Hydrocarbon exploration risk evaluation through Uncertainty and Sensitivity analyses techniques

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Abstract: The evaluation of the exploration risk in the oil industry is a fundamental component of the decision process related to the exploratory phase. In this paper the two basic components of the exploratory risk: trap *geometry* and trapped hydrocarbon quantities (*fluid*), are compounded in a single coherent uncertainty and sensitivity approach. The results clarify that the model geometry influences each Petroleum System Modeling step and that the *geometric* uncertainty is correlated with the *fluid* uncertainty. The *geometric* uncertainty evaluation makes use of geostatistical techniques, that produce a number of possible realizations of the trap geometry, all compatible with available data. The evaluation of the *fluid* uncertainty, through a Montecarlo methodology, allows to compute the possible quantities of oil and gas, generated in a basin and migrated from the hydrocarbon source location to each single trap. The final result is the probability distribution of oil and gas for each trap in the basin, together with other useful indicators like: the hydrocarbon filling probability map, the closure probability map, the drainage area probability map, the spilling paths probabilities, the trap filling scenarios.

Keywords: Hydrocarbon exploration, petroleum system modeling, uncertainty, sensitivity, risk evaluation

1. INTRODUCTION

In the hydrocarbon exploration activities the main goal is to find traps where oil and/or gas were accumulated and retained in quantities that are greater than a variable economic threshold. Neglecting all the economical variables that come into play, the basis of any drilling decision is associated to the presence/absence of hydrocarbons (hydrocarbon risk) in the potential traps of the basin. This evaluation is the result of the joint efforts undertaken by a team of geologists, geochemists, geophysicists and engineers, in trying to get the best picture of the prospects that may be potentially drilled.

This study can be schematically splitted into two components: the *geometric* one and the *fluid* one. The first one is the object of Basin Modeling (BM) [*] activity, that gives a 4D (in space and time) description of the basin status and evolution. The *fluid* one is the objective

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[*] Historically the term “Basin Modeling” has been used with slightly different meanings. In this paper it is used to describe the rocks properties distribution in space and evolution in time. In practice this is strictly correlated to the fluid properties distribution and evolution and therefore a clear distinction between BM and PSM is partially subjective.

of the Petroleum System Modeling (PSM), that produces the history of the geologic processes that led to generation and accumulation of hydrocarbons in the current traps.

2. METHODOLOGY

Modeling geological processes is subjected to uncertainty because input data are scarce and imprecise and also because the used modeling algorithms are an approximation of the true geological processes. This observation implies that a probabilistic approach is needed to account for the lack and imprecision of knowledge, enabling at the same time to compute the "hydrocarbon risk" for each trap of a basin.

Regarding Basin Modeling, geostatistical techniques can be used to model the uncertainties of both geologic layer geometries and facies[*] properties. Geometric uncertainty is related to the process of depth converting interpreted seismic time reflections into depth reflectors, as a function of the uncertainty of seismic propagation velocities. The evaluation of the uncertainty of facies properties distribution refers both to seismic data attributes and to sedimentological interpretation. In this paper we are considering only geometric uncertainty, as the methodology to take into account facies uncertainty is quite complex to set up, in basins case.

As the PSM is an inverse problem and the data available is scarce and uncertain, we have to deal with multiple possible "realizations" of the basin model as well as of the petroleum system evolution. Even if all the "realizations" are fitted to known available data, this calibration process just reduces the space of possible solutions but it is unable to justify by itself the choice of a unique, or most probable, or optimal solution.

Each of the phases of the PSM (including Basin Modeling) contributes to the overall uncertainty and can be explored with a sensitivity approach. As shown in Ref. 1, where a brief summary of the different approaches is presented, almost all the papers deal with the uncertainty evaluation of only some of the phases of PSM. In fact, aside to the great amount of CPU time needed, the main difficulty in applying Uncertainty and Sensitivity Analyses (UASA) to the entire PSM is given by the complex management of the complete workflow.

