UNIUNEA EUROPEANĂ GUVERNUL ROMÂNIEI Fondul Social European POSDRU 2007-2013 Instrumente Structurale 2007-2013 MINISTERUL EDUCAŢIEI NAŢIONALE OIPOSDRU Universitatea Politehnica din Bucuresti

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UNIVERSITATEA PETROL ȘI GAZE DIN PLOIEȘTI

Facultatea de **Ingineria Petrolului și a Gazelor**

Departamentul de **Geologie Petrolieră și Inginerie de Zăcământ**

DOCTORAL THESIS

- SUMMARY –

Studiul Potențialului Productiv al Zăcămintelor de Țiței Abandonate

Study of the Production Resumption Potential of Abandoned Oil Reservoirs

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Ploiești 2016

Abstract

When studying hydrocarbon genesis, the term "migration" is used to refer to fluid displacement under various forms, which have as a consequence the concentration and accumulation of oil in the collector rocks. There can be identified two stages of this displacement, having a net separation:

- *A primary stage (primary migration), represented by the dismission of hydrocarbons from the source rocks on short distances (meters, or tens of meters) until they reach the collector rock*
- *A secondary stage (secondary migration) which takes place inside the collector rock. This form of migration also takes into account the movement of the fluids through fissures/fractures and alongside faults, usually on long distances and large timescales.*

The mechanisms which are implied in the migration processes are very complex and are not understood to well. They have been the object of ample studies throughout the research history. Nearing the end of the primary production, after the reservoir is significantly depleted, besides the flow of fluids towards the producer wells, there can be identified a different type of flow of these fluids. After a long time of abandonment, in the order of hundreds of years, or even greater, the fluid phases continue to move in the porous space of the collector rock. This in-situu movement, after reservoir abandonment, is called the tertiary migration.

When modelling this process, the combined effect of aquifer advancement, primary (or secondary) gas cap and the interfacial forces alongside the gravity force have to be taken into account. The equilibrium towards this complex system is leading is reached with the help of four components: (1) a movement of the fluids from the higher pressure zones to the lower ones, including the one from the aquifer towards the productive layer (2) a movement of fluids towards a normal, gravitational setting from a density point of view (3) a tendency of lowering the phase dispersion to the smallest possible number of the fluid interfaces (in other words, to the lowest free surface energy possible) and (4) a repositioning of the fluid phases at the micro and macro scale so that the wetting equilibrium between the collector rock and every fluid phase is reached. All of these four components will have as consequence the reaccumulation of the fluid phases, which will be characterized by a distribution, similar to the one present before primary production.

While trying to analyze this process and to explain it thoroughly, two questions arise: which is the speed of the tertiary migration process and which is the time span of this process. The answer to these questions could consist in the basics of the four components mentioned earlier and, implicitly, the determination of the potential production resumption of the abandoned oil reservoirs. For the time being, only fractional explanations can be given regarding the tertiary migration components. However, there are cases where after a reservoir abandonment time of tens of years, and in certain favorable conditions, the tertiary migration process has been a fast one, so that production was restarted under favorable economic conditions, after the abandonment period.

Keywords

tertiary migration, micro and macro scale components of the tertiary migration, regeneration of the production resumption potential, gravity drainage, asymptotical saturation state, estimation of formation pressure in abandoned reservoirs, estimation of the extent regarding oil and gas saturated zones, screening criteria for the abandoned reservoirs with high production potential, and risk factors regarding production resumption.

I. Introduction

After the primary production has ended, when the reservoir is significantly depleted, besides the flow of fluids towards the producer wells, a different type of flow can be identified. After a long time of abandonment, the fluid phases continue to move in the porous space of the collector rock. This in-situu movement, after reservoir abandonment, is called the tertiary migration. To model this process, the combined effect of aquifer advancement, primary (or secondary) gas cap and the interfacial forces alongside the gravity force have to be taken into account. Two questions arise, as follows: which is the speed of the tertiary migration process and which is the time span of this process. For the time being, only incomplete answers can be given regarding these two questions. The complete answer could provide the basics of the four components mentioned earlier and, implicitly, the determination of the potential production resumption of the abandoned oil reservoirs.

