A novel approach to a quantitative estimate of permeability from resistivity log measurements

Dario Viberti*
Alessandro Cossa**
Maria Teresa Galli**
Marco Pirrone**
Eloisa Salina Borello*
Cristina Serazio*

* Politecnico di Torino, Italy
** Eni E&P Division, San Donato Milanese (MI), Italy

Description of the material. *In this paper a novel methodology for the estimation of the formation permeability, based on the integration of resistivity modeling and near wellbore modeling, is presented. Results obtained from the application to a real case is shown and discussed. The well log interpretation process provides a reliable estimation of the main petrophysical parameters such as porosity, fluid saturations and shale content, but the formation permeability is traditionally obtained through laboratory tests on plugs, at the scale of centimeters, and through well test interpretation, at the scale of tens or hundreds of meters.*
However, log measurements, and in particular resistivity logs, are strongly affected by the presence of the near wellbore zone invaded by mud filtrate. In turn, the extension of the invaded zone depends on formation properties and, in particular, on permeability.
As a consequence, the resistivity measured by the tools (the apparent resistivity) has to be properly corrected through a resistivity modeling process to obtain the true formation resistivity and the geometry and resistivity of the invaded zone.
Resistivity profiles within the invaded zone are function of fluid properties, petrophysical properties and rock-fluid interaction properties. The novelty of the approach is to numerically simulate the mud invasion phenomenon and match the resistivity profile provided by resistivity modeling to estimate the formation permeability. In the proposed methodology the match of the resistivity profile is obtained by integrating the near wellbore simulator with an optimization algorithm.
Application. *This novel approach was applied to a heterogeneous shaly-sand oil-bearing reservoir in the Norwegian offshore area. The analyzed sequence was characterized by a high degree of variations in the layers' thickness, from meters down to below tools' vertical resolution. A complete set of wireline logs were acquired in the considered well; several cores were cut and routine and special core analyses performed.*
Results, Observations, and Conclusions. *First, a conventional petrophysical characterization was achieved and the appropriate resistivity corrections were calculated. Then, the modeled resistivity was used as the input for the optimization algorithm so as to obtain a continuous quantitative estimation of permeability in the entire logged interval. The results were satisfactorily compared to core measurements: in both thick conventional layers and thinner beds the match was very accurate.*
Significance of subject matter. *The new approach provided a robust permeability estimate also in un-cored intervals and, more generally, can be used to predict permeability in un-cored and un-tested wells.*
Keywords: *resistivity log, mud invasion, permeability estimation, near wellbore simulator.*

Approccio innovativo per la stima quantitativa della permeabilità da interpretazione di misure log di resistività. Descrizione della metodologia. *In questo articolo viene presentata una nuova metodologia per la stima della permeabilità della formazione, basata sull'integrazione della modellistica di resistività e della modellistica dei fenomeni di flusso nell'intorno del pozzo. Vengono inoltre mostrati e discussi i risultati ottenuti dall'applicazione ad un caso reale.*
Il processo di interpretazione log fornisce una stima affidabile dei principali parametri petrofisici quali porosità, saturazione del liquido e contenuto di argilla. La permeabilità della formazione viene tradizionalmente ottenuta attraverso prove di laboratorio su campioni, alla scala dei centimetri, e attraverso un'interpretazione di prove di produzione, alla scala di decine o centinaia di metri.
Tuttavia, le misure log, e in particolare i log di resistenza, sono fortemente influenzati dalla presenza nella zona vicino al pozzo di filtrato di fango. A sua volta, l'estensione della zona invasa dal filtrato di fango dipende dalle proprietà della formazione e, in particolare, dalla permeabilità.
Di conseguenza la resistività misurata dagli strumenti (la resistività apparente) deve essere corretta attraverso un processo di modellizzazione della resistività per ottenere la vera resisti-

1. Introduction

According to conventional procedures the estimation of rock permeability can be obtained either by laboratory analysis (at the plug centimetric scale) or through the interpretation of a well test, representative of the portion of the reservoir investigated during the test (Verga et al, 2011). In the latter case a flow rate is imposed (by production or injection) and the pressure response of the system is usually recorded. The data are interpreted by adopting appropriate analytical models derived from the solution of the single-phase diffusivity equation coupled with appropriate initial and boundary conditions.