Another great source of uncertainty is given by the assumptions (the conceptual model) that are practically needed in the inversion of the scarce data available. These alternative conceptual assumptions, or geological hypotheses, are dealt by means of scenario variables [2]. To drop a scenario, or one of the combinations of different scenarios, means to hide a component of the uncertainty and thus to increase the risk of biased choices.

Our approach consists in considering all possible combinations of scenario variables and in producing, for each scenario, as many realizations as needed for uncertainty and sensitivity analyses. With regard to uncertain input variables these can be numerical (continuous or discrete) or categorical (e.g. a set of functions or maps).

Moreover the non linearities hidden in the modeled geological processes are such that there are threshold values of some variable or combination of variables that may trigger one event (e.g. generation of gas, …). For this reason the use of UASA approaches that assume linearity or continuity hypotheses need great caution, so that, in our opinion, it is preferable to use a Montecarlo approach to the extent that is allowed by hardware constraints.

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[*] A "facies" is a rock layer that differs from the others (as in composition, age, …) because of its formation .

2.1. Basin and Petroleum System Modeling

A general introduction to BM and PSM techniques can be found in many books (see for example Ref. 3), in the following only the main modeling steps are mentioned and the workflow that has been applied is described (see Fig. 1).

The BM (for the purposes of this paper) consists of: the shape definition of the geologic structures; the spatial distribution of the geological properties of interest for each geologic layer in the basin model; the structural evolution of the basin during geologic time (in this study only vertical compaction of sediments due to overlying sediment load was taken into account); the definition of the history of the heat flow at the basis of the sediments (coming out from the basement, in the earth upper crust).

The PSM can be grossly subdivided into: the description of the evolution of the Pressure & Temperature (P&T) fields in the sediments; the history of the Generation & Expulsion (G&E) of the hydrocarbons (oil and gas, in the simplest case) from source rocks; the Migration of hydrocarbons from source rocks to reservoirs and the preservation of Trapping conditions of the hydrocarbons throughout the evolution of the basin (M&T).