II. Tertiary migration in oil reserovirs

This chapter is structured in three subsections:

- tertiary migration concept
- tertiary migration mechanisms
- regeneration of the production potential of abandoned oil reservoirs

In the first subsection, the tertiary migration of hydrocarbons is presented which denotes a spontaneous movement of the phases, either individual (as liquid or gas) or under molecular form, as a result of the hydrodynamic imbalance or other factors, such as physical or chemical ones, without having human intervention. In opposition, the term hydrocarbon production denotes the movement generated by the presence of the oil producers, hence human intervention. After production ceases in an oil reservoir, the movement of the fluid phases continues, because there is a hydrodynamic, capillary, and in a smaller proportion, compositional imbalance, which is more or less ample, being dependent on the exploitation regime, the presence or absence of an aquifer and, equally important, the reservoir heterogeneity at both the micro scale and the regional scale. The tertiary migration's direct consequence is a modification of the saturation state inside the whole volume of the collector rock, towards a new equilibrium tendency. The result will be a redistribution of the fluid phases, which in certain favorable situations will translate into a sufficient regeneration of the production potential, by crossing a minimum value for the oil saturation in a specific area of the reservoir that can coincide, only partially, with the initial productive layer.

In the second subsection, the evolution of the tertiary migration process is presented, being an important basic in fluid phase distribution and phase stability inside the porous area. The relative arrangement of the water, oil and gas phases as well as their stability is the combined effect of interfacial, buoyancy and friction forces. An important aspect that needs to be outlined is that at the end of oil production, three phases will always be present in the pore space, this fact leading to an increased stability of the phases. Because the system tends to an equilibrium, which implies both minimum free surface energy and potential energy, the number of fluid interfaces is diminishing continuously at the same time with the gravity segregation of the fluid phases. The phase continuity-discontinuity dichotomy is at the basis of the tertiary migration process, because during production, phase continuity decreases, whereas after reservoir abandonment, phase continuity is increasing. The mechanisms through which phase continuity is reestablished are coalescence, transfer of fluids through bypassing channels in the absence of interfaces and fluid transfer through a marginal film around droplets.

Afterwards, different forms of flow through which the tertiary migration process acts are presented, being similar to the flow regimes encountered in the pore network at macro scale, that have the consequence of continuity regeneration of the fluid phases, with the mention that, in this process, all forms of flow are present and act simultaneously. At the starting point of the tertiary migration process, and in a short period afterwards, the fluid phases do not reposition themselves under one, or more, predominant flow regimes, but after a considerable time, only when the fluid phases regained a certain continuity state through the different mechanisms at the microscale level, will be posibile to nominate which flow regimes will be predominant. For that matter, what is characteristic of these flow regimes is a volumic redistribution of the fluid phases on somewhat longer distances and not a film-type redistribution. The flow regimes that are presented are homogenous flow, meniscous flow, bubble/dorpet flow and annular flow. Also, taking into account that all three fluid phases are present, these flow types will be *co-current* and *counter-current*.

The last subsection, presents the regeneration of the production potential of the abandoned oil reservoirs from two approaches: regeneration of the saturation state of a reservoir volumetric unit and the rebuilding and redistribution of the reservoir’s energy. By definition, the saturation state of the collector rock is defined as the volume occupied by each phase divided by the total pore space, the fluids being present in different proprotions within the reservoir, depending on the section analyzed. This definition, for the most cases, is applied zonal to better observe the evolution of the saturation state with production, but in evaluating the efficiency of the tertiary migration process, this definition will be applied to the whole reservoir, more exactly on the middle layer where a high oil saturation is expected and a mean value for it will be used to observe the regeneration of the saturation state for the reservoir volumetric unit. The oil regeneration of this unit is possible with the help of oil gain from the edges of the abandoned wells network and the oil driven by the water which penetrated inside the collector rock from the neighbouring areas, least or not at all affected by the production process prior abandonment.

At the end of production, inside the whole reservoir, a considerable pressure imbalance is present, around each producer a pressure drop-down surrounding being present, which is more or less ample depending on numerous factors, the most important of them being: production behavior, global skin effect and absolute permeability, as well as the heterogeneity associated with it. For the reservoirs with a high degree of heterogeneity and ample lithofacial variations, differences of pressure in the order of tens of atmospheres were noitced, the reservoir being consisted of a single hydrodynamic unit. These pressure gradients are, in fact, equivalent to energy gradients, the lelling of the pressure (energy) being an asymptotical process towards a point which is influenced by the manner in which the initial reservoir energy was used.

