Doctoral School of Earth Sciences

Practical applications of geological modelling workflows in the redevelopment of mature hydrocarbon fields – a case study

THESIS OF THE PHD DISSERTATION

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Introduction

The main events and bulk of the work took place between 2015 and 2017; consequently, various aspects of the thesis concentrate on this time period. In some cases, where understanding can be aided, additional data and information are also provided. Due to confidentiality, the hydrocarbon field the study focuses on is anonymised and is referred to as Field A in the documentation (accordingly, well names, precise volumetric data and coordinates remain undisclosed as well).

Due to the global oil price drop in 2014, the preventive/reactive measures taken by one oil company included increasing ownership of its assets by reviewing them individually and crosschecking historical volumes and potential and related costs so as to identify marginal or unprofitable elements within their existing portfolio.

The trigger for the work introduced in the PhD Thesis was the abovementioned market shock, with a secondary trigger being the fact that by 2018 approximately 65-75% of the world's total oil and gas production originated from mature fields, which, combined with the desire for reduced unit prices, put pressure on operators to allocate increased efforts to these elements of their portfolios (O'BRIEN et al., 2016; LUPU, 2019; GAFFNEYCLINE, 2020).

The study primarily aims to describe the methodology (with a key focus on the Petrel workflow) applied during the geological modelling of Field A. The task was split into two main parts: firstly, a quick-look model was built (Phase 1); later, a more complete geomodel was constructed (Phase 2). A secondary aim was to show the practical applications, impacts and benefits that were triggered by the geomodelling or apriori exercises. A further goal was to offer a way forward by spotlighting the remaining weak points that required upgrading.

Structurally, the thesis was divided into three main parts: 1) an overview of Field A; 2) the reservoir geological modelling process, including the preparatory work and the key impacts and results of Phase 1 (first-pass geological model); and 3) the Phase 2 geological model, with a main focus on the integrated workflow established.

Field A is a mature, onshore oil field in the Russian Federation discovered in 1947, coming on production in 1949. Geologically, the field is situated in the central part of the Volga-Ural Basin, south of the South Tatar Arch.

The field has four productive formations, of which three are carbonate (Tournaisian, Serpukhovian, Bashkirian Formation) and one is clastic – the Bobrikovian Formation (further details: SZILÁGYI et al., 2021) – with one underexplored possible upside potential in the Verejskij Formation overlaying the Bashkirian Formation.

All of the reservoirs are undersaturated oil reservoirs (hence, no primary gas cap exists), with medium-type black oil having an API gravity of 25-27°. The prevailing driving mechanism is weak to moderate aquifer drive and depletion. The dissolved gas content is low (5–40 m^3/m^3), and therefore plays an ancillary role as a driving mechanism.

The total cumulative oil produced as of 2020-03-01 was almost 13 million m^3 (~82 million barrels). However, the actual recovery factor is only around 10–14% (depending on the oil initially in-place case), providing room for detailed investigation to optimise development strategy. Based on analogous fields and calculations, the expected final recovery in similar reservoirs could be between 25-35%, or even higher with modern secondary and tertiary methods (PÁPAY, 2003).

Applied methods and discussion

A quick 'first-pass' geological model (a.k.a., Phase 1) was built for Field A so that the business requirements and deadlines for 2016 could be met. As soon as the main model (Phase 2) was finalised, the first-pass version was retired and not used for further analysis and planning.

The main quantitative goal of Phase 1 modelling was to have a quick preliminary in-place volume calculation and compare it to the legacy data in order to be able to carry out a sense-check and a rough estimation of volume changes, both in terms of in-place volumes and remaining recoverable resources (NEMES et al., 2021).

The Phase 1 model was initially built using Emerson's RMS 2013.1 software. The vintage (the input dataset closing date) of the Phase 1 model is 2016-01-01.