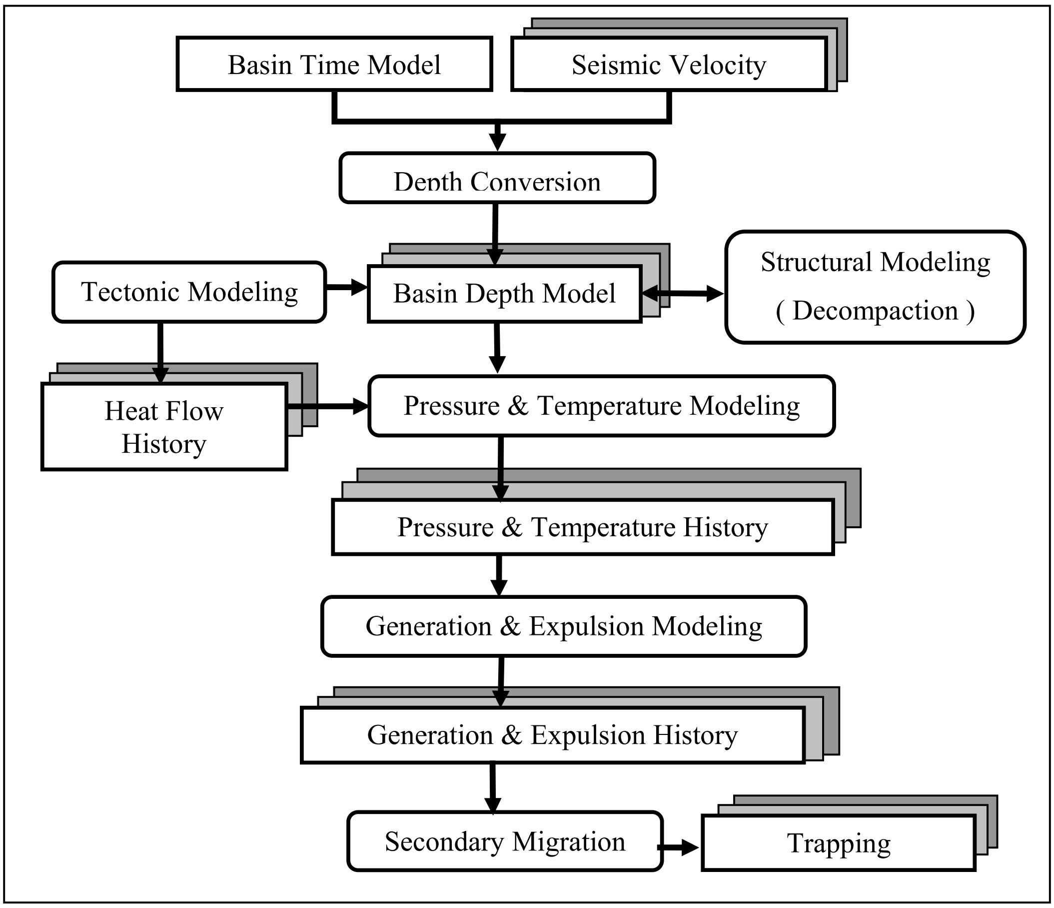


Figure 1. Workflow of the Basin Modeling and Petroleum System Modeling applied in this study. Boxes with rounded corners represent modeling steps. Rectangular boxes represent data. Repeated shadowed rectangular boxes represent multiple realizations/simulations of that data.

2.1.1. *Basin Modeling*

At the basin scale the depth model is suitably built using the *layer-cake* vertical depth conversion method from interpreted seismic time maps. This consists in the transformation of the time “thickness” into a depth thickness using the corresponding seismic layer velocity. In this way the depth model is constructed layer by layer, from top to bottom.

Velocity maps are obtained using geostatistical techniques because they allows to produce an optimal velocity map integrating different data sources: seismic velocities, Well velocity measurements and geological knowledge (called *a priori information*).

This approach has been applied in the current study to produce a basin model compound of 7 interfaces and 6 layers (see Fig. 2a). Layer 1 (dark blue) and layer 4 (brown) are the hydrocarbons source rocks (respectively “Source 1” and “Source 2”), while layer 3 (green) is the carrier for hydrocarbons migration into potential traps (in the same layer). In Fig. 2b the position of section AA’ is shown together with the top of layer 3 and the nine major traps.

The description of the resulting Basin Model was completed with information about layers parameters (porosity, permeability, thermal conductivity, …) derived from Wells, literature and sedimentological studies. The application of a decompaction law for each layer of the basin, allowed to recover the basin evolution history, that is the 4D Basin Model. In practice this is a set of 3D models, one for each selected geological time step, describing the evolution of the 3D Basin Model through the geologic time. According to the 4D Basin Model, a heat flow history can be established from tectonic modeling and Well data [4], resulting in a set of heat flow maps, one for each selected geologic time step.

2.1.2. *Thermal & Pressure Histories*

The distribution of temperature within the sediments is controlled by: the regional geothermal regime (heat flow at the base of the sediments and paleo-temperature at the top), the thermal properties of the rocks and the fluid movements through rock pores. The geothermal regime changes during the basin evolution in connection with variations of the basal heat flow and paleo-temperature fluctuations.

