Use of Seismic and EM Data for Exploration, Appraisal and Reservoir Characterization

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Summary

We argue that unless there is a common physical property in the physics underlying different geophysical exploration techniques, different data types should be processed and, where necessary, inverted independently to recover physical properties of subsurface rocks . These physical parameters can then be combined to infer petrophysical rock properties.

Introduction

The oil industry spends billions of dollars each year on geophysical measurements, well logging, and core analysis, in addition to all the physical and chemical measurements that are required for the principal business of hydrocarbon production. By far the most important geophysical technique is seismic exploration, which provides information on geological structure, stratigraphy and, to a lesser extent, on fluid content. In recent years electromagnetic methods have been applied to hydrocarbon exploration both offshore (e.g. Eidismo et al., 2002; McGregor et al., 2006; Ziolkowski et al., 2008) and onshore (Wright et al., 2002; Ziolkowski et al., 2007), because they measure electrical resistivity, which is very sensitive to hydrocarbon saturation. The industry has long recognized that there are major problems in combining all these measurements, but these problems must be faced if the potential benefits are to be realized.

We observe that where there are no common physical properties among techniques, joint inversion is not possible without imposing unhelpful constraints. We suggest that it is better to determine the physical and geophysical rock properties from the independent geophysical measurements and then determine the petrophysical properties from the resultant physical and geophysical properties.

We give a very brief summary of the problems of dealing with diverse geophysical data, we consider the problem of joint inversion of different types of data, and we then review the problem of combining seismic and electromagnetic data for exploration and reservoir characterization.

Problems of combining diverse geophysical measurements

The problems include the fundamental physics governing the techniques we are using, heterogeneity of the rocks, variation of fluid content, the different measurement scales, and anisotropy. Surface geophysical exploration methods make measurements of existing fields - for example, gravity, magnetics, and magnetotellurics - or measure the response of the earth to active known sources – for example, seismology and electromagnetics. The fields and the responses are described by well-known equations that are derived from physical laws formulated by Newton, Hooke, Maxwell, etc. The constants in these equations are the physical properties of the rocks under investigation.

The first problem is there is usually no overlap in physical properties between the methods, as is seen by inspection of Table 1. An exception is the combination of gravity and seismology: the governing equations both depend on density, so the measurements can be connected and have been used very successfully together to find, for instance, fragments of continents in the oceans. Where there is no overlap in physical properties between the methods, they cannot be connected unless the physical properties are correlated. No such universal correlation exists, which is one of the reasons life is so interesting for geoscientists.

Technique	Equations	Physical properties	Geophysical properties
Gravity and gravity gradiometry	Newton's law of gravitation; Laplace's equation	Density ρ	Density ρ
Seismic reflection and refraction	Wave equation (Hooke's law and Newton's laws of mechanics)	Bulk modulus K Shear modulus G Density ρ	P wave velocity V_p S wave velocity V_s Density ρ
Magnetism	Laplace's equation	Magnetic permeability μ_M	Magnetic permeability μ_M
Electromagnetics	Maxwell's equations	Electrical conductivity σ Magnetic permeability μ_M	Electrical conductivity σ Magnetic permeability μ_M

Table 1. Geophysical techniques, governing equations, physical and geophysical properties

Joint inversion of diverse geophysical data

Inversion is iterative forward modeling. Forward modeling is the computation of synthetic data from an earth model using the basic equations and appropriate initial and boundary conditions. The synthetic data are compared with the measured data and the model parameters are adjusted to reduce the differences between them. Model parameters are the physical or geophysical properties of the subsurface. The methodology of parameterization, parameter adjustment, and error minimization is a science by itself (Sen and Stoffa, 1995). The output of inversion is a range of models of subsurface physical properties. The inversion process does not derive the physical properties from the measured data: it only creates models from which it is possible to derive synthetic data similar to the measurements.

Simultaneous inversion of different data types, or joint inversion, should provide better constraints on the range of possible models, since variations in one parameter, say density, has an effect on other parameters, for instance P-wave and S-wave velocity.

