

Original Research Paper

# Optimal Subsurface Appraisal: A Key Link to the Success of Development Projects-Few Examples

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**Abstract:** During exploration and production phases, the life of a hydrocarbon field can be distinguished by five main stages: Exploration, appraisal, development, production and abandonment. Of particular interest is the appraisal stage, where billions of dollars are spent across the oil and gas industry on data gathering activities with a view to reducing subsurface uncertainties towards optimizing reservoir development and management. However, very limited attention is often paid to assessing the Value of Information (VOI) during data acquisition requirement planning, before requesting for such information. Appraisal, when conducted optimally, leads to informed sequential decisions resulting in a development plan that optimizes cost, hydrocarbon recovery and attempts to maximize Net Present Value (NPV). On the contrary, suboptimal appraisal, either in the form of under, or over appraisal, impacts project economics. Individual oil and gas companies use their own strategies, procedures and metrics to optimize subsurface appraisals and safeguard profitability and hence there are no industry standards. The capital intensiveness of the industry and emerging low oil price regime has necessitated scrutiny on every dollar spent on data gathering in the current business terrain. Appraisal should be optimized by way of case specific activity of data acquisition to ensure project deliverability under maximum residual uncertainties achieved by minimum appraisal cost. To ensure that the appraisal strategy is value driven, an effort has been made to briefly recapitulate the different components of appraisal strategy necessary for appraisal framing and evaluation workflow. The appraisal locations selection and their sequencing combines uncertainty reduction, probability of success with VOI technique to determine the number of appraisal wells, their sequence of drilling and their justification that is based on economic merit. The effectiveness of this systematic approach has been illustrated through some real field examples. This workflow along with periodic look-back analysis, during appraisal to development phases, has proven to be highly useful for (1) improving the understanding of geological model; (2) assess VOI from appraisal; (3) reduce subsurface uncertainties and (4) improve decision quality and whole cycle project economics.

**Keywords:** Subsurface Appraisal, Geological Risk, Value of Information, Development, Resources, Net Present Value

## Introduction

The phases associated with the search and the production of hydrocarbon reservoirs are known as the Exploration and Production (E&P) phases. Typically, a hydrocarbon field undergoes five major stages during the E&P phases: Exploration, appraisal, development, production and abandonment. Because each stage

depends on the prior, a combination of successful exploration, effective appraisal and commercial extraction is needed to ensure a successful E&P cycle. A successful exploration well may demonstrate that an oil reservoir exists, but there are typically still too many uncertainties around that resource to proceed directly to development decision. Size is often the issue (e.g., ultimate recoverable could be too small to justify

building of facilities or it could be too large that planned facility might become constraints and may end up destroying value by differing production unnecessarily. Therefore, following discovery, appraisal is used as essential step in deciding whether and how to develop a field. The minimum required resources or Economic Threshold Limit are estimated using standard discounted cash-flow model in which a relation between technically recoverable resources and NPV is established for the full project life cycle considering the most likely development scenario and minimum field size (Peacock and Jennings, 2014; Stigliano *et al.*, 2016). During appraisal a series of activities such as drilling appraisal wells, geologic and seismic studies, 3D reservoir modelling and simulations etc. are carried to obtain further information about the shape, size, storage, fluid properties and dynamic behaviour etc. to support informed decision.

Every year, E&P companies invest hundreds of billions of dollars for appraisal. Despite the large financial stakes involved, appraisal strategies often lack objectivity, transparency, are ill-defined or are sub-optimum. Suboptimal appraisal, under- or over-appraisal, ultimately has a negative impact on the project economics. Currently, there are no industry-wide recognized guidelines or criteria for appraisal (Bratvold *et al.*, 2009). Appraisal requires well-defined strategies aimed at optimizing activities to safeguard upstream profitability (Burkholder *et al.*, 2012). Field complexities and difficulty in selection of analogues set the stage for extensive, longer and expensive appraisal campaigns. As the appraisal campaign is executed, surprises may inevitably occur. Therefore appraisal strategy up-front should be driven by value creation.

The problem of determining the sufficient number of appraisal wells is discussed in the literature. However, none of the studies offered a comprehensive approach for determining the required number and location of appraisal wells for maximal profitability. Knoring *et al.* (1999) document three wells sufficient for appraising small accumulations and four to six wells for medium and large accumulations. However, there is no systematic approach as to how those numbers are determined and as to how the prospect sizes are labeled (small Vs. medium Vs. large prospect sizes). Haskett (2003) optimizes appraisal-well locations through the efficient uncertainty-reduction method. With the purpose of mapping the reservoir extents, this quantitative method prioritizes the appraisal-well locations in the reservoir. The best location is chosen for its ability to offer the greatest combined value of uncertainty reduction and Probability of Success (POS).