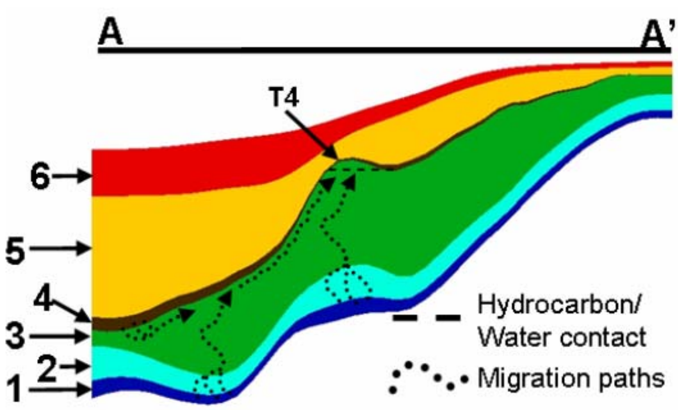


Figure 2a. Section of the basin model

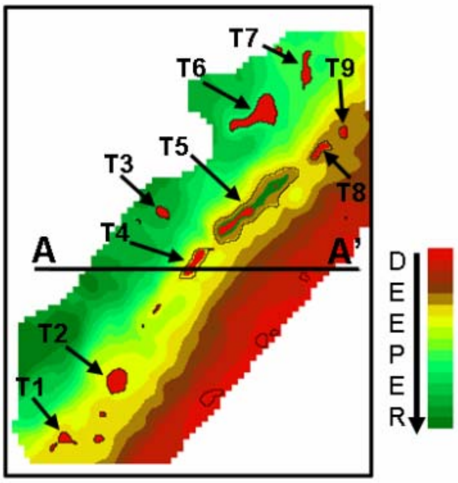


Figure 2b. Top of layer 3

Source Layers: 1 and 4. Carrier and Reservoir layer: 3. Potential Traps: T1, T2, T3, … , T9

At the same time, as the basin geometry changes due to accumulation and compaction of sediments, the bulk thermal properties of rocks are varying too. The compaction, resulting from depositional overburden load, reduces rock pores volume and squeezes the water out, accordingly to the permeability of the layers. When a low permeability layer is involved, water pressure departs from hydrostatic equilibrium and an overpressure results. The duration of the pressure disequilibrium is controlled by the filtration velocity, that is by the overpressure gradient and the permeability of the layers. The fluid flow is modeled through a Darcy equation. The computation of thermal and pressure histories is performed solving the corresponding equations of energy and momentum conservation through a finite element approach. The resulting pressure and temperature fields are obtained for each geologic time step.

2.1.3. Generation & Expulsion Histories

The "source rock" is a part of a low permeability layer (the *source rock layer*) and it is such that within it there is an abundance of organic matter that is playing the role of kerogen. The initial kerogen degrades through a number of parallel reactions (*primary* cracking) into hydrocarbons, which are more stable components (oil and gases). This is followed by *secondary* cracking, which transforms oils and wet gases into lighter components (dry gases) and coke. Both *primary* and *secondary* reactions are assumed to be independent of pressure and their temperature dependence is given by an Arrhenius type equation.

Expulsion of the generated hydrocarbons from the source rock is a very complex and still poorly constrained process. It is modeled as a multiphase flow (hydrocarbons and water) within a low permeable porous medium (the source rock itself), controlled by the relative permeability of each fluid phase. In practice hydrocarbon flow is driven by the overpressure resulting by the compound effect of the sediment compaction and of the hydrocarbons generated (by the transformation itself).

The result of this modeling step is a set of expulsion maps, one for each selected geologic time step and for each hydrocarbon component (oil and gas in the simplest case). These maps represent the result of the expulsion out of the *source rock layer*.

2.1.4. Hydrocarbon Migration & Trapping

Once the hydrocarbons are expelled out of the source rock layer, they move (secondary migration) along permeable rocks until they reach a trap. The simplest approach to model secondary migration is based on the so-called 'ray-tracing technique'. This technique assumes that hydrocarbons move, because of buoyancy, just at the top of a permeable layer overlain by an impermeable one (acting as a seal) and following the steepest path. Subsequent processes, like spillage and leakage, may cause hydrocarbons to migrate out of traps. All the processes are modeled over the geologic time scale, taking into account the evolving basin geometry and changing properties of rocks and fluids.

