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Multi-physics Inversion for Reservoir Monitoring

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SUMMARY

In this paper we consider the use of, time-domain electromagnetic, DC electrical and injection-production data in isolation and in combinations in order to investigate their potential for monitoring spatial fluid saturation changes within reservoirs undergoing enhanced oil recovery. We specifically consider two scenarios, a CO2 EOR within a relatively shallow reservoir, and a water flood within a deep carbonate reservoir. The recognition of the signal-enhancing role that electrically high conductivity steel well casings play makes the use of EM data possible in both these scenarios.

The work has demonstrated that reservoir fluid saturation changes from EOR processes produce observable changes in surface electric fields when surface-to-borehole (deep reservoirs), and surface-to-surface (shallow reservoirs) configurations are used and the steel well casings are accurately modeled. Coupled flow and TDEM data inversion can significantly improve estimate of fluid saturation levels and location compared to inversion of flow data only. The inversion of surface time-domain electric fields, including DC fields can resolve volumetric and resistivity differences that can distinguish between various water flood scenarios. Coupled flow and DC data can resolve the size and orientation of elongated fracture zones within limits that are considered a significant improvement over estimates made with traditional data.

Introduction

A key aspect of reservoir monitoring is mapping the movement of fluid within the reservoir as production and injection of fluids proceeds. Time-lapse changes in fluid properties and types in a reservoir affect the geophysical properties of the reservoir rocks. Rock stiffness, density and electrical resistivity are all affected to varying degrees with the relative changes in these geophysical parameters depending on rock type, reservoir conditions and the fluids involved. While monitoring time-lapse changes in seismic parameters (4D seismic) is the most common technology currently in use, new approaches of combining two or more types of data are being actively studied. Electromagnetic data is attractive because the electrical resistivity of reservoir rocks can change by orders of magnitude as water saturation changes within the reservoir during production and injection. Additionally, the changes in electrical resistivity of portions of the reservoir under study can be enhanced by injection of high salinity conductive brine.

In this paper we consider the use of three data types, time-domain electromagnetic (TDEM) data, DC electrical data and production data (injection pressure and flow rate). These data components are studied in isolation and in combinations in order to investigate their potential for monitoring spatial fluid saturation changes within reservoirs undergoing enhanced oil recovery (EOR). We specifically consider two scenarios, (1) a CO_2 EOR within a relatively shallow reservoir, and (2) a water flood within a deep carbonate reservoir. The recognition of the signal-enhancing role that electrically high conductivity steel well casings play (Hoversten *et al*. 2014) makes the use of both TDEM and DC data possible in both these scenarios.

Method and/or Theory

The first scenario considered is a CO_2 EOR simulation of a low porosity dolomitized reservoir with properties typical for the San Andres formation of the US Permian Basin. Reservoir and fluid properties taken from the literature (Saller *et al*. 2012) were used to build a flow simulation model covering three injection and three production wells. The objective is to improve the ability to predict fluid saturation changes within the reservoir compared to automated production history matching (flow data inversion).

We simulate a water-after-gas (WAG) process for CO_2 EOR. CO_2 is injected at a constant rate of 30 kg/s for 10 days, followed by 30 days of water injection at 45 kg/s, and another 20 days of CO_2 injection at 30 kg/s. Production of oil, water, and CO_2 is assumed to occur against a fixed downhole pressure of 10 MPa. Regression relations between porosity, saturation and the geophysical parameters, resistivity, velocity and density are generated at the wells, serving as a petrophysical link between the reservoir and geophysical parameters. During the WAG process surface TDEM, DC, and seismic data are simulated.

Starting models are generated by Kriging log parameters, which typically deviate considerably from the true model. Using geostatistical modelling, the joint inversion estimates porosity and permeability modifiers at a set of given pilot points. These reservoir properties are then mapped through Kriging into 3D meshes used for flow simulation, where the petro-physical link is further used to create corresponding geophysical attributes.