Conversely, the interpretation process of conventional well logs assesses the fractional volumes of the solid and fluid components of the system, typically expressed in terms of porosity and fluid saturations, but does not provide any direct estimation of the formation permeability (Viberti and Verga, 2012). Reliable evaluation of fluid saturations is strongly based on the measured resistivi-

vità della formazione nonché la geometria e la resistività della zona invasa.
I profili di resistività all'interno della zona invasa sono funzione delle proprietà del fluido, delle proprietà petrofisiche e delle proprietà di interazione roccia – fluidi. La novità dell'approccio consiste nel simulare numericamente il fenomeno dell'invasione della formazione da parte del fango, ricostruire il corrispondente profilo di resistività attraverso la modellazione di resistività e stimare quindi la permeabilità della formazione attraverso il confronto con il profilo misurato. Nella metodologia proposta la corrispondenza del profilo di resistività è ottenuta accoppiando il simulatore numerico con un algoritmo di ottimizzazione.
Applicazione. *Questo nuovo approccio è stato applicato ad un giacimento di olio in una formazione sabbioso argillosa eterogenea, situata in un zona offshore norvegese. La sequenza geologica analizzata è caratterizzata da un elevato grado di variabilità dello spessore degli strati dall'ordine dei metri fino al di sotto della risoluzione verticale degli strumenti di misura. Nel pozzo considerato è stato acquisito un set completo di log wireline; sono state prelevate diverse carote sulle quali sono state effettuate analisi di routine e special core analysis.*
Risultati, osservazioni e conclusioni. *Per prima cosa è stata effettuata la caratterizzazione petrofisica convenzionale e sono state calcolate le adeguate correzioni di resistività. Successivamente la resistività modellata è stata utilizzata come dato di input per l'algoritmo di ottimizzazione in modo tale ottenere una stima quantitativa del profilo di permeabilità lungo tutto l'intervallo considerato. I risultati sono stati confrontati con le special core analysis ed hanno mostrato una buona corrispondenza indipendentemente dallo spessore del livello.*
Significatività. *Il nuovo approccio ha fornito una stima robusta di permeabilità anche in intervalli non campionati e, più in generale, può essere utilizzato per prevedere la permeabilità in pozzi non campionati e non testati.*
Parole chiave*: log di resistività, invasione di fango di perforazione, stima di permeabilità, simulazione near wellbore.*

ty that has to be representative of the true resistivity of the formation. However, log measurements, and in particular resistivity logs, are strongly influenced by the presence of an invaded zone, saturated by drilling mud filtrate. Resistivity logs measure the so-called apparent resistivity and therefore the estimation of the true resistivity is not straightforward but it requires the application of suitable calculation models, i.e. resistivity modeling, which also provide the geometry and the value of resistivity of the invaded zone. This information is crucial for the calculation of permeability since the evolution of the invaded zone in terms of shape and depth depends on the characteristics of the fluids involved in the filtration process, on the rock properties and on the rock fluids interaction properties.

Assuming that all the information relating to the formation and the involved fluids can be defined and that the only unknown is the permeability of the formation around the well, it is possible to perform dynamic simulations to determine the permeability values capable to reproduce the resistivity profile assessed from resistivity modeling. The proposed approach provides an estimation of the formation permeability at a scale between the plug scale and the well test scale.

The proposed methodology was applied to a real case represented by an exploration well drilled in the Norwegian offshore area. An heterogeneous oil bearing shaly-sand layer was considered for the interpretation. The results provided by application of the methodology were compared with all the other available information such as permeability estimated from core data, and corrected for overburden pressure, and permeability estimated from NMR. Furthermore, uncertainties associated to some of the input data, such as relative permeability curves, were taken into account.

2. Methodology

The proposed methodology for the estimation of permeability from log measurements integrates two different approaches and, from a point of view two different disciplines: resistivity modeling which is conventionally part of the log analysis and dynamic simulation of multiphase flow which historically has been associated to reservoir engineering (Benetatos and Viberti, 2010). Resistivity modeling is approached as an inversion problem whereas numerical simulation of mud filtration can be approached as a forward model. However, in the proposed methodology, the numerical simulation of mud invasion is considered a part of an inversion process aimed at estimating the values of permeability that better reproduce the invasion profile calculated by the resistivity modeling. The integration occurs in three subsequent phases, as shown in figure 1.

The first phase of the process is optional and consists in performing sensitivity analyses simulating the invasion phenomena through the forward model. All the information characterizing the problem, such as geometry, petrophysical properties, mud properties, fluid properties, etc. are used to calculate the resistivity profiles corresponding to different permeability scenarios. The extension of the invasion profile and the consequent distribution of the electrical properties depends not only on absolute permeability, but also on the fluids parameters, on the formation parameters and on the rock fluid interaction properties.

In most real cases, several parameters are characterized by a high level of uncertainty, and when information is not available, values of some parameters are assumed or taken from the literature. In