The final results of the whole PSM workflow (modeling of temperature and pressure, generation and expulsion, secondary migration and entrapment) are the total amounts of hydrocarbons (oil and gas) that fill at the present time each trap of the basin area.

2.2. Uncertainty and Sensitivity Analyses

As already mentioned, this study addresses both *geometric* and *fluid* uncertainty and sensitivity evaluation in a 3D study. Even if it is possible to add more sources of uncertainty, this is the first time, to our knowledge, that such a complete approach is proposed.

2.2.1. Basin Modeling Uncertainty and Sensitivity Approach

The main sources of uncertainty of a basin depth model are the interpretation of seismic times and the estimation of seismic velocities. Disregarding the radical error of having misinterpreted seismic reflection (travel) times, the greatest uncertainty is associated to seismic velocities, as they are indirectly estimated from seismic signal coherency [5].

The geostatistical techniques used to produce an optimal velocity map, allow also to generate an infinite number of equally-probable simulated velocity maps. In this study the seismic velocity field of the most critical layers for the depth conversion was simulated using a specific geostatistical technique for probabilistic depth conversion [6].

As a result of this approach 100 simulated depth models have been computed, all of them geostatistically equally-probable but quite different from one another if compared with their possible effect on the PSM result. As 100 depth models were too many to be dealt with, a selection of 8 representative depth models was performed in such a way that they "optimally" sampled the "uncertainty space of the basin depth model". They are the ones that are the most different from one another in the main area of interest, that of trap T5, the biggest one.

A similar approach was used to select 4 heat flow maps, that is the selected ones are the most different from one another and they optimally sample the heat flow uncertainty space.

Both the depth models and the heat flow maps have been treated as scenario variables, which means that all the combinations among them have been considered, producing 32 different 4D basin models as input to the following PSM study.

2.2.2. PSM Uncertainty and Sensitivity Approach

In practice the P&T phase was run 32 times, one for each scenario, and for each of these P&T runs, the subsequent phases (G&E and M&T) were run 32 times. This produced 1024 runs with a LP-τ sample on all uncertain input variables associated to: Basin Model, P&T, G&E and M&T. This UASA approach extends that proposed in Ref. 7 where: the geometry of the Basin Model was kept fixed (instead of having 8 scenarios), the 3D P&T runs where only 8 (instead of 32), the G&E runs where 32 in total (instead of 1024).

Moreover this paper applies the method proposed in [8] as it allows to compute the uncertainty of the hydrocarbon trapped quantities (oil and gas) and evaluate, at the same time, the sensitivity indices of the first order, using the same set of 1024 runs. In order to analyze non linear effects between variables, a Neural Network (NN), trained on the set of 1024 runs, was then used to compute the sensitivity indices of the first and second order and the total effects, using the method of Sobol' with the extension described in Ref. 9 and Ref. 10.

2.2.3. Uncertainty and Sensitivity Evaluation

Fifteen uncertain variables were used, grouped in 4 subsets:

- Basin (2 variables) : 8 model *geometries* combined with 4 *heat flow* maps to get 32 Basin Models;
- Source (6 variables) : *Total Organic Carbon*, *Porosity-Stress* Curve, *Water Threshold Saturation*, for Source 1 (layer 1) and Source 2 (layer 4);
- Migration (4 variables) : *Expulsion Efficiency* from Source 1 and Source 2, *Leakage of Gas* and *Leakage of Oil* from a trap;

- Trap (3 variables) : *Net to Gross* ratio; *Water Irreducible Saturation*, *Thickness* of the reservoir layer.

The uncertainty evaluation of the trapped oil and gas quantities in each of the 9 main traps (Fig.2b) is based on LP-τ sampling of 13 uncertain variables for each of the 32 basin model scenarios. This means that the output variables are 18 (oil and gas volume in each trap).

At the same time first order sensitivity indices were computed in order to identify the driving factors of the G&E and M&T processes that cause an accumulation of oil and/or gas. As mentioned we have applied the method based on "State Dependent Parameter models" (SDP) [8] to estimate sensitivity indices of first order.