The second scenario considered is a water injection EOR in a deep carbonate reservoir, where the objective is to distinguish water-imbibition into matrix porosity versus water-flushing of matrix fractures. For water flood of a fractured carbonate reservoir to be successful, imbibition of water into the pore space of the matrix rock must occur to displace oil, rather than merely water flushing existing fractures.

Type logs from an area with deep carbonate reservoirs are used to define a matrix porosity of 3% and a matrix fracture porosity of 0.1%. Parameters are derived through regression of type logs to relate bulk electrical resistivity to reservoir saturations and porosities. For a given water injection volume and rate two end member scenarios are considered for simulating the affected reservoir volume. The end member scenarios are (1) all the water injected is imbibed into the matrix and (2) all the water injected flushes existing matrix fractures. TDEM, DC and flow data are generated for these two scenarios and inverted to estimate the resistivity, dimensions and permeability of the injection zones using ellipsoidal and rectangular parametric inversion.

There are three computational components used to study the capabilities of flow data and surface based TDEM and DC data for reservoir monitoring. For the forward modelling of the transient electric fields for electric dipole sources in the presence of steel casing we use the TDEM codes (DC is a subset of the TDEM data needed for boundary conditions) of Commer & Newman (2006) and Haber and Heldmann (2007). For the reconstruction of the dimensions of zones containing the majority of injected fluids we use a parametric level set methods, (Aghasi, Kilmer & Miller 2011) to build on the work of McMillan *et al*. (2014). Finally, we use the coupled flow-geophysical modelling and inversion of the MPiTOUGH package to calculate the time varying electric fields over injection into a permeable media as described by Commer *et al*. (2014). The MPiTOUGH package is also used for parametric pilot point based 3D property inversion as well as parametric zone based inversion of TDEM, DC, injection data and combinations of these in joint inversion.

Examples (Optional)

For the case of CO_2 EOR into a low porosity dolomitized reservoir Figure 1 shows the observed and predicted injection pressure, oil and water production as well as the predicted CO_2 saturation at 60 days in the WAG cycle from inversion of the injection and production data from the six wells. The cross section shown runs through the center of the model. The top of the reservoir is at 1300m depth (0m in the figures). There are two injection zones, -100m and -275m below the top reservoir. The production data is well fit but the major CO_2 zone is incorrectly positioned at the first injection interval when in fact the majority of the CO_2 is injected at -275m below top reservoir depth.