The Value of Information (VOI) technique has been used as a powerful tool for both short and long term justification of data-acquisition costs by the oil and Gas industry. Demirmen (1996; 2001) makes use of the VOI concept to justify proposed appraisal well locations. In the appraisal context, the VOI is the difference between

the value of developing the project with appraisal and the value of developing the project without appraisal. If the VOI is positive, then the benefits outweigh the costs and the appraisal activity is justified (Demirmen, 1997; 2001). Coopersmith and Cunningham (2002) have described a twelve steps methodology to evaluate the VOI and emphasized that VOI as being the interplay of three main factors: The proportion of the time the decision makers choose the wrong decision (function of the uncertainty abiding in the reservoir), the monetary impact of such a wrong decision and finally the reliability of the information under consideration.

Although, VOI concept has been applied in oil and gas industry since more than five decades (Grayson, 1960) but it has not yet been fully integrated on the decision-making process (Bratvold *et al.*, 2009). Because the value of data acquisition usually spans through many of the E&P stages, the VOI analysis is thus a short-term and long-term cost-cutting and value-creation process. This stretch over the E&P stages requires the VOI to consider a full-life-cycle approach, necessitating the collaboration and contribution of a multidisciplinary team, ranging from geoscientists to top management, often adding to the complexities of this method. Cunningham and Begg (2008) capitalize on the potential for learning to occur between the drilling of two wells. The VOI approach is used in this context to analyze the predicted value of this learning on development wells and to maximize it by providing recommendations regarding the best sequence of well locations (Cunningham and Begg, 2008). Three appraisal targets were reviewed by Burdett and Haskett (2012) through the application of the VOI approach. One key takeaway of their work, which the authors stress as being a pillar of the VOI approach, is the capacity of the new data acquisition to change a potential development decision (i.e., the new information to be collected should have the potential to change the development decision) (Burdett and Haskett, 2012). Very recently, El Souki and Saad (2016) have made suggested a stochastic approach to determine the number of wells, their sequence of drilling including their justification that is based on economic merit. This approach couples the uncertainty reduction with VOI techniques. Very recently, David *et al.* (2016) have carried out a case study using multiple subsurface scenarios for production forecast and VOI approach to support a key decision whether or not to drill an appraisal well to test for fluid contact and possible presence of an oil rim in a gas reservoir with Lowest Known Gas (LKG) prior to initial gas development. This analysis indicated that the range of oil rim thickness proved to be noncommercial and the VOI analysis showed that drilling of an appraisal well will result in negative value giving the VOI and cost of drilling an appraisal well. This work also indicated that the amount of oil volume estimated in the oil rim will not trigger a change in the current development strategy of the gas

field. This work allowed to stop the drilling of appraisal well which resulted in significant cost savings, provided a robust basis for a commercial decision without compromising on regular standards and industry best practices and resulted in improved project economics.

The goal of this paper is to first briefly recapitulate the different components of appraisal strategy necessary for appraisal framing and evaluation workflow. The appraisal locations selection and their sequencing combines uncertainty reduction, probability of success with VOI technique to determine the number of appraisal wells, their sequence of drilling and their justification that is based on economic merit. The effectiveness of this systematic approach has been illustrated through some of the real field examples to optimize the subsurface appraisal with minimum costs and maximum profitability.

### **Subsurface Appraisal Framing and Analysis Workflow**

Appraisal, viewed in the larger context must impact decisions related to field development and translate into risk reduction, confidence building or higher profitability for the project. A well-designed and well-executed appraisal campaign should help improve ability to make timely and quality decisions. Appraisal must help manage residual uncertainty during the field life through economically viable interventions. The reservoir-specific uncertainties may be Hydrocarbon In-Place (HIP), recovery efficiency, fluid type and its quality, or a combination thereof (Lawrence *et al.*, 2008; Singh *et al.*, 2009; Rose, 2010; Nandurdikar and Wallace, 2011; Romundstad *et al.*, 2013; Singh *et al.*, 2013; Orellana *et al.*, 2014). The appraisal framing and analysis workflow can be based on following considerations.