In order to estimate sensitivity indices of the second order it would be necessary to run a huge number of times the entire BM and PSM workflow, requiring an unaffordable CPU time. This suggested the use of a NN approach [11] to model the global PSM workflow. For this purpose the NN was trained on the 1024 uncertainty runs, using all the 15 input variables and the 18 output variables. The goal of this NN was the computation of Sobol' indices and in particular of second order indices, in order to better understand non linear interactions between variables.

3. RESULTS

The analysis of the results shows that, as expected, some non linear relationships among variables exist (Fig. 3a shows an example for an input and an output variable). Moreover some scenario yields "discontinuous" results, as (Fig. 3b) for model geometry 3 where trap T4 never contains oil and always gas, while all the other model geometries "convey" both oil and gas in trap T4 (in the Fig. 3b they are in gray).

The spilling from one trap to outer regions of the modeled area or to other traps is quite important in the correct evaluation of the hydrocarbon trapped quantities. This is better understood looking at the spilling scenarios, shown in Fig. 4a, where also the probabilities of each spilling path has been computed, using a statistics of 30 model geometries (including the 8 ones used for UASA). It is important to remark that the spilling paths coming out of a single trap are alternative cases, as only one of them could be the real one.

Taking a look to the hydrocarbon quantities that may have filled a trap, as is shown for trap T5 in Fig. 5a for gas and in Fig. 5b for oil, the total amount coming out from all the simulations summarizes the contributions due to the different spilling scenarios. For example the case "no spill-in" represents all the simulations where trap T5 was filled only directly from the drainage area, while the case "T4" is the set of all the simulations in which trap T5 was filled both directly from source and from the spilling of trap T4. For the filling of trap T5, only the 6 scenarios listed in Fig. 5a and in Fig. 5b are possible and again they represent alternative cases as only one of them could be the real one.

Other useful statistical results are the *probability maps* that summarize the *probability of presence* of a characteristic of interest for each point of that map. For example Fig. 4a shows the "Hydrocarbon Filling Probability" map that represents the probability that each point has to be inside an hydrocarbon (gas and/or oil) accumulation. While the "Closure Probability map" measures the probability that each point has to be inside a *closure*, defined as the maximum volume available to hydrocarbon accumulation for that trap (trap T5 in Fig. 4b) before that a spilling out will take place.