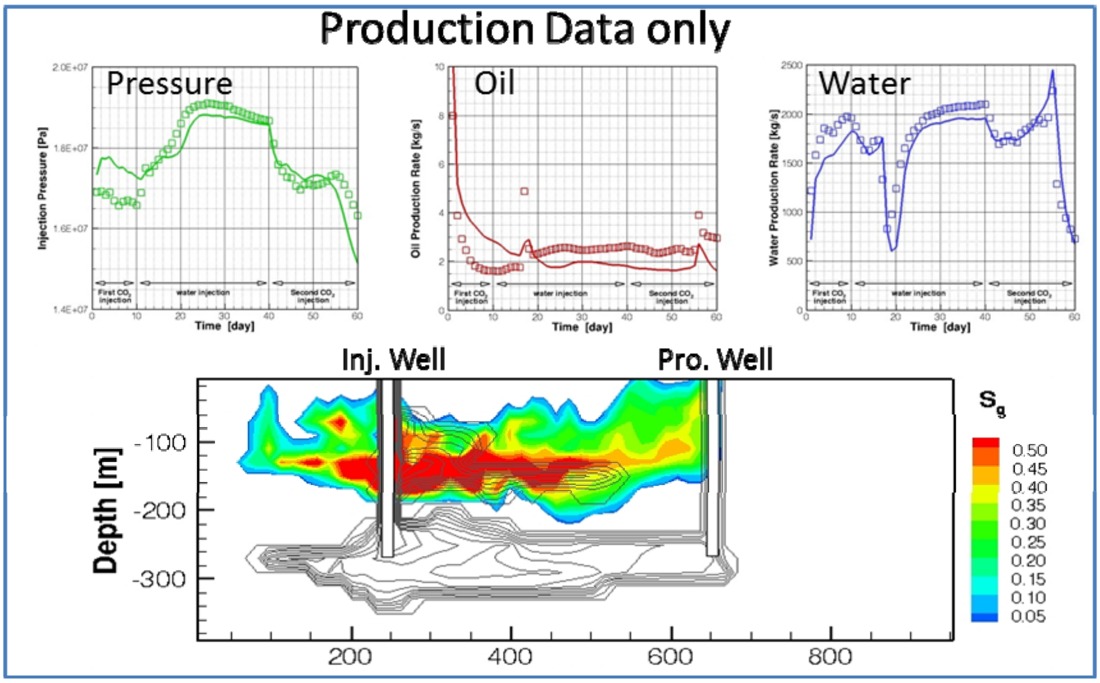

Figure 1 *Inversion of production data only. The black contour lines are the true S_{CO2} saturation. Two injection intervals, -100, -275m from top reservoir are used. The injection pressure and flow rate at the injection and production wells is used to invert for reservoir porosity and permeability. The fluid saturations (S_w, S_o, S_{CO2}) are calculated from the flow simulation of the inverted permeability & porosity. The inversion matches the injection pressure and fluid flow rates quite well but miss-positions the S_{CO2} concentration badly.*

A single 25m long electric dipole source centered at x, y, z of 112.5, 0, 0 transmits into a surface array of 60 receivers covering 0 to 1000m in x and +- 500m in y. When TDEM data from this array is added to the inversion the production data fit deteriorates slightly but the prediction of the spatial location and saturation levels significantly improves (Figure 2). The production data is dominated by the water component, which are nearly three orders of magnitude greater than the oil production.