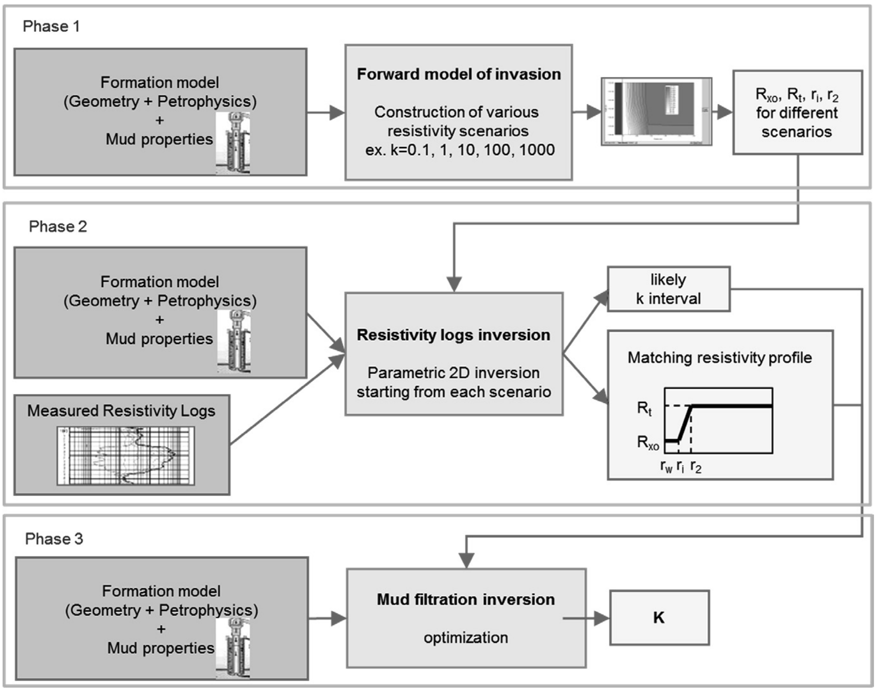

Fig. 1. Workflow of the presented methodology.
Diagramma di flusso della metodologia presentata.

many practical situations it is interesting to perform dynamic simulations in order to preliminary evaluate the impact of those uncertainties on the resulting resistivity profile. This constitutes phase 1 of the presented workflow (fig. 1). The resistivity profile is mainly characterized by three parameters: the radius of the completely invaded zone (r_i), the extension of the transition zone (r_2) and the resistivity of the invaded zone (R_{XO}). The results of these simulations can provide guidelines for accelerating both of the workflow subsequent phases: resistivity modeling (phase 2) and optimization (phase 3) shown in figure 1.

The second phase of the workflow consists in the conventional resistivity modeling approach aimed at evaluating the true resistivity of the formation. The process requires as input data the measured resistivity logs and a hypothesis of formation model, expressed in terms of geometry and petrophysical properties, and the mud properties. The results are obtained in terms of true resistivity of the formation, resistivity of the invaded zone and depth of invasion. This operation is performed with the aid of a commercial software.

Finally, in the third phase, the formation permeability and other unknown parameters are identified as a result of the inversion of the mud filtrate invasion model. This is automatically performed by an heuristic optimization algorithm which explores the unknown parameter space, identified in the previous phases, searching for a configuration whose forward model results give an optimal match of the target resistivity profile obtained in phase 2.

2.1. Forward model of the dynamic mud invasion process

The numerical model for simulation of invasion phenomena is based on the system of equations (1) (Settari & Aziz, 2002) representing the flow of two immiscible fluids, water and oil. The model simulates the immiscible displacement of the resident hydrocarbon by water based mud. It was solved by adopting an implicit finite difference scheme in which the simultaneous solution is calculated at each time-step.

$$\begin{cases} \dfrac{\partial}{\partial t}\left(\dfrac{S_w \phi}{B_w}\right) + \nabla \cdot \mathrm{u}_w + q_w = 0 \\ \dfrac{\partial}{\partial t}\left(\dfrac{\left(1-S_w\right)\phi}{B_h}\right) + \nabla \cdot \mathrm{u}_h = 0 \\ \mathrm{u}_i = -\dfrac{k k_{ri}}{B_i \mu_i}\left(\nabla p_i - \gamma_i z\right) \qquad i = w,h \end{cases} \tag{1}$$

The mud filtrate is assumed to be miscible with the aqueous phase originally in place, thus the salinity exchange between the mud filtrate and the formation water is modeled. In fact, inside the invaded zone, the filtrate comes into contact with the formation water and, if the two fluids have different salinity, the equilibrium in the mixture tends to be restored through migration of the chloride ions, sodium and other elements. Namely, applying the principle of mass conservation to the salt component in the mixture, the transport diffusion equation (2) (Nield and Bejan, 2006) is explicitly coupled to the system of flow equations (1).

$$\begin{aligned} &\frac{\partial}{\partial t}\left(\phi S_w C\right) + \nabla \cdot \left(C \mathbf{u}_w\right) + \\ &-\nabla \cdot \left(\phi S_w D \nabla C\right) = 0 \end{aligned} \tag{2}$$

Mudcake formation, including erosion effects, is modeled by an empirical correlation. Basically the variation in time of the filtrate flow rate, q(t), is described through fitting curves of experimental data (Ferguson & Klotz, 1954) later revisited and revised by Bilardo *et al.* (1996).

