Chemistry, a step ahead in Rock Physics applied to Time-lapse Seismic

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Abstract

In carbonate rocks, oil production monitoring by seismic is always defiant, and things become much more difficult when this kind of reservoir is found at big depths, as in brazilian pre-salt offshore fields. Due mainly to the high stiffness and low porosity, we need leading edge geophysical technologies in order to get some indirect information about reservoir dynamics. Knowing that, the very first step to support the decision of investing in a 4D seismic project is the feasibility study, i.e., the numerical simulation of changes in rock properties and, consequently, seismic attributes.

Geophysicists routinely simulate these changes taking into account a multitude of methods developed since the classical Gassmann´s work (from the 1951). For fluid substitution most of models have a mathematical formulation, while pressure variation effects are more dependent of empirical relations established from laboratory measurements. Anyway, the state-of-art modelings assume that rock matrix is invariant, what is an acceptable premise in many cases. However, reality is more complicate when carbon-dioxide is present in a carbonate reservoir, as happens in many fields of Santos Basin, Brazil.

Several laboratory experiments could show variations of matrix elastic modulus due to the interaction between carbonate minerals and fluids that become acid due to chemical reaction of CO2 and water. This fluid, generally named carbonated water, has a smaller pH when compared to brine because of the formation of carbonic acid (H2CO3). Even though this phenomenon is well known, we do not have yet a consolidated methodology to numerically model it.

In this way, assuming that rock-physics is not all we need, the purpose of this paper is to propose the incorporation some chemical theory in order to build, in the future, a time-lapse seismic modeling methodology that could take into account the effect of acidification in carbonates. A methodology that could be informally denominated "rock physical chemistry".

Introduction

Some of the Santos Basin´s oil fields in carbonate reservoirs have high contents of CO2. In order to follow environmental regulations, this gas is reinjected into reservoirs after separation from hydrocarbons. Consequently, its saturation raises and it leads the rock-fluid system to a new chemical equilibrium, what can result in reaction of water and CO2 to generate carbonic acid (H2CO3). Under this new (smaller) pH pore fluid value, dolomite and calcite may be partially dissolved, as verified in laboratory experiments where one injects carbonated water in this type of rock. Alteration of rock matrix causes some small changes in porosity, but significant changes in bulk and shear modulus, mainly because of less cementation. Vanorio (2015) is one enlightening example of such investigation.

In spite of partial dissolution of a carbonate rock matrix by acidification being widely known, geophysicists are yet poorly served of methodologies to numerically estimate variations of reservoirs elastic properties due to it. Most of the current rock-physics models can vary fluid saturations, pressure and porosity when updating P and S impedances, but they assume matrix as invariant (a heritage from Gassmann theory).

The humble ambition of this work is to outline a future research program with an ultimate target: development of a new time-lapse feasibility study workflow where one can incorporate chemical interactions between pore fluids and rock matrix.

Method

The first insight to my proposal came from Aimoli et al. (2015), who estimated pressure, density and viscosity for a mixture of CO2 and CH4 flowing at different temperatures. Their objective was to characterize an homogeneous flow of this composed fluid in pipelines. Although they don´t take into account chemical reactions, the work illuminates the path for the application of

statistical thermodynamics in molecular simulations, once the authors could represent numerically the behavior of some small amount of molecules and then performed statistical analysis to establish the most likely behavior of much bigger volumes.

Going to the case here, It seems feasible to adopt a similar approach to model reactions encompassing CO2 and H2O and, in a later step, H2CO3, dolomite and calcite. Assuming that is impossible to link chemical simulations directly to their impact in reservoir elastic modulus, the most promising alternative is to build templates from laboratory measurements and extract petrophysical and elastic parameters from them, after estimating the amount of matrix corroded.