A normal workflow was applied in Phase 1 regarding 3D geological modelling, the main milestones being structural modelling, facies modelling, property modelling and volumetric calculations. As the main focus is on the Phase 2 model, its details are disclosed here.

Alongside Phase 1, preparations were made for a second (Phase 2) detailed modelling, aiming to mirror the actual behaviour of the field, incorporate the data and provide an understanding of the non-available or non-interpreted data from the first model. The vintage of the input dataset was 2017-10-31. The descendants of the Phase 2 model are still in daily use in terms of Field A's life.

First and foremost, it is critical to mention that the Phase 2 work was done mainly in Petrel 2015.5 (Operating system: MS Windows 7 64-bit), hence, any updates in the software to date – in the last four years – are not reflected in the thesis.

A workflow is a sequence of steps making up a process. It can be used for model updates, uncertainty analyses (including experimental design), scenario analyses, idea testing and creation, as well as for general, daily tasks. The main advantages of a workflow include automatability, repeatability, scalability, modularity, auditability and shareability.

All these advantages make workflows an effective tool in terms of time (by reducing the number of clicks and mouse movements needed to reach the same outcome) and energy being saved and creative capacity being enhanced while minimising the chance of human errors being made during updates and reruns. Therefore, the description of Field A's geomodel workflow is one of the pillars of the current work.

The Field A geomodelling workflow was split into several subworkflows (eight main elements, and two optional). The subworkflows were split so that the optimisation of the update processes could be done in such a way that partial workflows could be rerun as well (e.g., only for upper reservoirs, or only for lower reservoirs, or only for the property model). In addition, dividing up a multi-hundred step workflow makes it more transparent and manageable. All these subworkflows combined consist of 818 rows, or steps.

The backbone of the created workflow is comprised as described, at a high level, in the following paragraphs.

Data preparation (a.k.a., data wrangling) and loading are inevitable primary steps in any analytical or statistical work (PEDERSON et al., 1998). The conventional 'garbage in, garbage out' is not an empty phrase after all. During the data preparation phase, several subtasks are carried out, the most critical ones being: the standardisation of datatypes; naming convention unification; the standardisation and unification of units, coordinate systems, reference levels and undefined values; flagging and/or filtering of outlier or extreme data, if necessary; loading of data to a predefined database and/or reference projects; establishing the practice of future data management and perpetual updates.

Structural modelling is the process of establishing the tectono-stratigraphic skeleton of the reservoir by integrating seismic and well data in line with the regional geological concept. A structural model defines the fault-fault, horizon-horizon and fault-horizon relationships, fault throws and pinch-outs. Field A's structural modelling was based on (manually) interpreted seismic horizons that were converted to depth domain using a velocity model. Only the top horizons were interpretable, hence, the bottoms were modelled based on the corresponding top and with the use of the well tops identified in the wells. A bounding fault – which plays a crucial role in closure – was modelled based on the fault sticks interpreted on seismic and converted to depth domain. Initial oil-water contacts were identified for each formation based on logging and inflow testing information.

The structural modelling and related preceding steps are all scripted in the first two subworkflows, Surface manipulation and Structural modelling, consisting of 230 and 30 steps, respectively.

A grid model – *3D grid model* – can be described as a 3-dimensonal representation of the relevant characteristics of a reservoir with a predefined resolution. Each grid cell represents a data point for each modelled property, and its shape is dictated by the structural framework and the grid's user-defined dimensions. The 3D grid modelling methodology applied for the creation of an integrated structural model based on the input data described above was pillar gridding (within the corner point gridding group).

The grid modelling A subworkflow describes the generation of the lower reservoirs' geocellular grid (without properties); it consists of 88 steps. The grid modelling B subworkflow describes the generation of the upper reservoirs' geocellular grid (also without the properties yet) and consists of 68 steps. The two workflows are very similar, and the concept behind them is identical, although the number of steps is different. Since subworkflow A is of slightly greater complexity, the description is based on that.