$$\begin{cases} q(t) = q_{eq} + \left(q_0 - q_{eq}\right) e^{-\beta t} \\ q_0 = -2\pi h \dfrac{k}{\mu_{mud}} \dfrac{P_{mh} - P_w}{\ln\left(r_e / r_w\right)} \\ \beta \approx \dfrac{1}{\bar{t}} \ln\left(\dfrac{1-\varepsilon}{0.1\varepsilon}\right) \end{cases} \tag{3}$$

Where the $q_{eq} = q_0\varepsilon$ is supposed to be a percentage (expressed as the fraction of decay ε) of the initial filtration rate q_0 reached at the equilibrium time ($\bar{t}$). $\bar{t}$ is defined as the time at which the equilibrium between formation of the mudcake and erosion due to mud circulation is supposed to be reached. The equilibrium time and fraction of decay are experimental parameters which depend on the composition of the mud.

Once the water saturation and salinity profile are simulated, the corresponding resistivity profile can be calculated as a post processing operation. Calculation of formation resistivity is obtained through application of Archie's law (Archie, 1942) for pure sand formation and Indonesia formula (Ellis and Singer, 2007) for shaly sand formations, equation (4).

$$R_T = \frac{1}{S_w^n} \left(\frac{V_{sh}^{1-0.5(\alpha+\beta V_{sh})}}{\sqrt{R_{sh}}} + \sqrt{\frac{\phi^m}{aR_w}} \right)^{-2} \tag{4}$$

When the shale volume is supposed equal to zero ($V_{sh} = 0$) the Indonesia formula reduces to the Archie's equation. The values of the parameters α, β, m and n are case dependent and are assessed in the resistivity modeling phase.

2.2. Resistivity log inversion

Formation resistivity measurements do not directly provide the true formation resistivity as they are influenced by shoulder effects and mud filtrate invasion effects. The latter mainly depend upon the fluid electrical behavior and by the geometry of the zone invaded by drilling mud filtrate. In some cases, when calculating the water saturation, it is possible to assume that the resistivity provided by the deepest invasion curve is representative, or at least a good approximation, of the true resistivity of the formation. However, it is often necessary to apply a more rigorous approach by means of suitable computational inversion models which are categorized as resistivity modeling. Such a process provides, in addition to the true resistivity profile, a description of the geometry of the invaded zone by means of some synthetic models comprehensive of a large series of real-life situations. Once the most representative model of invasion is identified (i.e. step profile, radial ramp or vertical ramp) and the values of the resistivity of the flushed zone (R_{XO}) and the undisturbed area (R_T) are assigned, the software generates a synthetic resistivity log profile which is then compared with the measured log. The model parameters are then recursively modified until a satisfactory match is obtained.

2.3. Mud filtrate inversion

The extension of the invasion profile around the well and the consequent distribution of the electrical properties depend on fluids and formation parameters as well as on the rock-fluid interaction parameters. Because of the non-linearity nature of the equation system and the combination of complex phenomena, the invasion model cannot be solved analytically and it requires the adoption of a numerical simulator. The nature of the problem and the variability in the number of potential unknown parameters (permeability, relative permeability, capillary pressures, porosity, initial saturation) led to the adoption of an heuristic optimization algorithm of inversion in which the dynamic simulator was treated as the forward model. An objective function has been appropriately defined in order to minimize the discrepancy between the resistivity profile resulting from resistivity log inversion and the one obtained by the mud filtration simulation. After several preliminary analyses, a Simulated Annealing (SA) (Kirpatrick *et al.,* 1983) algorithm was chosen among the metaheuristic optimization algorithm mainly because it is characterized by a reasonable computational cost as it requires a limited number of evaluations of the objective function with respect to metaheuristic methods based on population. This is particularly advantageous in practical applications since each single evaluation of the objective function requires a dynamic simulation. Because of its random nature, the algorithm ensures a good exploration of the space and it is able to handle functions with local minima. The algorithm is quite reliable even in the presence of a moderate number of degrees of freedom. Extensive analyses showed that the maximum degree of freedom corresponds to 5 parameters to be optimized for the considered problem.

3. Application to a real case

In order to fully illustrate the strength of the novel permeability estimation approach, an interesting heterogeneous shaly-sand interval was chosen and properly modeled.