Where there is no common parameter between data types there may be a correlation between key parameters of two different geophysical methods. For example, Colombo et al. (2008) found that P-wave velocity V_p and electrical resistivity (reciprocal of conductivity σ) from logs in a well in the Columbia River Basin were correlated in an approximately log-linear relationship. Their seismic and magnetotelluric (MT) data sets could then be connected via the correlation and inverted together, giving a better inversion of both data sets. One feature of joint inversion is to give different weights to different data. This is important for at least two reasons. First, the ranges of the key parameter, say P-wave velocity V_p for the seismic data and conductivity σ for the MT data, are very different; V_p might vary by a factor of 5 between maximum and minimum, while σ might vary by three orders of magnitude. Second, the spatial resolution and quality of the two data sets might not be the same, and might vary laterally and with depth over the survey area.

The inherent problem in relying on an accidental correlation to derive one physical property from another is that it biases the investigation and may lead to erroneous conclusions.

Exploration, Appraisal, and Reservoir Characterization

Most rocks are inhomogeneous and contain fluids and it is the nature of those fluids that is usually of most interest. In exploration we want to know: Are there any hydrocarbons? For appraisal we want to know: How much hydrocarbons? And for reservoir characterization and monitoring we want to know: How do the petrophysical parameters porosity ϕ, permeability ν and brine saturation S_w vary in the reservoir? The answers to these questions require knowledge of the rock physics. Processing and inversion of geophysical data can yield only geophysical parameters; they cannot yield petrophysical parameters. To get at the petrophysical properties from the physical or geophysical properties requires a rock physics model that connects them, and this can be further fine-tuned with wireline logs and core data from the area of interest.

The physics of fluid-filled rocks is so complicated that there is, as yet, no rigorous theory to describe the propagation of seismic waves in fluid-saturated permeable rocks. In the absence of rigorous theories it is necessary to rely on empirical methods to look for correlations of properties within rock types. By their nature these methods must rely on measurements of the properties of rock types, and any correlations of properties found apply only to the rocks within the set that have been measured.

It is well known, for example, that variations in brine saturation in the pore space can have a dramatic effect on the physical properties of some rocks. For example, the resistivity can decrease by three orders of magnitude in a sandstone reservoir as hydrocarbons are produced, while the P-wave velocity may vary by only a few per cent. That is, for a fixed porosity ϕ, the relationship between V_p and σ is a function of fluid saturation. Where hydrocarbons may be present, therefore, it is of critical importance *not* to impose any kind of relationship between key physical parameters.

Migration of EM data

The seismic industry has developed confidence in its ability to find geological structure from seismic data, using depth migration and full waveform inversion. The algorithms are tested on synthetic data and we know what happens when, for example, the data do not have enough low-frequency content.

A similar approach needs to be developed for EM data, with resistivity corresponding to velocity. Obviously, bandwidth and sampling are critical, just as they are for seismic data. If this can be done (and several people are working on it), the output from EM data processing would be electrical conductivity as a function of subsurface position. The seismic and EM data would then yield elastic properties and electrical resistivity as a function of subsurface position.

Until migration of EM data is able to image subsurface electrical conductivity contrasts – in the same way that migration of seismic data is able to image subsurface acoustic impedance contrasts – we must rely on inversion.

Combining the seismic and EM properties to infer petrophysical properties

It is well known that seismic data can resolve low gas saturations of 0 – 30 % quite accurately in sandstones, whereas EM struggles to resolve low hydrocarbon saturation. However EM becomes increasingly more sensitive with higher hydrocarbon saturation.

In carbonates we often find low porosities at shallow depths of burial and surprisingly high porosities at larger depths. The diagenetic process for carbonates is much more complicated and variable than for sandstones, involving for example dolomitization that increases the matrix density, hence increasing the porosity also. Hence we find that the first order effect on acoustic impedance in carbonates is porosity variation, whereas the fluid saturation is a more subtle second order effect. In carbonates seismic data alone will show the overpowering effect of porosity variation, but *combined with EM and cross-plotted*, it can show the hydrocarbon saturated volumes as having anomalously high resistivities at lower acoustic impedances, as shown in Figure 1.