#### *Confirming or Refining the Understanding of Geological Context*

In frontier areas, the actual exploration well rarely matches predrill geological hypothesis or assumptions. With this background, appraisal strategy should address upfront regional and local scale geological context to understand impact of continuity and connectivity, field performance, recovery efficiency and possible development schemes.

#### *Hydrocarbon In-Place Volume*

Perhaps most straight forward objective of an appraisal strategy is to determine the reliable range of in-place hydrocarbon volume for the discovery by addressing lateral extent, fluid contacts, structural uncertainty, rock properties, fluid type and compartmentalization or connectivity issues.

#### *Recoverable Volume and Flow Potential Rates*

Estimation and reaffirmation of reservoir flow potential and recoverable volume is the most critical

requirement for determining economic viability and selection of appropriate well and facility design. A cumulative distribution curve of contingent resource with gentle slope indicates wider possible values. After appraisal, the slope should generally be steeper, indicating reduction in uncertainty. The case illustrated in blue is unfavorable, as the curve after appraisal is below the economic threshold. Such appraisals deliver value by preventing development investments. In the other case, as shown in green, the post appraisal curve is in the economic realm to support development. An assessment of Value of Information (VOI) to justify appraisal must be appropriately undertaken. To illustrate the value from an appraisal well, the cumulative Density distribution for the Contingent Resources before and after appraisal along with the economic threshold limit can be analyzed (Fig. 1). As the knowledge of reservoir improves, variance is likely to reduce with additional new data. Exceptions to this rule, however, are common as often estimations of the uncertainty range are poorly appreciated in the early phases.

#### *Development Strategy*

Visualization of development options usually begins just after discovery and is firmed up after appraisal campaign. Development and phasing options should be visualized by assessing technical and non-technical risks. A rigorous understanding of overall context through which project will pass to achieve maturity must be built to reduce cycle-time and risks.

#### *Understanding/Reducing Risks for Field Development*

An optimal appraisal strategy is one where uncertainties that have the greatest impact, on development decision and project NPV, are reduced in a timely and cost effective manner and properly understand the risks which can be carried forward. One of the key assessments is to prevent any loss of opportunity if the field is abandoned for the reasons not attended by appraisal. Loss of opportunity also includes suboptimal development or slower monetization despite possible higher productivity. At the same time uncommercial development should not be undertaken with flawed assumptions without appraisal.

#### *Evaluate Development Strategy without New Information (No Appraisal)*

Evaluation of development strategy without appraisal must be undertaken to understand the project's risk profile. However, due to field complexity and uncertainty, it may be necessary to evaluate multiple development options in order to decide a base project value. This base project value may be used as a reference to compare VOI for planned appraisal activities.

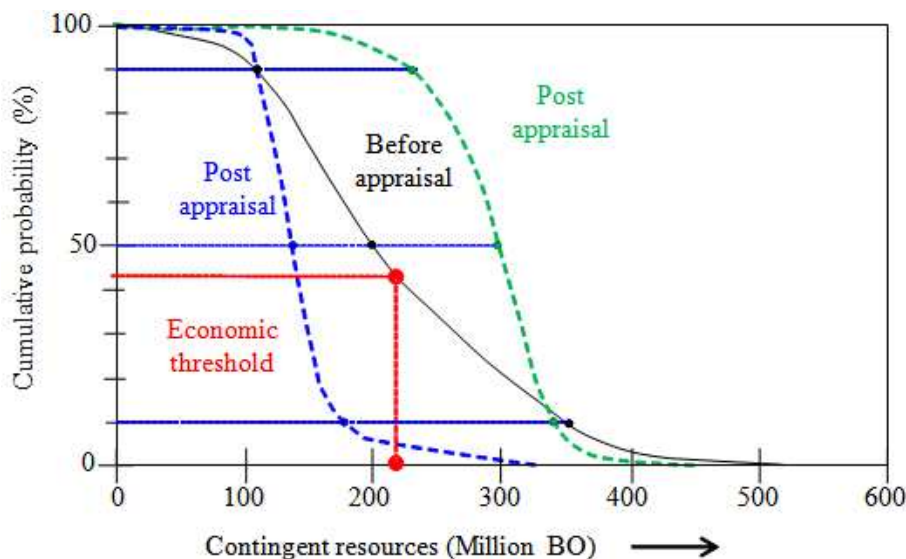


Fig. 1. Cumulative distribution of contingent resources before and after appraisal. After discovery (black curve with gentle slope), resources distribution is wider. Post appraisal scenarios are (a) may confirm the discovery resources (black-gentle slope with wider distribution), (b) P90, P50 and P10 range reduces (blue-steep slope with narrow distribution) and (c) P90, P50 increase but P10 reduces (green-steep slope with narrow distribution)