The analyzed sequence was drilled by the exploration well A

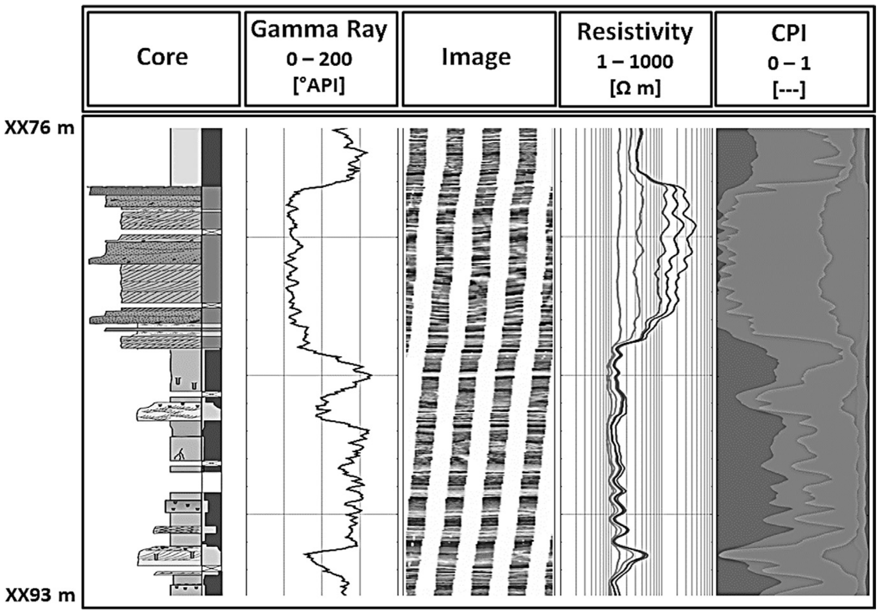

Fig. 2. Interpretation of the studied interval. Track 1: sedimentological description. Track 2: gamma ray log. Track 3: image log. Track 4: resistivity logs, from shallowest (light) to deepest (dark). Track 5: standard formation evaluation volume fraction with (from left to right) dry clay, silt, sand, oil, non-clay water and clay bound water.

Interpretazione dell'intervallo studiato. Traccia 1: descrizione sedimentologica. Traccia 2: log Gamma Ray. Traccia 3: log di immagine. Traccia 4: log di resistività, a profondità di investigazione crescente (da sinistra a destra). Traccia 5: risultati della standard formation evaluation in termini di frazioni di volume di (da sinistra a destra) minerali di argilla, silice, sabbia, olio, acqua non legata all'argilla e acqua legata all'argilla.

in the Norwegian offshore area. The reservoir is oil-bearing and characterized by sandstone bodies interbedded with deltaic shales: a high degree of variations in the layers' thickness, from meters down to tenths of centimeters, exists. Formation water salinity is about 75 ppk, while the drilling fluid used was a salty (230 ppk) water-based mud.

A complete set of wireline logs was acquired in the considered well: photoelectric, resistivity, image, acoustic, gamma ray, density, neutron and nuclear magnetic resonance logs. Several cores were cut and routine and special core analyses performed.

In order to ease the comparison with log data, core measurements underwent two preliminary steps. First, porosity and permeability data acquired at room condition were brought to reservoir condition using the transforms identified on the measurements at different net confining stress conditions (from 15 to 150 bar). Then, core measurements were matched against the log curves, using the sedimentological description as a reference.

In particular, the collected data show that sandstone bodies are characterized by high values of porosity and permeability. A water/oil contact is evident from log interpretation and it is also confirmed by pressure analysis: the studied reservoir sequence is well above the contact and it is at irreducible water saturation. Moreover, wettability analyses showed that the rock is slightly water-wet. Figure 2 shows the interval under investigation where sedimentological description (track 1), gamma ray log (track 2), image log (track 3), array resistivity logs with 5 galvanic resistivity measurements (track 4) and standard formation evaluation interpretation (CPI in track 5) complete the picture.

The interpretation was carried out in three main steps:

1. conventional petrophysical interpretation;
2. 2D resistivity modeling to remove invasion and shoulder effects on resistivity in order to improve S_W estimation;
3. permeability estimation in un-cored or un-sampled intervals by means of the novel and previously discussed modeling and inversion approach.

In figure 2, the analysis of deep-reading resistivity measurements (track 4, deepest resistivity in blue) held to the consequent standard hydrocarbon saturation determination (track 5, oil in green shading and water in cyan and blue). However, it is well known that the most common types of environmental noise (e.g. borehole effect, shoulder bed resistivity contrasts, invasion, presence of dips, anisotropy) may alter the measured resistivity; thus affecting the estimation of the true resistivity in oil bearing levels and the next water/hydrocarbon saturation. In order to remove these alterations and to compute a more accurate saturation profile, a dedicated 2D resistivity modeling and inversion technique was applied to the selected interval (see Galli *et al.*, 2005).

The output was a better estimation of the true resistivity of the defined layers, together with other parameters of interest related to the invasion profile. In the presented case, a step profile has proven to be sufficient to describe the invasion behavior and hence the considered geometry consisted of two cylindrical zones: a shallow invaded zone with resistivity R_{XO}, and a deep virgin zone with resistivity R_T. The radius of invasion is r_i. Since the step-profile invasion model was adopted, capillary forces were neglected in the following permeability modeling step.