III. Gravity drainage in oil reservoirs

This chapter is structured in four subsections:

- general considerations regarding gravity drainage
- the importance of the force of gravity phase redistribution
- gravity drainage modeling
- the influence of rock wettability and Darcy velocities in gravity drainage

In the fist subsection, a brief history is presented on the notion of gravity drainage where different approaches are prezented, both theoretically and practically and the way they have been used by the scientists. Also, the adaptation to this notion made because there are similarities between gravity drainage and the tertiary migration process, is presented.

In the second subsection, the forces that act towards the redistribution of the phases are presented, and they are consisted of: friction forces, interfacial forces and the force of gravity. The contribution of these forces is different, depending on the location where the phase redistribution takes place: in the vicinity of the wellbore or at greater distances from them. The main contributor, common for most of the reservoirs, is given by the balance between the interfacial and friction forces. For some particular cases, it has been observed that the gravity force also plays a major role in fluid redistribution, greatly improving the flow of fluids in the porous media. The main factors, which make the force of gravity an important one, are given by absolute permeability of the rock and the distance from the wellbore.

In the third subsection, a classification is made on all the laboratory experiments used to model gravity drainage in order to observe the efficiency of the process. The most common used solid materials and fluids are listed and the ways they can be adapted to better simulate gravity drainage according to the initial conditions of every experiment.

The last subsection, according to its title, presents the influence of the two on the gravity drainage process, rock wettability being defined as the attempt to determine quantitatively the measure in which two immiscible fluids from the porous space interact with the pore walls. Rock wettability is a direct consequence of the tri-phase interaction between the solid medium and the two present fluids and shows the tendency of one phase to occupy more space on the pore walls than the other. The movement of the fluids within the porous space has maximum efficieny only in certain situations that strictly depend on the tri-phase interaction and the selective interaction of the two fluids, but at the same time, the same efficiency depends on a flow parameter, the Darcy velocity of the phases. This velocity is very important because if it is too great, early phase fragnetation will occur and will lead to a rapid ceasing of flow.

The necessity of studying gravity drainage is pointed out by the similarities between it and the tertiary migration. By having a better understanding of the flow models and the mechanisms which affect the gravity drainage process, a parallel can be made to obtain an image of the efficiency of the mechanisms which are implied in the tertiary migration. Small values for the remaining saturations in the displaced phase, reched after a process like gravity drainage, will give valuable information on estimating the saturation state for the inferior, median and upper zone of the reservoir, the last two being presented in the following chapter.

IV. The evolution of the saturation state and pressure in oil reservoirs after abandonment

This chapter is structured in four subsections:

- the evolution of the saturation state during oil production
- asymptotical saturation state

- method for estimating pressure in abandoned oil reservoirs
- method for estimating the extent of the oil saturated layer and gas cap

In the first subsection, the saturation state in unexploited reservoirs is presented which is different according to the initial reservoir energy. For the reservoirs where the initial pressure is greater that the bubble-point pressure, there will exist an oil saturated layer and below it, will be present an aquifer. For the reservoirs where the initial pressure is smaller than the bubble-point pressure, besides the two zones mentioned earlier there will be present a gas cap which is found on top of the oil layer. However, because of the pore dimensions, pore geometry and the tri-phasic interaction, the passing from one zone to the other will not happen sharply, but through a transition zone. For the three major zones, aquifer, oil layer and gas cap, the saturation state can be obtained with sufficient accuracy, but not the same can be said about these transition zones, where the difficulty consists not only in determining the saturation state but as well as in determining the extent. If a flow test is conducted in the transition zone, the fluid with the highest mobility will be recorded and erroneous results will be obtained. Afterwards, a method is presented on how the saturation state can be roughly measured for all the zones inside the reservoir. Once the reservoir is put into production, the saturation state will change according to the present reservoir energy and the more, or less, rational exploitation of the reservoir. Regarding the evolution of the saturation state during oil production, two extreme situations can be identified: a first one, where a small and continous variation occurs, which is characterstic for a mild and long-term exploitation and the second one, which refers to an intense exploitation followed by water, or gas, channeling, gas being able channel either from the gas cap of from the free gas. Two major differences are noted between the two situations: the first difference refers to the phase continuity at the micro scale, greatly diminished for the first scenario and the second difference refers to the ample variations in the saturation state, which are more visible in the second scenario. Moreover, water, or gas, channeling lead to the existence of immense volumes of unswept rock where oil saturation is high the continuity is very good, at the micro scale. This fact represents a very good condition for an efficient start of the tertiary migration process.

