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Formation compaction vs land subsidence to constrain rock compressibility of hydrocarbon reservoirs

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HIGHLIGHTS

- A method for uncertainty quantification of deep hydrocarbon reservoirs is proposed.
- The vertical uniaxial compressibility is estimated by assimilation of deep compaction and surface displacements.
- Uniform and heterogeneous compressibility distributions are investigated.

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ABSTRACT

Quantification of uncertainty is becoming increasingly important in any general modelling activity. In this study, the ensemble smoother, i.e., an ensemble-based data assimilation algorithm, is used to quantify and reduce the uncertainty associated with the geomechanical parameters of deep hydrocarbon reservoirs. The aim is at estimating the vertical uniaxial compressibility c_M of the producing layers by assimilation of: (i) ground or seabed vertical and horizontal displacements measured with InSAR, multibeam surveys, and GPS; and (ii) reservoir deformation obtained from specific well logs (e.g., the radioactive marker technique) and extensometer stations. Usually subsidence measurements are characterized by large datasets (in both time and space) with a relatively low accuracy. Conversely, the compaction monitoring techniques provide more accurate measurements, although their availability is at limited points and over few time intervals. In this contribution, we test the capability of these two types of data to reduce the uncertainty associated to c_M for a producing reservoir. Although dealing with a test case application, this investigation originates from the need of properly addressing and explaining the seafloor displacements observed over a real offshore gas field. The numerical tests are carried out with two different conceptual models for c_M, based on the common structure of gas fields. The first model considers a compressibility distribution varying with depth and effective vertical stress, but uniformly distributed within the reservoir. In this case, compaction measurements at the reservoir depth result very effective. However, when the reservoir is composed of several compartments bounded by faults and thrusts, the possible heterogeneity of c_M among different blocks reduces the effectiveness of compaction measurements in data assimilation algorithms compared to that of surface displacements.

1. Introduction

The withdrawal of fluids from deep hydrocarbon reservoirs may cause environmental problems on the ground surface, with the loss of land elevation than can particularly affect coastal low-lying areas. Vertical displacements are due to the deformation (compaction or expansion) of the depleted formation and its consequent propagation from underground up to the land surface [e.g., Refs. 1, 2]. In this context, a number of inversion methodologies have been recently developed to characterize the geomechanical properties of deep reservoirs and provide an estimate of the parameters that mostly control the process.

Data Assimilation (DA) methods can be used to reduce the parameter uncertainty by assimilating measurements, such as land surface displacements, deep deformations and formation pressure, within a 3D numerical modelling framework, e.g. Ref. 3. In reservoir geomechanics, the Ensemble Smoother (ES) algorithm[4] has been usually preferred to other methodologies[5]. ES is based on Monte Carlo (MC) simulations where the forward model, i.e., a geomechanical finite element (FE) model, is run deterministically as many times as the ensemble size. An early study, based on Monte

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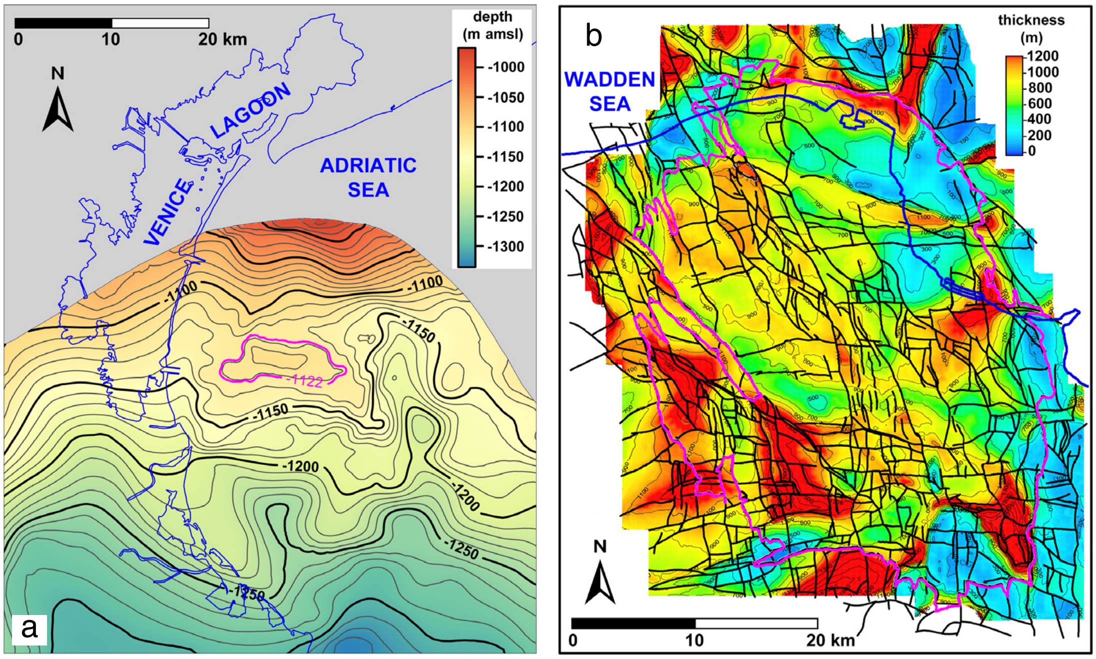