One of the most significant issues addressed by 2D resistivity modeling is the presence of sequences of thin beds generally related to the overbanks in the flood plain. As a matter of fact, the reduced thickness of these layers (definitely below the resolution capability of most of the conventional logging tools) suggests the possibility of an incorrect measurement of R_T and porosity, and consequently the possibility of an overestimation of water saturation. This can be observed in the studied interval of well A (fig. 2), where a series of hydrocarbon bearing layers, each one less than 0.5 m thick, induces a strong reduction in the measured RT (track 4, bottom part of the sequence; the alternations are evident from the image log in track 3). As mentioned, an accurate 2D resistivity modeling provided a more correct RT for further elaboration.

The initial layering was driven by the sedimentological description of the cores and by image log data interpretation (see figure 2, track 1 and track 3). The 2D modeling of the thick sand bed in the top part of the interval was quite straightforward, while in the thin layered sequence in the bottom part R_T was constrained to maintain the same value in all the layers. This assumption is supported by the evidence of hydraulic continuity confirmed by formation tests, and by the high homogeneity of the textural/sedimentological facies.

Tab. 1. Indonesia equation parameters.
Parametri del modello Indonesia.

R_w	0.084 Ω m
R_{sh}	10 Ω m
a	1
m	1.96
n	2.3
α	1
β	1.5

As mentioned in Galli *et al.* (2005), the petrophysical interpretation was concluded by the computation of the value of water saturation, according to the new R_T profiles and the Indonesia formula (4): the necessary exponents and coefficients were calibrated against core analysis data and are collected in table 1.

The results obtained from resistivity modeling just characterize the first step of the approach, since the resistivity modeling outputs (R_T, R_{XO} and r_i) also represent the main input for the inversion-based permeability estimation approach. The remaining input consist in the modeled petrophysical properties of the different layers, the drilling history of the well, in-situ fluid and mud properties, pressure, temperature and the dynamic behavior of the mudcake related to the water-based mud used. All of these information were available for the studied interval of well A (see tab. 2).

Tab. 2. Fixed input parameters for permeability estimation approach through dynamic modeling.
Parametri di input fissati utilizzati nella metodologia per la stima di permeabilità attraverso modellazione dinamica.

Formation Water	
Salinity	75 ppk
Viscosity	0.4 cP
Density	1091 Kg/ m^3
Volume factor	1 r m^3/st m^3
Compressibility	3.19 × 10^{-5} bar^{-1}
Oil	
Bubble point	12.11 MPa
Volume factor	1.15 r m^3/st m^3
Compressibility	2 × 10^{-4} bar^{-1}
Viscosity	1.728 cP
Density @ ST	793 Kg/ m^3
GOR	100 sc m^3/st m^3
Gas gravity	0.7
Mud	
Salinity	230 ppk
Viscosity	8 cP
Density	1250 Kg/ m^3
Filtration Model	
Equilibrium time	0.5 hours
Equilibrium rate factor	0.01

Special core analyses provided important insight on water/oil relative permeability curves. Excluding shaly samples, the average residual oil saturation is 0.32 while oil relative permeability end-point is close to 0.7. Water behavior is more variable and will be further discussed in what follows.

After a dedicated sensitivity analysis, a layer-by-layer inversion was performed in order to obtain the absolute permeability, k. The most critical input proved to be the range of water relative permeability end-point, k_{rw}, which is commonly obtained from special core analysis. In this case study, we had no robust way to assign a unique value of k_{rw} to a given layer since relative permeability measurements were not continuous in well A. To avoid miscalculation, we preferred to perform two inversions by fixing k_{rw} to its minimum and maximum values [0.2-0.3] so that, at the end, we provided a range of inverted absolute permeability that gives insight on its uncertainty. It is worth mentioning that the other parameters that entered the modeling process were known or were proven to bring negligible effects in the optimization process.

An example of the inversion results in a given layer is shown in figure 3: the target resistivity profile is the red continuous curve, while the reconstructed points from k-inversion are the blue dots. The final output is the absolute permeability of the considered layer.