To better understand the saturation evolution tendency after abandonment, in the second subsection, explanations are given for the minimum values of saturation reached for every phase within the collector rock. Afterwards, the author proposes a concept named *asymptotical saturation saturation state*, for short *asymptotical saturations*, which implies the therotecial values of the rock saturation for each of the three phases that will be reached after a sufficient amount of time, when the tertiary migration process will have lead to the possibility where restarting the production becomes technically feasible. At the same time, at this stage, a new wettability equilibrium is considered to be reestablished. The attempt to assing values, even probable ones, to the asymptotical saturation state proves to be very difficult because the values are dependent on the tri-phasic interaction and the composition of the fluid phases, and do not depend on the displacement processes.

In subsection three, the author proposes a probabilistic method which aims to highlight a range of values in which the reservoir pressure can be found, by using a material balance equation. This method can be applied only when the recovery factor is evaluated with sufficient accuracy, which implies knowledge of the oil and gas (free and dissolved), cumulative production of water, oil and gas, production GOR, volume factors and solution GOR, the last two being obtained with the help of pVT analysis. The method consists in plotting the recovery factor with pressure, values for the recovery factor being calculated for different reservoir pressures in accordance with various gas cap resources (M) and water cumulative which entered the porous medium (W), that result from history matching. The intersection of these various curves with the horizontal line given by the recovery factor will give the mean pressure in the reservoir at abandonment. If for an estimated value of W, which had been achieved at the end of production, the volume of water that entered the porous medium adds up, the point of intersection will give the actual reservoir pressure. This way, a range of probable values is obtained for the actual reservoir pressure. The subsection ends with an example.

In subsection four, the author proposes, when estimating the saturation state for the three new zones, as well as their extent, to start from a balance of volumes and to consider only the portion of the reservoir whici is above the water - oil contact. Thus, a new saturation state for each of the three new zones will be defined, as well as the mean saturation in every phase for the whole reservoir. The symbols used for these values of saturations are presented, the equations system is given, along with its solution, which will help in obtaining the extent of the three new zones. The proposed equation system can be easily customized for the situation where the active aquifer is absent, or is inactive, in this case being defined only two zones: the median zone, with high saturation in oil, and the upper zone, with a high saturation in gas. To resolve this system, different experimental results from the literature are used regarding the minimum saturation values in every phase that were obtained from displacement test on large number of cores and of different lithology. The subsection ends with an example.

V. Selection criteria for abandoned oil reservoirs with high production resumption potential

This chapter is structured in four subsections:

- screening criteria for abandoned reservoirs with high production potential
- data sources used in studying the production resumption potential of abandoned reservoirs
- uncertainties and risk factors regarding production resumption
- example of a field where production was restarted succesfuly

The first subsection separates the screening criteria in two categories: the technical ones and the economical ones. Technical criteria analyses physical reservoir conditions, forms of energy, production history and the degree of uncertainty that surrounds the available data to try and evaluate the measure in which the tertiary migration process evolvet satisfactorly and to see if the rearranging of the fluid phases towards a normal gravitational position has reached an advanced stage that sustaines production resumption. One of the eliminatory criteria from this category is represented by simultaneous production of more hidrodinamic units, aslo known as comingling, however an exact time limit cannot be given to clearly distinguish whether or not the reservoirs are lightly or deeply affected. Cumulative of fluids produced, during comingling, offer more reliable information on reservoir degradation.

Following these stages, it will be easier to establish the volume of remaning oil and its distribution inside the reservoir along with the mechanisms that acted while the reservoir was abandoned. Afterwards, the technical condition of the wells will be analised and the wells with good tehnical condition will be pointed out which could be reopened with minimum of costs. In a first stage, base case scenarios will be created regarding production resumption that will be based on the smallest expenses possible and where the situation will impose, more complex and ample scenarios will be created that can imply not only the reopening of existing wells but also drilling of new ones.

The economical criteria are very important in studying the feasibility of production resumption because they will indicate, in the end, the profitability when reopening the production, but the fluctuation of the global oil price have to be taken into account, because they limit the extent of this criteria. The economic factor is strictly related to the recovery factor, respectively the recuperable oil reserve because the latter will have to pay off the investments made with production restarting and to generate profit. It is a goal that all of these investments have to be the smallest possible but this does not exclude more complex, and expensive, projects that can boost up the production, once reopened. As a result, it will be seen that the economical factor can be an eliminatory criterion only in certain conditions.