With the creation of the empty 3D grid, the next step is the distribution of the petrophysical parameters to the interwell space – where each grid cell represents a value for each parameter – while preserving realistic reservoir heterogeneity and matching the well data (SCHLUMBERGER, 2021), that is, *Property modelling*.

Most of the statistical methods and the probability theory are also founded in normal distribution. Hence, data transformation sequences are inevitable prior to the running of any modelling algorithms so that the actual input dataset is normally distributed and spatial trends are removed. This step is the Data Analysis.

The Property modelling A subworkflow describes the process for the Bobrikovian and Tournaisian reservoirs, while B describes the upper reservoir pair. Subworkflow A consists of 205 steps, while B is built up of 144 steps. The difference is due to the differing modelling approaches in the case of Bobrikovian compared to the other three formations. For Bobrikovian, first the discrete reservoirflag ('rocktype') is modelled and, subsequently, the petrophysical parameters are constrained by the reservoirflag. For all of the other reservoirs, the total property modelling approach is used.

The main input data to property modelling were the petrophysical interpretations and core measurements. In the case of Bobrikovian, 2D trend maps were also incorporated to guide the spatial distribution. In other cases variograms and vertical proportion curves were applied without 2D or 3D trend maps/cubes.

The most important output parameters (3D properties) for each formation are interconnected porosity, permeability, initial water saturation and net-to-gross. A comprehensive overview of saturation modelling and its theoretical background is given in NEMES, 2016).

With the completion of the property modelling, all the input parameters are available in the 3D grid necessary to calculate hydrocarbon initially in-place, which is one of the goals of the modelling job. The *Volumetrics* task delivers calculated gross rock, net, pore, hydrocarbon-pore and in-place volumes, along with distribution maps (volume height maps) and the 3D properties, which are direct inputs to dynamic modelling. Volumetrics subworkflows A and B consist of 6 and 5 steps, respectively, being the shortest of the subworkflows within Field A's Petrel Project.

Results

Phase 1

The main result of the Phase 1 modelling exercise was that a huge amount of historical knowledge and experience, seventy years of data, and generated information started to become a structured set of understanding, where focus points and gaps were revealed. The preparatory works, the multidisciplinary interpretation and the modelling all revealed new information or outdated, old, erroneous 'beliefs', which are equally important and crucial in terms of the road to transparency (NEMES et al., 2021).

Quantitatively, the main results were the *first-pass updated volumetrics* (and related volume reconciliation) and the reference case 3D geological model with spatially distributed reservoir parameters that could be used to start the dynamic modelling.

Phase 1's geomodel had already been having a significant impact on ongoing operations in areas such as *new wells planning*, both in number and placing of wells, *field development strategy* and a *data acquisition programme* (NEMES et al., 2021). The planned wells were fine-tuned, and more than 50% of them were moved so that more prospective subsurface targets could be drilled. The drilling of dedicated Bobrikovian wells was suspended, and the sidetracking of existing wells was cancelled due to subsurface and economic considerations. The drilling sequence of the new wells was optimised to accommodate the post-drill evaluation of individual wells prior to the drilling additional one(s) in the same part of the field, an approach which was called staged drilling.

New (advanced) *well log acquisitions* were proposed in some of the new wells, with the intention of mitigating part of the revealed information gaps.

Simultaneously, the number of tools run as a conventional logging set was rationalised, and excess measurements were removed, for example, the induction log (NEMES et al., 2021); in addition, cased hole logging practices were revisited and optimised.

Additional *core* (>100 plugs) and *fluid measurements* were requested to fill-in revealed data gaps, mainly for permeability measurements and oil properties.

Detailed geological investigations were initiated based on the recently acquired understanding in aid of the upcoming Phase 2 modelling (NEMES et al., 2021): Bobrikovian facies analysis; Bobrikovian old wells petrophysical investigation; Serpukhovian paleokarst mapping; correlation of intra-formation subzones (Tournaisian and Bobrikovian); identification of Tournaisian bottom horizon; hardcopy data digitisation (trajectory; production); and numerous minor adjustments (e.g., well name contradictions, wellhead coordinates and elevation, logset anomalies).