In figure 4, the final interpre-

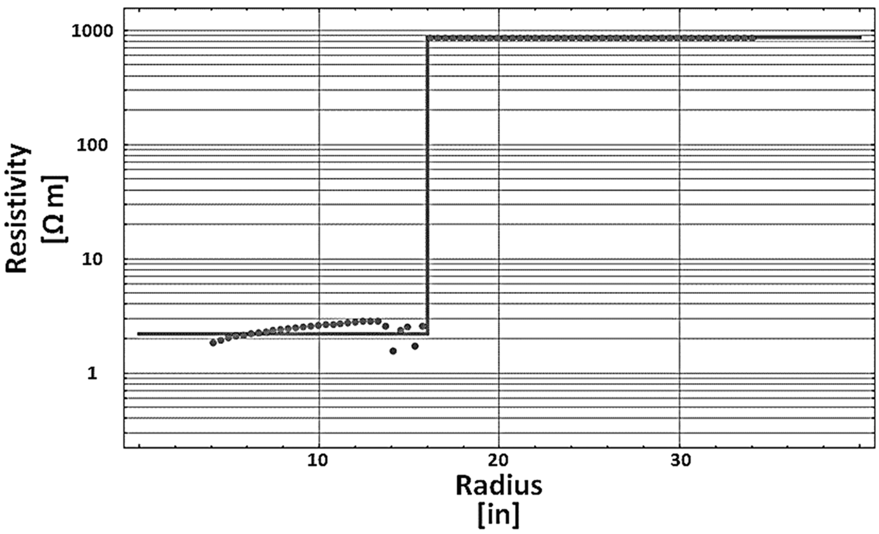

Fig. 3. Example of inversion results. Continuous curve: target resistivity profile. Dots: reconstructed resistivity profile for the related inverted absolute permeability.
Esempio di risultati di inversione. Linea continua: profilo di resistenza target. Punti: profilo di resistenza ricostruito per la corrispondente permeabilità assoluta da inversione.

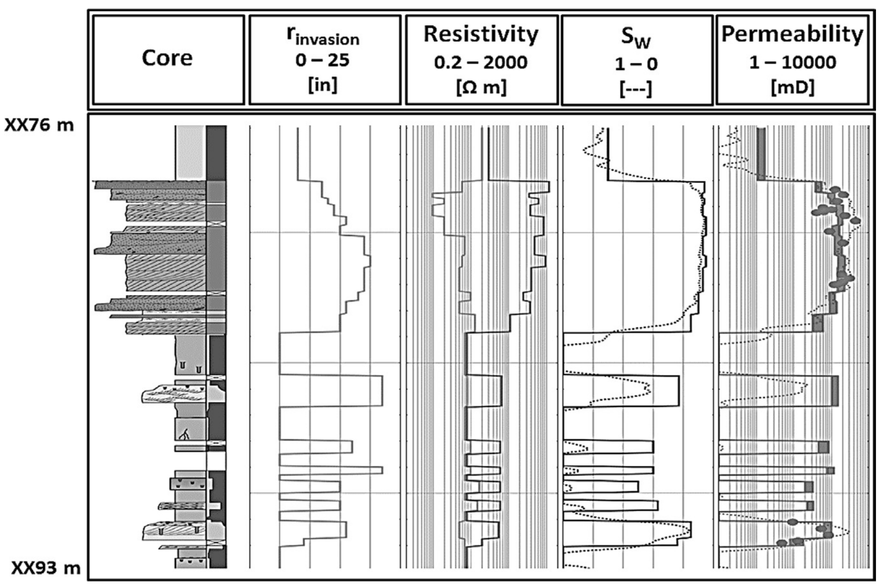

Fig. 4. Final modeling of the studied interval. Track 1: sedimentological description. Track 2: invasion radius. Track 3: true resistivity (dark line) and flushed-zone resistivity (light line). Track 4: modeled water saturation (solid line) and standard one (dashed line). Track 5: modeled permeability (solid line and shading representing the min-max interval obtained from different water relative permeability end-points), NMR-derived one (dashed line) and core data (points).
Modellazione finale dell'intervallo studiato. Traccia 1: descrizione sedimentologica. Traccia 2: raggio d'invasione. Traccia 3: resistività vera (linea più scura) e resistività della zona flussata (linea più chiara). Traccia 4: saturazione in acqua da modello (linea continua) e saturazione in acqua standard (tratteggio). Traccia 5: permeabilità da modello (linea continua e ombreggiatura rappresentante l'intervallo min-max ottenuto con diversi endpoint di permeabilità relativa all'acqua), permeabilità da NMR (tratteggio), permeabilità da log (pallini).

tation is shown, together with a comparison between the two different saturation profiles (CPI and R_T-modeled dashed line and solid line respectively, in track 4). In the thin layered sequence, the new squared saturation profile (solid line in track 4) is consistent with the field data and with core analysis data (irreducible water saturation from NMR and from capillary pressure tests). Then, the inversion-based permeability range is shown in track 5 (solid lines and shading) and it is in good agreement with the overburden corrected permeability values from core (dots). It is worth mentioning the comparison of the new result with the dashed permeability curve obtained from NMR interpretation and core calibration. In the thick sand beds the two curves are coherent from the quantitative standpoint, where the NMR curve is calibrated on core data while the new approach is completely independent from the measured permeabilities. As expected, the NMR approach completely misses the permeable thin layers in the bottom part of the interval due to the poor vertical resolution of the logging tool. On the other hand, the inversion-based modeling provides a quantitative permeability estimation range also in these layers thanks to the preliminary resistivity modeling.

4. Conclusions

A novel methodology, based on the integration of resistivity modeling and numerical simulation of multiphase flow, was introduced, discussed and validated against real data. The method provides a permeability mean value representative of the volume in the vicinity of the well, at a length scale between the core-plug dimension and the radius of investigation of a shallow depth well test such as a Mini-DST. However, after a careful calibration in wells/zones with core data available, an estimation of the formation permeability in the wells/zones where core data and well tests are not available can be provided.