In the second subsection, the data sources used in studying the efficieny of the tertiary migration process in abaondoned oil reservoirs and production resumption potential are presented, as well as the whereabouts of them. The latter is represented by: reservoir studies and archives of the production units from the oil company, measurements of pressure and temperature, the old published works could give helpful, even those with a qualitative manner only and last but not least, the old experienced men from the industry that worked on the specific reservoirs could prove very useful.

Once the necessary information has been gathered, they will be grouped under the following chapters: geological model, physical model, oil and gas resource, production history, assignation of the new zones: superior, median și inferior, tertiary migration stage and actual reservoir pressure.

In the third subsection, the errors that surround the data sources presented earlier are analised because the data recorded is not always correctly recorded or, in many cases, the data is missing. These two aspects will lead to uncertainties which, in order to study as efficient as possible the production resumption potential of the abandoned oil reservoirs, will have to be dimihshed, if possible eliminated. The main type of errors is given by the limited possibility of interpretation with the given data, as well as the technological level at the date of measurement/acquisition and the errors implied while measuring.

A special catergory of uncertainties is represented by the so-called "similarities", in which the collector rock properties and the fluid properties from a different reservoir are accepted for the case reservoir, on the idea that some characteristic are very similar, sometimes identical. Another type of uncertainties refers only to the collector rock properties and is represented by the usage of a single value for the entire reservoir. This approach is higly unrecommended all the more so the number of measurements for the certain parameter is small. Number of measurements means all the determinations made for a certain parameter through the same method but on different cores taken vrom various locations. Thus, well logs, mechanical cores and well testing are used to obtain the collector rock properties. For reducing these types of uncertainties, the author proposes to solutions:

- to reperform, phtsically, the interest parameter measurements (collector rock) or to resample the fluids so their properties could be later determined in the laboratory (fluid properties). The difficulties that arise are given by the costs and the, somewhat, lengthy time needed for the analysis. Determinations could be done on already existing probes but the probability of having them ready is very small and some properties, like the probe's saturation state cannot be redetermined. For the fluid properties, and some collector rock properties, probes from neighbouring blocks can be used if they are the same geological age
- to utilize empirical equations, present in the literature to estimate and obtain a range in which the parameters of interest could be and so, to have a general idea if the tertiary migration process has been an efficient one for the case field

Instead of using a single mean arithmetical value and applying it to the whole reservoir, just like in the case of the collector rock properties mentioned earlier, the author presents an example in which considers the reservoir divided into a network of cells in which the nodes are represented by the wells and the parameters of interest will populate the cells with the help of interpolation methods and, thus, a variation is obtained instead. Afterwards, as an attempt to make the representations as more complete as possible, the author proposes that the first parameter to be interpolated in the grid to be the porosity, because it is the least affecet parameter by measuring errors, being determined in many cases on core plugs. Having a distribution of porosity, empirical equations could be used to obtain a grid for other collector rock parameters, and even for other properties of highly interest, such as relative permeabilities.

In the last subsection, two examples of successful production resumption are shown, where there were more attempts for that purpose, some having success, whereas others not. It is important to mention that these attempts have represented simple "coincidences" and have laid solely on the intuition and of the geologist and reservoir engineers. The sarmatian and meotian from the Mărgineni structure represent the fields in whici production resumption was a success and they are discussed in this subsection.

VI. Case studies

This chapter contains five case studies which have been examined and where it is believed that the production resumption potential is very probable to have satisfactorly regenerated after an efficient tertiary migration process. Resuming the production on these reservoirs is yet to be realized and an in-extenso presentation is made in this chapter. Computerized simulations were used only in particular cases. The main stepts that were followed in the case studies are:

- identification of all the parameters regarding reservoir geometry and reservoir parameters that influence the flow of the fluid phases
- redefining/reviewing some properties like: lithology, rock-fluid properties, capillary pressure and pVT analysis
- defining the limit conditions, so that the resources can fit with the volumes of fluid produced until abandonment time.
- individual analysis of the producing wells: types of fluids produced, injection/extraction rates, water cuts, production GOR and establishing these as control variables.

and the output was:

- volume of redistributed oil
- volume of recoverable oil at abandonment time
- mechanisms used for production resumption
- the distribution of oil inside the collector rock

All the wells are analised, including their technical condition. Those wells with a good technical condition that allow rapid reopening (reentry, reperforating…etc) will be taken into account in the final scenarios.