### Options for High-Level Appraisal Roadmap

The objective for the high-level appraisal roadmap is to identify various appraisal options and schedule to assess their incremental value. It is necessary to raise and sort the key issues and categorize them as (Coopersmith *et al.*, 2003): (a) Decision already made and inherent uncertainties (e.g., facts: Known data or background information, policies and key assumptions), variables over which the team has no control. (b) Focus or strategic decisions (e.g., appraisal well type/numbers, area to develop, facility capacity, export, build-in flexibility), team has influence but no control. (c) Tactical (implementation or later decisions), team has full control.

### Individual Appraisal Stages

The purpose of framing individual appraisal stages is to understand which uncertainties to be reduced in each appraisal stage. Framing should be focused on the key uncertainties mainly rather than on a multiplicity of uncertainties that may not impact development. Individual appraisal stages should be optimally designed with potential walk away points defined.

### Agree the High-Level Appraisal Road Map

This step is to agree for the individual appraisal activities along with their schedule and order of priority based on the identified and ranked uncertainties. This is an ever evolving dynamic process and must be continuously reviewed. The sequential planning of appraisal activities will either encourage going ahead with next activity or modifying its scope, or even remove it from the appraisal program altogether.

### Appraisal Well Location Selection

Drilling of a well to acquire data is one of the most common activities during appraisal. Each appraisal well is characterized by the resources of the segment in which it occurs along with identified risks. When multiple geological models are applied, the benefits of appraisal activity include identification of applicable model. The proposed workflow for appraisal well location selection comprises of four steps.

### Post Discovery Resources Estimation

The process of identifying key uncertainties should follow a systematic approach using following data sources and analysis techniques:

- Assess rock property averages using well data
- Screen field data to determine suitable analogues related to key identified uncertainties
- Probabilistic and model based volumetric analysis using ranges of key uncertainties to provide an initial range of volume potential for a field in terms of In-place, recoverable and expected production rates (Singh *et al.*, 2009; Wolff, 2010; Singh *et al.*, 2013)
- Experimental design could be a useful tool to quantify uncertainties (Cebastian and Osbon, 2011)
- Integration of new data e.g., reprocessed seismic data, nearby well information or new insights gained
- Focused subsurface studies to understand geological environment and impact on recoverable volumes

### *Geological Model Review, Risk Assessment and Segmentation*

Post discovery, the geological model review should focus on:

- Review of the predrill assumptions in light of new well information
- Assessment of multiple geological models with their chance of occurrence
- Review of predrill risk assessment and determine post-drill risks
- Identification of segments and their associated risks

Uncertainty in the possibility of different geological model should be fully captured. Risk is assessed using standard approach in order to facilitate the evaluation of the relative merits of appraisal well options and locations (Milkov, 2015).

#### *Appraisal well Location for Segment De-Risking*

An appraisal well location can be characterized in three approaches, depending on the degree of uncertainty and risk associated with the geological model and the resources category distribution, which are:

#### *Segmentation*

A risk of one or more geological elements may be common between two or more segments. When common risks occur, a successful appraisal well in one segment may de-risk other segments. Thus the total resources of both de risked segments should be used to evaluate appraisal location.

#### *Multiple Geological Models*

When multiple geological models are employed, appraisal activity may verify the more likely model. Where there is no bias, model chances are equal. As a guide, the following description for a two model case (Table 1) can be used. In the absence of risk, the appraisal well will find hydrocarbon, however the resources associated with a location may be different based on occurrence of different geological model. If geological risks are identified for any of the geological models, there is a chance of appraisal well failure and this must be incorporated into the appraisal location characterization. In this case, the overall chance of success associated with a specific well location will be the sum of the segment chance weighted models chances.

#### *Value of Information (VOI)*

The intuitive reason for gathering information is straight forward if the information can reduce uncertainty about future outcomes, decision can be made that have better chances for a good outcome. However, such information gathering is often costly. The questions that arise include: (a) is the expected uncertainty

reduction is worth its cost, (b) if there several potential sources of information, which one is the most valuable and (c) which sequence of information sources is optimal. However, it is not trivial to answer such question because it is necessary to assess value before any measurement is taken.