Phase 2

The *dataset* available during the Phase 1 modelling was not final; trajectories, measured and interpreted logsets, core data, finalised completion and production logs, and historical reports were not all integrated, and a fine-tuned seismic interpretation was also missing. The placement of all the data integration, standardising and quality-checking activities into a common *single-source-of-truth database* was in-progress throughout the Phase 1 modelling. These tasks were finished in Phase 2 and incorporated into the subsurface models and subsurface database.

In order to simplify and standardise the dataflow, the data sharing processes were updated and *data governance* was implemented.

The optimal solution was to use a Petrel and OFM *reference model*, where all the input and interpreted data was loaded (except for special data types that were stored separately, but with strict data governance rules also), at which point the data were labelled as final versions and could be modified by data managers exclusively.

As a *quality assurance protocol*, several cross-checks and validation points were implemented during data loading into the Reference projects, such as anomaly detection (e.g., negative values in porosity logs), log-end effect check, wellhead and trajectory reality check.

A *new seismic interpretation* was done, incorporating the adjusted and synchronised well-pick set, the newly digitised data and the newly drilled wells.

In *structural modelling* several outlier datapoints had to be removed from horizon adjustment due to anomalous depth values compared to offset wells during Phase 1.

The structural model was significantly simplified as during the Phase 1 history-matching process, the *in-field faults* showed a marginal impact on the flow pattern; hence, these were not modelled so that the unnecessary complexity involved in increasing the runtime (54 faults with subseismic throw if any were removed) could be avoided.

A particular set of wells (~100 wells) had a high impact on the *Bobrikovian Formation's* modelling and history matching since these wells provided approximately 50% of the historical production from the formation. As a result, these wells were reevaluated, and the derived information content was incorporated into the Phase 2 geomodel, providing the possibility of higher-quality history matching and a more reliable dynamic model.

In rocktype (and petrophysical) modelling for the Bobrikovian Formation (Bb), the need for *trend maps* became evident so that the high degree of horizontal heterogeneity could be spatially distributed and controlled.

The *subzonation* of the Tournaisian Formation (V1) also had a significant effect on property models, namely, that the lower part of the formation shows lower permeability compared to the upper zone, having a critical effect on saturation profile, productivity, and production-related water encroachment as well as water injection schemes.

The *property modelling* approach was altered – in three reservoirs (except Bobrikovian) total property modelling (TPM) was implemented so the modelling workflow could be made more flexible and the end results made more realistic geologically. In addition, the fine-tuned, *adjusted petrophysical interpretation* served as the basis for the property modelling, which also involved the revisiting of a cut-off set (NEMES, 2022).

The *permeability model* was updated with porosity-permeability regression curves updated through the incorporation of new core measurement results and subzonation.

The hydrocarbon initially *in-place volume update* is based on the newly updated geomodel, which is the main input to the dynamic modelling; it can also be used to identify by-passed oil, which can also drive further field development activities.

A *fully integrated workflow* was outlined (>800 steps) so that the model could be updated on a regular (bi-weekly) basis in a standardised, automatable manner as new data (new wells, adjusted interpretations) arrived. With the workflow in place, the regular model updates were a minimum five times faster (up to ten times) through a significant reduction in the number of clicks and mouse movements compared to fully manual updates; in addition, human mistakes due to the monotonic updating process were overcome with a well-structured workflow (NEMES, 2022). This also means that geoscientists can dedicate more time and energy to creative tasks which really require the cognitive capacity of the expert instead of monotonous clicking.

Along with the geomodel construction, a quality-check *guideline (*a.k.a., *checklist)* for geomodelling was outlined and implemented so that a high-level guidance in terms of quality assurance could be provided. Also, a *version tracking framework* was implemented so that updates of the geomodel can be followed in the future.