With the help of those presented above, a base case scenario will be created for production resumption with minimum costs. The existing wells and surface equipment will be first evaluated. Other scenarios regarding production resumption take into account the possibility of drilling new wells or comparisons between existing EOR scenarios with the production resumption base scenario. The final report will contain a decline curve analysis and the cumulative of fluids produced which will be matched with the resource.

Original contributions of the author

1. The exhaustive bibliographical study made on the tertiary migration mechanisms, with highlighting the conditions in which oil flows through films and has a very big contribution to phase repositioning, as shown on one of the case studies. For layers with small thickness and small dip, contrary to the immediate perception, the author describes an important aspect of the tertiary migration that shows two stepts: the first step, in which the gas phase concentrates to the upper part of the reservoir and water phase to the lower part, respectively and in the absence of mobile water, the concentration of the oil phase to the lower part of the reservoir, by traveling on small distances, so in a relative short amount of time, having as effect a rapid regaining of phase continuity, and the second step, a volumic flow, which is possible in the presence of high saturation values for one of the phases, with the limiting of interfacial forces, alongside the top and bottom of the layer and on longer periods of time.

2. The review made onto the gravity drainage concept, on which numerous studies exist with the purpose of establishing time frames needed for an advanced tertiary migration, based on the Darcy velocities recorded in experiments in a variety of initial conditions referring to rock properties, fluid properties, wettability and resewrvoir temperature. It has been estimated that, in the most favorable cases, a time interval around 40 years represents a limit in which production resumtption could prove efficient.

3. The introduction of a new concept, asymptotical saturations, which are defined as reference points for rock saturation in water, oil and gas after a long time has passed, when the variations in saturation become insignificant. These landmarks have been obtained with the help of experimental data that studied gravity drainage. A graphic representation is realized in a ternary diagraf dorm to better illustrate where the asymptotical saturation points can be found.

4. An overview of the uncertainties which surround the initial data needed to evaluate the process of the thertiary migration, for estimating the actual reservoir pressure, actual saturation state, volume of recoverable oil and gas and the potential production resumption of the abandoned reservoir. Solutions are proposed for minimizing these uncertainties, adapted for each available data set, by using the best matched corelations and thoroughly completing the available data with other data from similar reservoirs.

5. An overtview of the screening criteria for reservoirs which are eligible for production resumption, completing the first ones with data referring to reservoir

heterogeneity, minimum abandonment time, as well as applying these criteria to a number of reservoirs on which the author has directly participated in a project completed for an oil company.

6. The analysis of five case studies, with the direct implication in two of them, for the project mentioned above. The approach is a complex one, impying the reviewing of the geological model, physical model, production history, estimating actual reservoir pressure, the extent of the oil saturated zone and gas saturated zone and placing these on the corresponding bathymetric chart, establishing the areas with maximum probability for a successful production resumption and the forecast that would be recorded for such a scenario.

7. The proposition of a well design for a reservoir with very favorable conditions for a successful tertiary migration process, reservoir which actually meets all the selection criterias for this purpose but with a low estimated actual pressure which is insufficient for economically attractive flow rates. The proposed design consists in drilling of a first well that passes through the productive layer, in which the pressure will be measured for correlation and, eventually, running a flow test. In the case of an unfavorable case, meaning approval of the low estimated pressure, the productive layer will be isolated, the well will be drilled further towards an inferior layer which was found flooded, but to be very active and putting this layer in communication with the producing upper layer, in the end placing a tight plug above. Afterwards, at an appropriate depth, a deviated well will be drilled at a distance arround 200 m from the first one, through which the well will be put into production, while the reservoir is supplied with water at high pressure.

Recunoștințe (Acknowledgement)

Rezultatele prezentate în această lucrare au fost obtinute cu sprijinul Ministerului Fondurilor Europene prin Programul Operational Sectorial Dezvoltarea Resurselor Umane 2007-2013, Contract nr. POSDRU/159/1.5/S/134398.

Autorul vrea să mulțumească, în mod deosebit, Agenției Naționale pentru Resurse Minerale a României și companiei OMV – Petrom S.A. pentru ajutorul acordat în elaborarea acestei lucrări.

The work has been funded by the Sectoral Operational Program Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/134398.

The author would like to give special thanks to the National Agency for Mineral Resources of Romania and OMV – Petrom S.A. for the help given in elaborating this work.