In simple terms, the VOI can be described as the amount a decision maker should be willing to pay for a piece of information. This can be estimated in terms NPV for with and without information scenarios using standard cash-flow model. It quantifies the value of decision-relevant information and hence facilitates the management of opportunities. The application of the VOI concept provides a predictive, analytic and quantitative framework for decisions and justifications for data gathering activities including but not limited to log data acquisition; downhole fluid sampling; subsurface diagnostic tests; core data acquisition; appraisal drilling and seismic acquisitions. Such information gathering may be worth if it has the potential to change a decision. The VOI analysis evaluates the benefits of collecting additional information before making a decision and it involves three key components: (a) prior uncertainty, (2) information content of data and (3) the decision problem. The VOI can be expressed as:

$$VOI = [\text{Expected value with additional information}] - [\text{Expected value without additional information}]$$

To quantify the value of appraisal drilling using VOI method, a step wise approach as given below:

- Create subsurface scenarios for the Appraisal outcome based on available information and identified key uncertainties
- Develop a decision tree to demonstrate possible subsurface scenarios and resulting outcomes on development (e.g., gas only development, concurrent oil and gas, sequential oil then gas, etc.) decision (with and without appraisal)
- Assign probability of occurrence to each scenario based on regional knowledge, available subsurface data, analogue reservoir information and detailed reliability assessment
- Perform economic analysis for each scenario/outcome to obtain different economic indicators (e.g., NPV, Unit technical cost per barrel, EMV, etc.)
- Compute Expected Monetary Value for each scenario using assigned probabilities and corresponding NPV
- Carry out sensitivity analysis on assigned probabilities of each realization to test robustness of the analysis and identify key risks and probabilities that may be managed to enhance value

VOI decision is most powerful when a clear go vs. no go decision depends on additional new information.

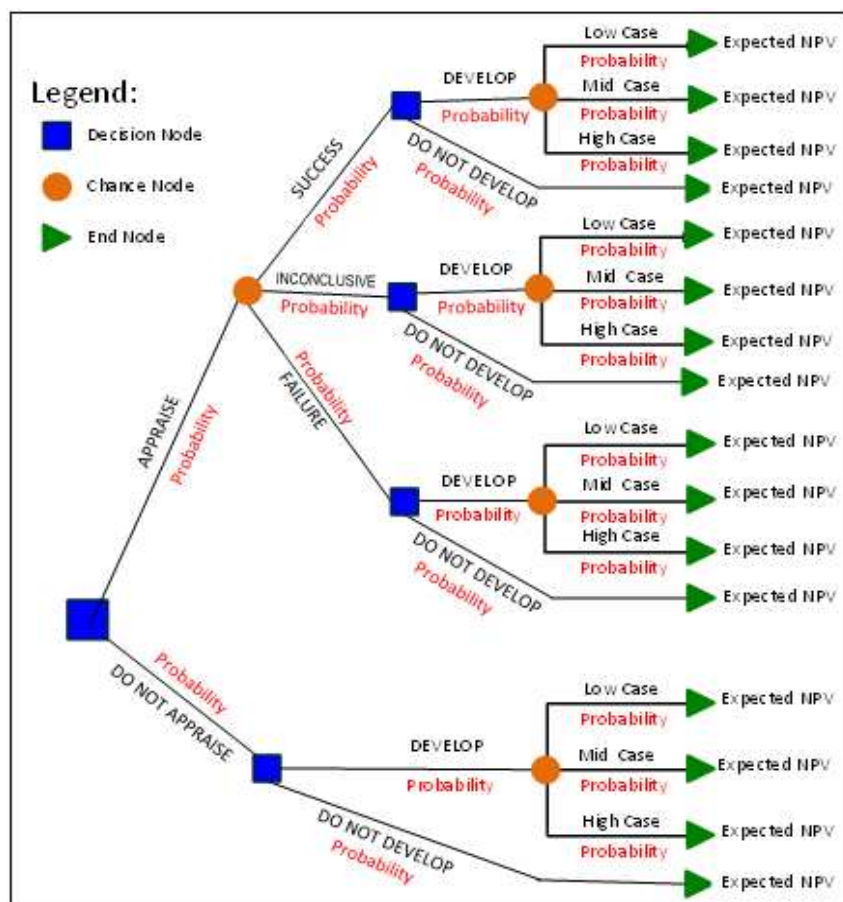


Fig. 2. Schematic diagram of VOI decision tree showing net present value with and without appraisal