The history-matched geomodels and dynamic models are used routinely in both the operation of Field A and for the planning of field development activities, such as:

- production and injector well placement (including targeting by-passed oil), or conversion and post-drill analysis (well success rate increased by minimum 15%);
- workover planning (squeezing, adding perforations, commingling production or, of equal importance, preventing it, and dual completion applicability);
- filtering opportunities of cost optimisation by extending existing wells instead of drilling new ones from the surface (no practical application yet);
- planning well stimulations (e.g., radial jet drilling, hydraulic fracturing) or other production optimisation activities;
- proving the suboptimal manner of actual water injection patterns and the replanning of the strategy sector-by-sector to reenergise the reservoir(s), which is the key challenge in improving the recovery factor in the main reservoirs;
- drilling horizontal wells (in the Lower Tournaisian Formation due to lower reservoir quality, but significant in-place volumes);
- highlighting upside potential in undrilled areas within and outside the actual license area, aiding the decision-making on license extension (if any);
- reinstating drilling of dedicated Bobrikovian wells;
- submission of updated field development plan to related authorities;

- reporting expected production profiles (and recoverable volumes) to related authorities as well as internally to key company stakeholders;
- reconciliation of volumetric data;
- an aid which supports daily operative decisions in the field;
- a tool which supports surface facility and ALS (artificial lift system)-related decisions (e.g., extension of capacity, optimising capacity, change of ALS).

The work delivered an improved level of understanding and triggered a *full reassessment* of the half-century-old development concept, including the pressure maintenance system, workover strategy, sidetracking strategy and well stimulation practices applied in the field.

Secondarily – beyond field development planning/optimising – the Petrel project also serves as:

- a source of up-to-date basic data about the field and its wells (as a data repository) and historical information due to having the full-cycle workflow to promptly update the model with new data;
- a source of visual aids (maps, cross- and well-sections, animations), statistical parameters (geological, fluid and dynamic), in-place volumes and production and pressure forecasts for decision-making materials;
- a source of tabular information information regarding stock reports, well attributes, well tops, and volumetric data;
- an optimisation tool for wellpad utilisation, whereby unnecessary costs and environmental damage can be avoided by building new ones;
- a data and information sharing tool which can be used with business partners, as each piece of new information regarding subsurface is loaded and can be easily shared and combined with the version tracker Excel sheet directly, which shows where changes can be expected;
- an aid during data gathering planning and optimisation (e.g., the earlier-described logging dataset adjustment);
- (with a post-study update) a tool to quantify the untapped oil resources of the Verejskij Formation (above Bashkirian Fm.) and identify further steps (if any).

A work the size of a Field A reevaluation not only has a direct technical impact, but also builds a highly effective project team and establishes data and information flow channels (front and back channels as well). This leads to smooth, more effective, collaborative work, which can be an incubator for fresh ideas and innovation.

Conclusion

Both the methodology and the extended range of practical impacts of the geomodelling and related work were introduced in detail in the dissertation. The broader context explains the triggers of the task, and the detailed description of the creation of the applied workflow can be used for other projects as well, either directly or indirectly.

The dissertation formulated eight goals and has reflected upon and met all of them, providing new modelling and field application results and, most importantly, improving the link between a computer-based model and a producing oil field:

1) Establish a single, quality-checked, standardised database, for both static and dynamic subsurface data. – *Petrel Reference Project (static data) and OFM Reference Project (dynamic data) were built, and data loading guidelines and processes were put into operation.*

2) Drive a better understanding of the current and past events in the field that can aid in the future planning of data acquisition. – *The integrated reevaluation of Field A had an impact on almost all aspects of the ongoing field development (data acquisition, drilling, well workovers, further potential).*

3) Build an up-to-date 3D geological model to serve multiple purposes. – *The model was built with a full-cycle Petrel workflow, proving all of its benefits. The model is used for visualisation purposes, source of data and statistics, input to full-field dynamic modelling, and re-conciliation of initial in-place volume.*

