsive source more suited for marine operations. These three Patents cover the range of requirements of mapping and characterizing the fractures and conductive faults in reservoirs with different geologic environments.