Fig. 1. Typical geologic setting of hydrocarbon bearing formations: (a) a reservoir in the unfaulted Quaternary sequence of the Northern Adriatic basin, Italy (modified after Ref. 18); (b) the Groningen reservoir in the faulted Rotliegend sandstone formation, The Netherlands (modified after Ref. 19). The trace of the reservoirs is shown in magenta, the Adriatic and Dutch coastline in dark blue. The maps provide the depth and the thickness of the gas-bearing formation in (a) and (b), respectively. Thick black lines in (b) represent the fault traces. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Carlo (MC) simulation, to predict subsidence in the Po river plain based on a-priori unknown compressibility was already carried out by 6. Reservoir compaction was estimated through a Bayesian inversion scheme from levelling measurements in Ref. 7. In Ref. 8, subsidence data obtained from levelling campaigns and persistent scatterer interferometry (PSI) measurements were used to reduce the uncertainty about the reservoir architecture. An ES algorithm with multiple data assimilation was developed by 9 to constrain the reservoir compaction coefficient and the subsurface basement elastic modulus by assimilating ascending and descending line-of-sight displacement observations provided by PSI. ES with PSI records are employed by 10 to reduce the uncertainty of a transversely isotropic stress–strain constitutive law characterizing the geomechanical model of an underground gas storage (UGS) field situated in the upper Adriatic sedimentary basin (Italy).

A key role in the quality of the assimilation outcome is obviously played by the representativeness of the selected forward model with respect to the process of interest. Forcing the reality into non-representative conceptual schemes might twist the actual understanding of the physical phenomena and produce unrealistic results. On the other hand, the use of sophisticated models can be of no help if not supported by an appropriate amount of data. In real-world applications, the assimilated data in a geomechanical model are usually:

- surface displacements, including observations collected from levelling, PSI, time-lapse bathymetry maps, and GPS;
- reservoir compaction records as possibly obtained from well logs, e.g., by the radioactive marker technique [e.g., Ref. 11], extensometers, and optic fibres[12,13].

Obviously, the two sources of information have a different spatial and temporal distribution depending on the type of measurement. The possibly limited availability in space and time of such pieces of information, however, can prevent the ability of conditioning some forward models describing in a realistic way the rock constitutive behaviour. Although the geomechanics of deep rocks is generally governed by non-associated elasto-plastic and rate-dependent laws, e.g. such as those reported by 14 and 15, a simplified model, supported by available measurements and able to capture the main deformation effects, can still be preferable, at least as a basic indication. For this reason, in the present work we focus on the geomechanical parameter that mostly control the compaction of producing underground reservoirs, i.e., the uniaxial vertical compressibility c_M, within a probabilistic framework[16,17].

This study is aimed at investigating the effectiveness on c_M uncertainty reduction of jointly or separately assimilating ground surface displacements and reservoir compaction records. Two different conceptual models for c_M are accounted for, reflecting two typical geological settings that characterize hydrocarbon reservoirs. In the first one, the compressibility depends on the effective stress only, i.e., it is assumed to be uniformly distributed within a reservoir located in an unfolded sedimentary basin (e.g., the Northern Adriatic sedimentary basin, Italy, Fig. 1a). In faulted formations, c_M is also expected to vary in a patchwork way according to the block compartmentalization that composes the reservoir (Fig. 1b). The governing rock constitutive behaviour is selected according to the potentially available observations. As mentioned above, in many cases, the lack of spatial and/or temporal distributed data might force a simplification the model complexity, by neglecting those processes that can increase the dimension of the parameter space and are not directly supported by measurements.

The numerical simulations are carried out for a synthetic test case where the geometry of the reservoir is real and a realistic distribution of the pressure variation is prescribed for a reference time interval of one year. Synthetic land subsidence and reservoir compaction are assimilated. The same test case has been previously used in Refs. 20, 21 to investigate the effectiveness of assimilating land subsidence to infer a possibly uneven distribution of c_M within the reservoir. The new contribution of this study relies on how different sources of information, and related errors, can combine in the ES approach to constrain both uniform and heterogeneous model parameters.

The paper is organized as follows. Initially, the geomechanical model used for the forward simulations and the methodology applied for the update are briefly described, providing specific details