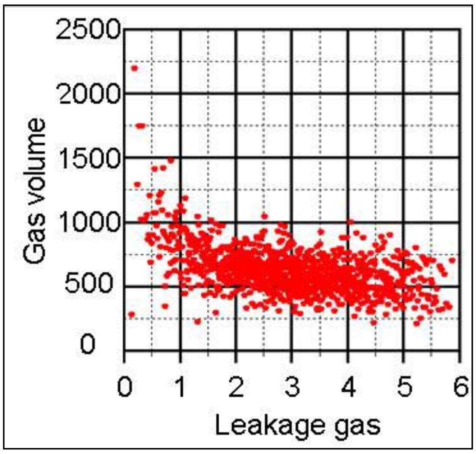


Figure 3a.
Trap T5 – Non linear relationship

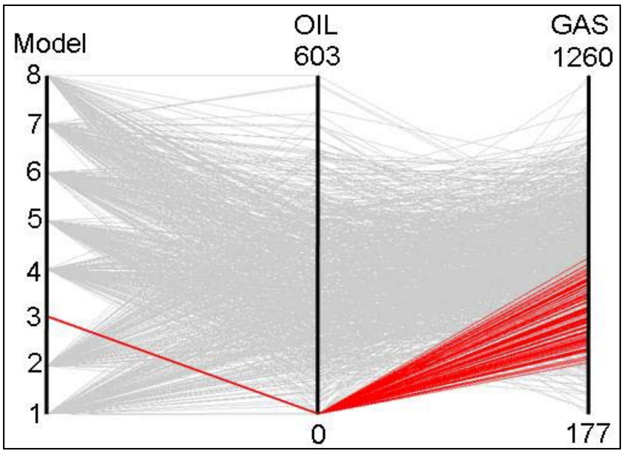


Figure 3b.
Trap T4 for Model 3: never oil and always gas

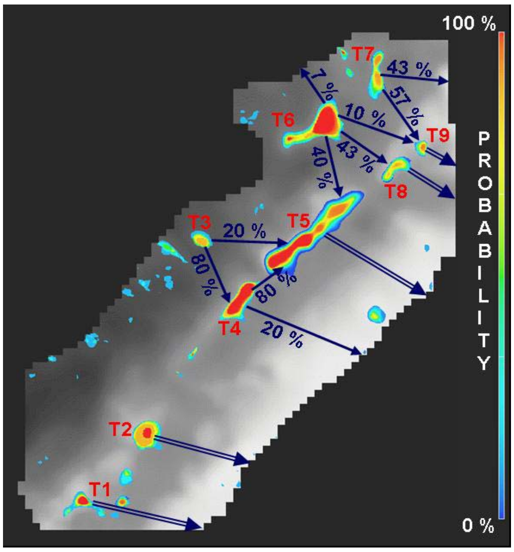


Figure 4a. Top Layer 3 in gray - Hydrocarbon Filling Probability in color - Spilling Scenarios probabilities as vectors connecting Traps.

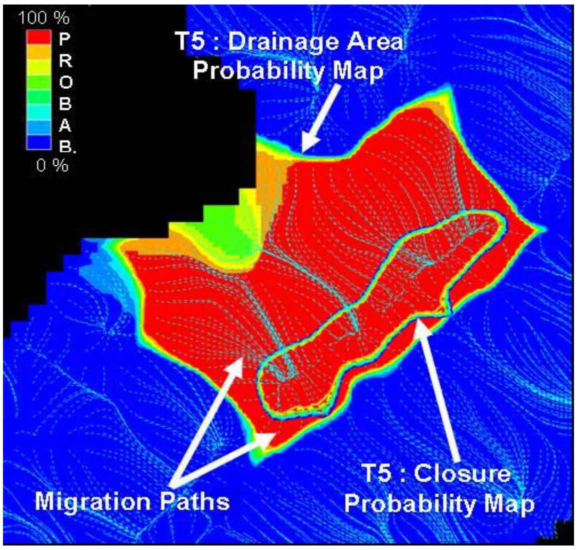
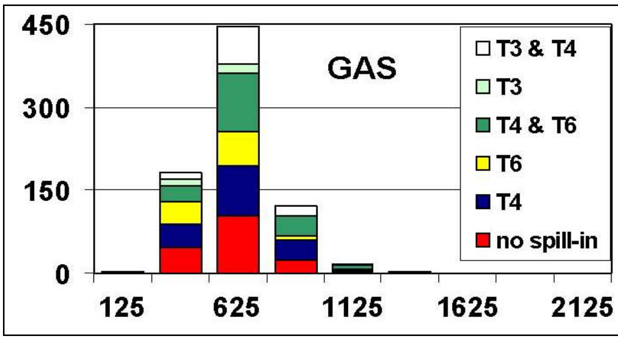


Figure 4b. Zoom on Trap T5 – Migration paths in dashed light blue - Drainage Area and Closure Probability Maps in color.