Table 1. Multiple model chance table

Chance	Description	Comments
0.5	Equal weighting	Both models are equally likely
0.6	Weakly favourable	One model is slightly more likely than other
0.7	Moderately favourable	One model is tangibly more likely than other
0.8	Strongly favourable	One model is possible but unlikely
0.9	Near certainty	One model is possible but very unlikely
1.0	Certainty	Only One model applies

This situation requires a realistic application of the decision threshold. Use of conservative/optimistic decision threshold can distort the VOI materially, because the analysis may mischaracterize go decisions (go as no go or otherwise) and misrepresent the value associated with those decisions. Appraisal justification should be expressed in terms of the expected NPV Value that the appraisal will have on the project. The VOI approach is well-suited for this purpose (Howard and Abbas, 2015). This can be represented by a simple schematic diagram (Fig. 2) in which the NPV of development with and without appraisal information is estimated. The decision tree provides assessment whether the value is enhanced or diminished by appraisal drilling.

### Appraisal Strategy and Decision Process

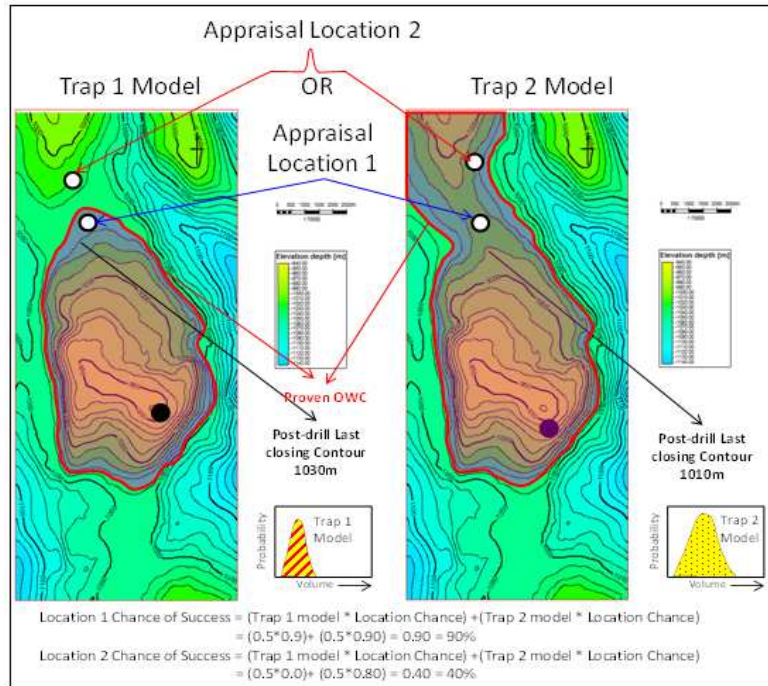
Appraisal strategy and decision process then must depend on the value likely to be created by virtue of risk and uncertainty reduction. With all available information and analysis, a strategic informed quality decision becomes possible.

To have complete knowledge on all the geological characteristics is almost impossible based on a single discovery well. Therefore, there is always a possibility for residual risk and resources loss on appraisal drilling. Defining the post discovery resource uncertainty and risks are the fundamental concepts that are imperative for optimal and informed decision making and formulation of the appraisal strategy. In Summary:

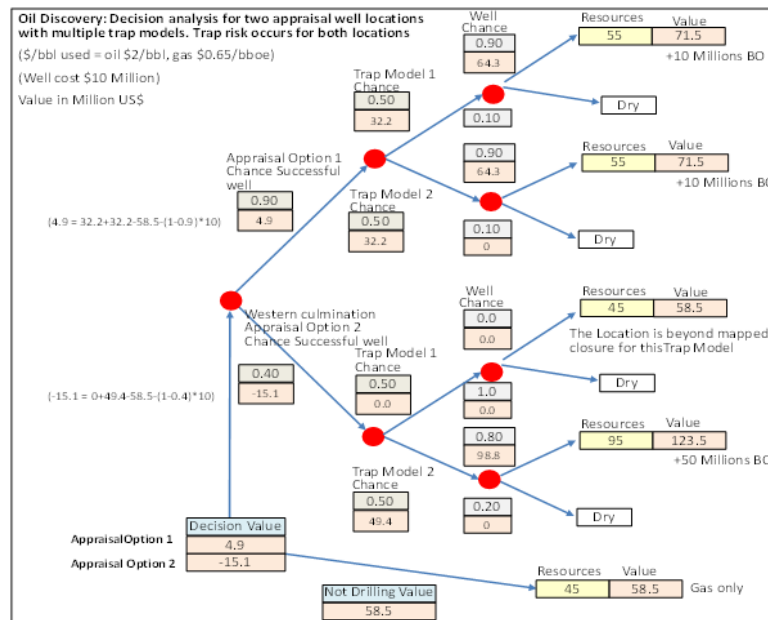


- Chance of success of an appraisal well location is related to the absence or non-effectiveness of reservoir, seal, trap and/or charge
- Resources uncertainty occurs due to property ranges and/or geological models used for resource assessment. Post discovery static and dynamic

properties of the reservoir and fluid need to be investigated in order to increase the confidence of the resources description and determine the optimum development scenarios. The uncertainties can be considered on two scales: (1) geological model scale and (2) reservoir scale



(a)



(b)

Fig. 3. (a) Illustration of Trap uncertainty for a large structure with three separate culminations. Two interpretation models show possible appraisal options. Each trap model chances are assumed at 50:50, (b) Decision analysis for two appraisal well locations with multiple trap models. The option of location 2, with only 40% chance erodes value of the project. Option 2, with trap models 1 and 2 chances (50:50), is not attractive

To illustrate the appraisal location selection workflow, an example of multiple trap models and associated uncertainties has been taken. In this example, hydrocarbons have been established below spill point. Two trap models, based on 2D seismic interpretations, are generated (Fig. 3a). Risk in reservoir presence and effectiveness has been identified in the north of the discovery. The chance of each trap model is 50:50, whereas the chance of success of reservoir on the northern flank at pre-drill stage was around 80%. Note, the location chance of success for model 1 is 0% as the appraisal location is beyond closure. With only sparse 2D seismic grid and possibility of different velocity models, the closure to the north is uncertain and two alternate interpretations are possible and hence a dry hole is possible if a well is located where only one trap model has closure.

Appraisal location 1 is within closure in both trap models and will confirm additional resources of 10 Million BO. Location chance of success for each trap is estimated around 90%. The location 2 is within closure in only trap model 2 which has an additional resource potential of 50 Million BO. A location chance of success for trap model 2 is estimated at 80%. A dry hole will result if trap model 1 is correct. The risk has been assessed by assuming the chances at 50:50 (Fig. 3b). The initially confirmed resources are 45 Million BO.

Similarly, the possibility of having multiple models (e.g., reservoir, charge, seal, etc.) can be evaluated and their associated chance of success should be assigned using all available data and knowledge. Appraisal location chance of Success is the product of model chances, incorporating any segment risk. The risk for the presence of reservoir, seal, trap and charge for each model needs to be evaluated. As an example, two different depositional models (e.g., Shoreface and Fluvial channels) will have different Gross Rock Volumes (GRV) and reservoir properties which will lead to different resource assessment. For the fluvial channel model case, there is the possibility that the discovery well encountered an isolated channel and that the other interpreted channels do not exist or are mud filled. In the shore face model, there is no risk of reservoir presence. Risk segmentation should be applied to this reservoir model to capture this geological risk and incorporated into the decision analysis. Depending upon the specific model and its chance of success, the merit of appraisal locations can be assessed. The overall chance of success for each option will be equal to the model chance multiplied by the specific location chance.

### **Real Field Examples Illustrating the Effectiveness of Appraisal Evaluation Workflow**

The author's experience on different E&P projects shows the difficulty of achieving hydrocarbon-in-place

estimates within the evaluated uncertainty band (P90 and P10). This is mainly because of (1) the need for more data to be acquired as the project moves from one stage to the next (exploration/appraisal/early development) during the early asset life and (2) suboptimal or limited use of existing data/information where the uncertainties of different input parameters and their ranges are often not estimated properly. History look-backs, from discovery to appraisal phase of two real field examples, shows the evolution of hydrocarbon-in-place estimates over time and the impact of additional data on reduction of uncertainties and demonstrate that the hydrocarbon-in-place uncertainty look-back approach (Yu *et al.*, 2011) has been useful in tracking the impact of new data. There is a need for comprehensive assessment of uncertainties upfront and developing an understanding of their impact from the existing data/information and how these uncertainties evolve with time as new data/information are acquired.