The application of the methodology requires a set of information that is commonly available (e.g. conventional logs, drilling fluid properties, etc.); as a consequence it is significantly less expensive than any other methodology available in the market for permeability estimation.

The permeability value estimated by the process in many cases should be considered mainly as indicative of the order of magnitude of the permeability of the formation because of the level of uncertainty of the available information and assumptions on non-measurable phenomena such as the mudcake growth time, the decline of the filtering flow etc.

However, dedicated experiments on mudcake growth and filtering behavior can be done in order to reduce these uncertainties and to provide a robust quantitative estimation of permeability.

The methodology was implemented and successfully applied to a real case presenting both thick and thin layers. First, a conventional petrophysical interpretation was performed, then the resistivity profile was corrected by 2D resistivity modeling. Finally, after a dedicated sensitivity analysis, a layer-by-layer inversion was done in order to obtain the absolute permeability. The inversion-based modeling provided a quantitative permeability estimate in good agreement with core data both in thick and thin layers.

References

Archie, G.E., 1942. *The electrical resistivity log as an aid in determining some reservoir characteristics: Trans.* AIME, SPE 942054-G, Vol. 146, No. 1, pp. 54-62. DOI 10.2118/942054-G.

Benetatos, C., Viberti, D., 2010. *Fully Integrated Hydrocarbon Reservoir Studies: Myth or Reality?* American Journal of Applied Sciences, Vol. 7, Issue 11, pp. 1477-1486. DOI 10.3844/ajassp.2010.1477.1486

Bilardo, U., Alimonti, C., Chiarabelli, A:, Colacicchi Caetani, F., 1996. *Formation water saturation from drilling fluid filtrate invasion: comparison of displacement modelling and induction well log response*. Journal of Petroleum Science and Engineering, Elsevier, Vol. 15, Issue 2-4, pp. 251-259. DOI 10.1016/0920-4105(95)00079-8.

Ellis, D.V., Singer, J.M., 2007. *Well logging for earth scientists*. Dordrecht, Springer, 692 p., ISBN 978-1-4020-3738-2.

Ferguson, C.K., Klotz, J.A., 1954. *Filtration from Mud During Drilling, Journal of Petroleum Thecnology, Trans*. AIME, SPE 289-G, Vol. 6, No. 2, pp. 30-43. DOI 10.2118/289-G.

Galli, M.T., Gonfalini, M., Mele, M., Belik, P., Faivre, O., Jammes, L., Litman, A., 2005. *Resistivity modeling of array laterolog tools: an application in an offshore Norway clastic reservoir*. Paper SPE 89072-PA, SPE Reservoir Evaluation & Engineering, Vol. 8, No. 1, pp. 77-87. DOI 10.2118/89072-PA.

Kirkpatrick, S., Gelatt, C.D., Vecchi, M.P., 1983. *Optimization by Simulated Annealing*. Science, New Series, American Association for the Advancement of Science, Vol. 220, n. 4598, pp. 671-680. DOI: 10.2307/1690046.

Settari, A., Aziz, K., 1975. *Treatment of nonlinear terms in the numerical solution of partial differential equations for multiphase flow in porous media*. Int J. Multiphase Flow, Pergamon/Elsevier. Great Bretain, Vol. 1, pp. 817-844. DOI 10.1016/0301-9322(75)90037-3.

Verga, F., Viberti, D., Salina Borello, E., 2011. *A new insight for reliable interpretation and design of injection tests*. Journal of Petroleum Science and Engineering, Elsevier, Vol. 78, Issue 1, pp. 166-177. DOI 10.1016/j.petrol.2011.05.002

Viberti, D., Verga, F., 2012. *An Approach for the Reliable Evaluation of the Uncertainties Associated to Petrophysical Properties*. Mathematical Geosciences, Springer, Vol. 4, Issue 3, pp. 327-341. DOI 10.1007/s11004-011-9358-1

Nomenclature

B_w = water formation volume factor
B_h = oil formation volume factor
C = saline concentration
D = diffusivity coefficient
h = layer thickness
k = absolute permeability
k_{ri} = relative permeability to i-th fluid (i = w, h).
p_i = pressurei-th fluid (i = w, h)
P_{mh} = mudcake pressure
P_w = borehole pressure
q(t) = filtrate flow rate
q_0 = initial filtration rate
q_{eq} = equilibrium filtration rate
q_w = water flow rate for unit volume
r_e = external radius
r_i = radius of the completely invaded zone
r_w = well radius
r_2 = extension of the transition zone
R_{sh} = shale resistivity
R_T = true resistivity of the formation
R_w = water resistivity
R_{XO} = resistivity of the invaded zone
S_w = water saturation
V_{sh} = volume of shale
z = vertical coordinate
ϕ = porosity
μ_w = water viscosity
μ_h = oil viscosity
γ_w = water gradient
γ_h = oil gradient

Pedexes

w = water
h = hydrocarbon