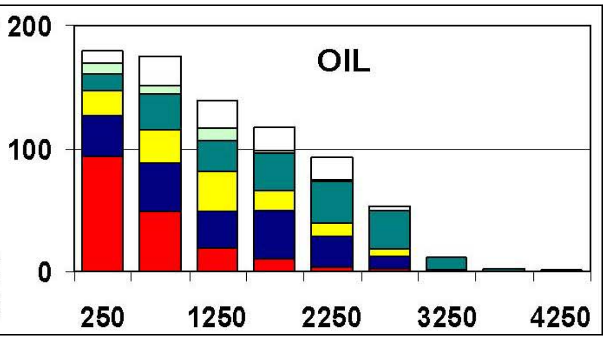


Figure 5a. Trap T5 – Volumes of Gas **Figure 5b.** Trap T5 – Volumes of Oil
Colors are related to the different trap spilling scenarios (e.g. T4 means: gas/oil from spilling of T4)

The Filling Probability can be computed even if the model geometry is fixed, while the Closure Probability requires a number of different model geometries (in the example 30). The same is true also for the "Drainage Area Probability map", that describes the probability that a point has to be inside the drainage area of a trap (as trap T5 in Fig. 4b).

As regards the trapped hydrocarbon quantities, the result of the study is that all the traps are filled by gas and, as only traps T4 and T5 have a median value of the oil probability distribution greater than zero, only these actually contain both oil and gas. To be precise only trap T6, among others, has the 3rd quartile of the oil probability distribution greater than zero.

The analysis of the first order sensitivity indices (computed with the SDP method) can be only shortly summarized. The observation just mentioned on gas prone traps is reflected in the sums of the first order indices, in fact these are less than 0.40 for the (improbable) oil accumulations of these traps. In all other cases the sum of first order indices of hydrocarbon accumulations (gas or oil) is greater than 0.70, with the exception of trap T6 which is in the middle with a value that sum to 0.56 for the oil accumulation.

According to the sensitivity analysis, based on (reliable) first order indices, the most critical parameter for the gas prone traps (T1, T2, T3, T6, T7, T8, T9) is the Model Geometry. For traps T4 and T5 the most critical parameter for gas accumulation is related to Trapping Conditions (Net/Gross and Gas Leakage, respectively), while for oil accumulation it is related to Model Geometry for trap T4 and to Source parameters (Porosity-Stress curve of Source 2) for trap T5.

A double comparison was done between the first order indices computed with SDP method on real data (from model simulations) and those computed with SDP and Sobol' methods on data produced by the trained NN. The result is that the first two most critical parameters are found all the same as far as gas accumulations are concerned and also oil accumulations but only for traps T4 and T5. This justify the use of second order indices, computed on NN data, to understand possible correlations among variables. In synthesis this analysis reveals as critical the interactions among Model Geometry and : Source parameters (TOC, Porosity-Stress Curve), Migration parameters (Expulsion Efficiency, Gas Leakage) and Trapping parameters (Net/Gross, Reservoir Thickness).

4. DISCUSSION

The current study was possible thanks to the porting of the G&E modeling phase on a parallel platform, in practice a cluster of Linux workstations that amounts to 24 CPU (including a Linux cluster of 16 CPU). The CPU time needed to perform the study, with this setting, was about 84 hours (72 hours only for the 1024 runs of the G&E phase).

Obviously the use of a NN could reduce the CPU time needed, but as mentioned above, this can not be a straightforward or blind choice, in fact the analysis of the results confirms that the NN has a tendency to linearize the model behavior and has difficulties in modeling categorical variables. This do not exclude that a more advanced NN could give better results.

As the sensitivity study has suggested, the Model Geometry plays an important role in the different modeling phases, its effect on the results is non linear and it may also introduce discontinuities in the space of results. All this claims for a more systematic use of Model Geometry uncertainty, which means the ability to manage at least 32 model geometry simulations, that in turn requires the setting of a semi-automated procedure in substitution for the manual one used in this preliminary study.

The scenario approach is, as already mentioned, the only way to properly manage an interpretative uncertainty, but as the analysis of the results has shown (see Fig. 5a and Fig. 5b) it is not possible to identify *a priori* a set of parameters that will produce a *pessimistic* result or an *optimistic* one. On the contrary we have to look for *pessimistic/optimistic* cases only *a posteriori*, applying a careful analysis of the behavior and of the characteristics of the basin model and of the petroleum system under study.

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