4) Build a full-cycle geomodelling workflow in Petrel to make regular updates faster and smoother. – *The outlined workflow was comprised of more than 800 steps, from data loading to volumetric calculation; it is modular, and can be automatically run as new data arrive or other updates are necessary..*

5) Prove that a complete geomodelling workflow can be built that is capable of automatising routine updates in the geomodel. – *This was proven as the whole workflow was used in practice multiple times following the completion of the geomodel.*

6) Make the ever-current model shareable with business partners and third parties, if necessary. – *The reference projects, the* *working geomodel (Phase 2) and the workflow itself are shareable and were continuously shared after the finish of the geomodel as well. All the updates and adjustments can be followed in a version tracker sheet so that transparency can be maintained.*

7) Introduce the practical implications the work done can have on field development. – *The outcomes are described in detail for both the Phase 1 and Phase 2 modelling and beyond.*
8) Highlight opportunities and risks associated with the area of interest and recommend a way forward. – *The last subchapter of the thesis lists the identified recommendations (which at the same time highlight the weak points of the model) for a way forward, which have already been partially implemented since since the study was completed.*

The dissertation also provides a short list of recommendations on possible ways forwards for the upgrading of the Phase 2 geomodel, both in terms of input data quantity and quality and modelling techniques. Some of these recommendations have already been implemented since 2017-2018, and several in-field applications have already proven the benefits of this multidisciplinary reevaluation of Field A's subsurface.

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Hungarian summary

A tanulmány fő témája a rezervoármodellezés hozzáadott értéke érett szénhidrogén-mezők esetén, külön figyelmet fordítva a modellezés teljes menetét leíró lépéssorra („workflow”).

Jelen tanulmány a teljes folyamatot leírja az adatgyűjtéstől a geomodel utóéletéig, mindezt egy az Orosz Föderáció területén található érett mező (Mező A) esettanulmányán keresztül.

Mező A egy érett – 1947-ben felfedezett, 1949-ben termelésbe állított - szárazföldi olajmező az Orosz Föderáció területén.

Nem technikai okok miatt, hanem üzletpolitikai megfontolásból két geomodell készült. Egy első, egyszerűbb (Phase 1), és ezt követően egy részletesebb, több bemenő adatra építő és az első hiányosságait áthidaló második (Phase 2).

A Phase 2 modell deklarált célja volt a Phase 1 változat hiányosságainak orvoslára adatminőségi és -mennyiségi, metodológiai és “workflow” szempontból is.

A két modellváltozat különbségeit és hasonlóságait részletesen tárgyalja a dolgozat. Kiemelt hangsúlyt fektetve a részletes és teljes “Petrel workflow”-ra, amely hivatott a jövőbeni frissítéseket és mindennapi használatot felgyorsítani, optimalizálni. A geomodellezés minden lépésének elméleti háttere is röviden bemutatásra kerül, együttesen a gyakorlati alkalmazással és a “workflow”-ban elfoglalt helyével. Minden „subworkflow” bemutatása előtt röviden összefoglalásra kerül az adott részt koncepciója, kiindulópontja és célja.

A teljes „workflow”, amely lehetővé teszi a geomodell átfogó frissítését több mint 800 lépésből áll és 10 „subworkflow”-ra van bontva.

A dolgozat keretét adja az annak elején kitűzött tételszerű nyolc cél, amely célok mindegyikére reflektál a szerző az utolsó fejezetben. Minden cél teljesült.

A geomodell utóéletét, hatásait részletesen tárgyalja a dolgozat, ezzel megteremtve a hidat a számítógépes modellek a mező üzemeltetése között. Külön fejezetet szentel a geomodell további fejlesztési lehetőségeinek és gyengeségiből fakadó kockázatoknak, ezzel teljessé tévé a leírást.