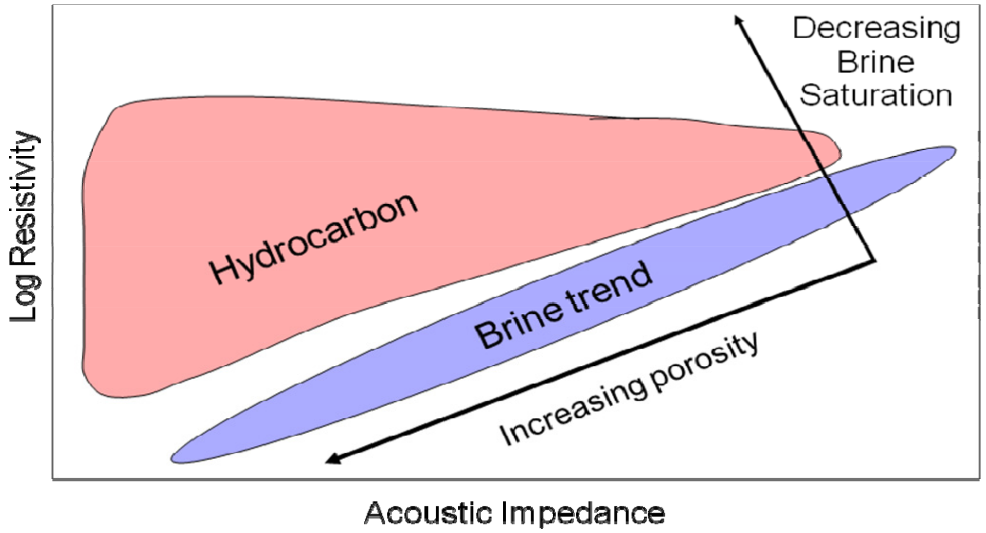

Fig. 1. Resistivity versus acoustic Impedance for carbonate reservoirs

Acoustic Impedance in carbonates is dominated by porosity variation and the sensitivity to light fluids is a secondary effect. Resistivity is sensitive to both porosity and fluid content. Therefore the combination of EM and seismic data has the potential to be very powerful for reservoir characterization in carbonates.

Conclusions

We have shown that unless there is a common physical property in the physics underlying geophysical exploration techniques, joint inversion must rely on correlations between physical parameters that may bias the answer. Different data types should be processed and, where necessary, inverted independently. Independent geophysical parameters can then be combined to infer petrophysical rock properties.

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References

Colombo, D., Mantovani, M., Hallinan, S. and Virgilio, M., 2008, Sub-basalt depth imaging using simultaneous joint inversion of seismic and electromagnetic (MT) data: a CRB field study: Expanded Abstracts, SEG Annual meeting, Las Vegas.

Eidesmo, T., Ellingsrud, S., MacGregor, L.H., Constable, S., Sinha, M.C., Johansen, S., Kong, F.N., and Westerdahl, H., 2002, Sea Bed Logging (SBL), a new method for remote and direct identification of hydrocarbon filled layers in deepwater areas. First Break, 20, 144-152.

MacGregor, L., Andreis, D., Tomlinson, J., and Barker, N., 2006, Controlled-source electromagnetic imaging on the Nuggets-1 reservoir. The Leading Edge, 25, 984-992.

Sen, M. and Stoffa, P.L., 1995, Global optimization methods in geophysical inversion: Elsevier.

Srnka, L.J., Carazzone, J.J., and Ephron, M.S., 2006, Remote reservoir resistivity mapping. The Leading Edge, 25, 972-975.

Wilt, M. and Alumbagh, D., 1998, Electromagnetic methods for development and production: State of the art: The Leading Edge, 17, 487-492.

Wright, D., Ziolkowski, A., and Hobbs, B., 2002, Hydrocarbon detection and monitoring with a multicomponent transient electromagnetic (MTEM) survey: The Leading Edge, 21, 852-864.

Ziolkowski, A., Hobbs, B.A., and Wright, D., 2007, Multitransient electromagnetic demonstration survey in France: Geophysics, 72, 197-209.

Ziolkowski, A., Wright, D., Hall, G., and Clarke, C., 2008, Successful transient EM survey in the North Sea at 100 m water depth: Expanded Abstracts, SEG Annual meeting, Las Vegas, EM3.6