It seems important to take advantage of the work of Yuan et al. (2017), who developed a numerical modeling of carbonate dissolution due to CO2 injection, specially when running flow simulation. Redy and Balasubramanian (2013), as well as researchers at Berkeley Lab and the University of California (2015), pointed the very short lifetime of carbonic acid in a carbonated solution, what is an essential information for unconsidering H2CO3 concentration in estimation of pore fluids acoustic properties. It´s also necessary to mention that PETROBRAS, in partnership with Stanford Rock Physics Laboratory, did in the recent past non-published laboratory experiments and flow simulations in carbonate rocks with similar objectives.

After all this scientific effort, the novelties brought by this paper are the incorporation of statistical thermodynamics and the proposal of a research program that would establish a complete numerical modeling workflow, from the CO2 injection until the determination of updated seismic amplitudes. In this very preliminary stage, my idea can be synthesized in the following steps:

- Run flow simulation to estimate the extension of injected CO2 plume after a given time and obtain CO2 saturation for all grid cells, as well as pore pressure.
- Parameterize reservoir environmental conditions (temperature, pressure, saturations, salinity, etc).
- Run molecular simulation to verify if conditions are suitable for CO2 and H2O reaction, forming H2CO3.
- Considering an adequate (very small) rock volume and a given effective porosity, calculate the total area of the connected pores walls.
    - Here we probably will need a digital rock model of the reservoir facies we are working on.
- Considering the case of mono-mineral matrix (only calcite, for example), determine the number of CaCO3 molecules in contact with fluids in the pores.
    - As the methodology evolves, some day we will be able to model multi-mineral matrixes.
- Run molecular simulations to check if conditions are suitable for calcite dissolution and, if yes, estimate the chemical reaction velocity and the volume of calcite dissolved by carbonated water (what is function of CO2 saturation and elapsed time since the arrival of injection fluid).
- Calculate porosity increase, what is proportional to dissolved calcite..
- After updating porosity, determine new dry-rock elastic modulus (K_{dry} and μ_{dry}) from correlation with laboratory measurements with the same reservoir facies.
- From correlation with the same laboratory measurements, determine new values of permeability.
- Given fluid composition, update fluid bulk modulus (K_{fluid}), .
- Considering some theory (as Gassmann, for example) calculate saturated-rock modulus (K_{sat} and μ_{sat}).
- Iterate on all previous steps until comprise a range of typical scenarios, in terms of pH and time since the corrosion started.
    - As molecular simulations can demand large computational effort, il looks advisable (and realistic enough) to discretize CO2 concentrations and time since the trigger of reaction between calcite and carbonated water.
- Interpolate results in order to update all cells of the elastic model (P-velocity, S-velocity and density).
- Run seismic modeling to obtain updated seismic amplitudes.

In this first version of the workflow, we would assume an unique chemofacies, i.e., an homogeneous chemical behavior of reservoir when in contact with injection plume. Under this premise, weakening of rock matrix will be spatial-dependent only on the time of arrival of carbonated water at each grid cell. Nonetheless, it´s not difficult to imagine that we would be able to perform 4D seismic modeling on a more realistic oil field representation. The additional challenge will be to characterize more than one chemofacies from our knowledge of the geologic model and its lithofacies and then to settle the distribution of them.

As pointed by Vanorio (2015), permeability can increase a lot after acidification. In some cases, we possibly will have to perform a second loop, running a new flow simulation after updating permeabilities.

Conclusions

From bibliographic review of works involving thermodynamics, molecular simulation, flow simulation and rocks physics, as well as my experience with time-lapse seismic, I propose the opening of a research program whose final goal would be to establish a novel 4D seismic modeling methodology specific to the cases of CO2 injection in carbonate rocks. Thus, we could incorporate alterations of rock matrix due to the chemical reactions with acid fluids. Once we could do that, we would have a chance to improve our 4D feasibility studies in carbonate oil fields, now taking into account the already known decrease of compressional and shear modulus of rock matrix by acidification, as well as the minor increase of porosity.

It´s pretty obvious that the proposed workflow will suffer significant changes as soon as some people decide to follow the suggested path. This work is no more than the first draft of a travel plan.

Finally, I´d like to emphasize that such idea of a research program, as any other one, has the risk of miscarriage. The only way to check its feasibility is doing the research.

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