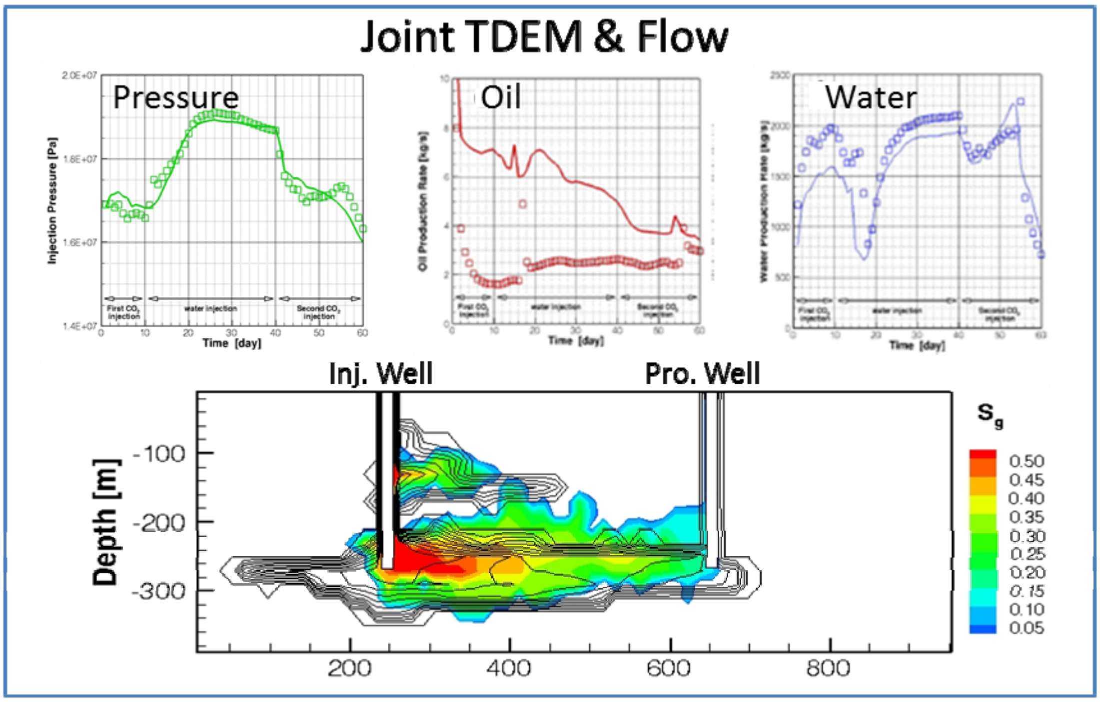

Figure 2 *Inversion of production and surface TDEM data. The black contour lines are the true S_{CO2} saturation. Two injection intervals, -100, -275m from top reservoir are used. The injection pressure and flow rate at the injection and production wells is used to invert for reservoir porosity and permeability. The fluid saturations (S_w, S_o, S_{CO2}) are calculated from the flow simulation of the inverted permeability & porosity. The inversion matches the injection pressure slightly better; the oil flow rate match has deteriorated somewhat with only a minor deterioration in the water flow rate data compared to the production data only inversion. The S_{CO2} saturation prediction has significantly improved.*

For the second scenario of a deep carbonate reservoir undergoing water flood, TDEM, DC, and injection data were inverted separately and in combination. The model has a 5 Ωm overburden to 3200m, an underlying layer of 10,000 Ωm to 5200m and a 5 Ωm basement. The reservoir interval starts at 4500m. The background and injection zone permeability's are $1x10^{-15}$ and $1x10^{-12}$ m^{-2} respectively. Steel casing extends to the top of the reservoir, with the bottom several hundred meters uncased. Up to four cased wells are modelled for their cumulative effects on the TDEM data. Brine at 200,000 PPM salinity is injected.

Analysis of the surface electric (E) field for a source with one electrode in the uncased section within the reservoir and one electrode 1km away from the well, shows that changes in the E fields away from transient zero crossings can be as large as 30% with field levels above the assumed noise floor of $1x10^{-10}$ V/m. When water is imbibed into the matrix porosity the resulting volume is $2.3x10^6$ m^3 with a resistivity of 3300 Ωm. When water fully flushes the fracture porosity the volume is $8.8x10^6$ m^3 with a resistivity of 6500 Ωm. Parametric inversion of TDEM data solved for the resistivity and dimensions of a rectangular region about the injection well. For the two cases (water-imbibition into pore space and water-flushing fractures) the inversions of the two data sets were started from the opposite model. Gaussian noise was added to the E field data with 2% of amplitude and a $1x10^{-10}$ V/m noise floor. In both cases, the inverted resistivity was within 2% of the true value and the estimated volumes are within 25% of the true values. Separate inversions using DC data reach similar estimates implying that the computationally much less expensive DC data might be an alternative to TDEM data.

Coupled flow and DC data parametric inversions that represent the injection zone as an ellipsoid with resistivity and permeability show the injection zone permeability can be estimated to within 25%. The strike angle of the injection zone, when it is elongated, can be estimated to within 5%.

Conclusions

The work to date has demonstrated that reservoir fluid saturation changes from EOR processes produce observable changes in surface electric fields when surface-to-borehole (reservoirs as deep as 4.5km), and surface-to-surface (for shallow reservoirs) configurations are used and the steel well casings are accurately modelled. Coupled flow and TDEM data inversion can significantly improve estimate of fluid saturation levels and location compared to inversion of flow data only (automatic history matching). The inversion of surface time-domain electric fields, including DC fields can resolve volumetric and resistivity differences that can distinguish between various water flood scenarios. Coupled flow and DC data can resolve the size and orientation of elongated fracture zones within limits that are considered a significant improvement over estimates made with traditional data.

Significant challenges remain in two areas. First the computational demands of EM modelling with multiple steel casings, as is needed in operational fields, is extreme and work continues to increase computational efficiency. Secondly, data acquisition costs are high and work needs to be done to optimize target sensitivity while minimizing the required data acquisition.

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