#### *Example 1*

The first real field example, demonstrating the value of new data/information, is from a carbonate field where a total of six wells have been drilled (including the discovery well). The field is a four-way dip closure (interpretation based on 3D seismic data) bounded on the east and west by normal faults. The discovery well (A) encountered a microbial carbonate, deposited in Aptian age as ramp, with well-defined oil-water contact. The well test confirmed a daily production of about 5000 b/d of 30° API oil with GOR of 700 scf/barrel. After discovery, appraisal plan for this field was defined which included two wells and high resolution wide azimuth 3D seismic acquisition. After new 3D seismic interpretation, the second well (B), drilled close to the eastern fault, encountered a lower OWC than well A, but indicated more reservoir heterogeneity than assumed after discovery. An extended well test for 90 days was carried out in Well-B which gave an average production of around 22000 BOPD with restricted gas burn rate of 500,000 m<sup>3</sup>/day (18 Million SCF/day) as per the country regulation. Well C, drilled in the center of the structure, was dry. The results of two appraisal wells along discovery data were analyzed in detail which indicated that some more data is required before making decision to develop or drop the project. Therefore, appraisal plan was extended in which three additional wells were proposed. Well D, drilled to the west of well B, encountered a different OWC. Well E, drilled in the western part of the structure up-dip from well A, encountered similar OWC as in well A. Well F, drilled to the north, confirmed the OWC of well B. Appraisal well results show more complex depositional model and higher reservoir heterogeneity.



To better represent the reservoir characteristics of Carbonate field, different tectonic-sedimentary studies were carried out by integrating all the available data/information. Integration of newly acquired 3D seismic and well data interpretation allowed us to establish a relationship between seismic-facies and structural evolution. The identified three categories of seismic-facies, strongly dependent on paleogeography at rift age, are: (1) plane-parallel, deposited in syncline, (2) chaotic, domo shaped, preferentially deposited on structural highs (3) chaotic, in tabular form, deposited on a structural high. This new depositional model, suggesting isolated carbonate build-ups and inter build-up depressions, provide a better understanding of the reservoir facies distribution and providing an optimization of Carbonate field development plan.

The original-oil-in-place and Recoverable Resources (RR) for different categories (P90/P50/P10) was estimated using probabilistic approach and results were compared over the time. With the incorporation of additional data from new wells, the differences in the overall RR cumulative distribution were reduced. The RR uncertainty index and P50 recoverable resources were computed after each well with a similar workflow. The Summary of P90/P50/P10 RR values, P50 resources and RR uncertainty index obtained from 3D reservoir models for a Carbonate field after drilling of each new appraisal well (Table 2).

### Example 2

The field, discussed in this example, covers an area of around 120 km<sup>2</sup>. It was discovered in late sixties through drilling of W1 well which encountered lower Devonian clastic reservoirs (three separate Units-A, B and C) at depth of 2750-4050m TVDSS (Fig. 4). However, out of three units only one the B unit flowed gas (26 Million SCF/day) for a short duration and other two units could not flow and were dry. Based on available seismic, well logs and limited core data, a conceptual geological model was built for lower Devonian reservoirs integrating sedimentological and petrology details. The depositional environment for these reservoirs was identified as the tidal-dominated estuary with storm-dominated shoreface. Therefore, the reservoirs deposited in this environment are expected to have limited thickness, areal extent, highly variable density and reservoir quality. Based on the outcrop study for the Lower Devonian reservoirs, the width of tidal channels was between 50 to 200 m, with thickness ranging between 2 to 5 m. The channels can be amalgamated in each unit up to 15 m thick. However, due to limited available data, it is not possible to predict channel dimensions, geometry and their density with confidence as they were well below the seismic resolution. The lateral facies variations between shoreface, foreshore, ripple bedded and sigmoidal cross-bedded sandstones observed in the cores and the log signature for each reservoir unit in the discovered field along with diagenesis played a critical role

in reducing the reservoir quality and their properties and further complicated the delineation of producible reservoirs. Keeping in view all these complexities, the project was kept on hold almost four decades.

After 2006 with the improvement of oil and gas market, 3D seismic data over the discovered structure was acquired, processed and interpreted to assess its full potential. An appraisal plan for the project was prepared based on identified key uncertainties and well-defined objectives. Each appraisal well has different chance of success. The chance of finding at least one unit gas bearing was very high (around 65%) and chance of missing all the units were low (around 35%). Subsequently, 4 appraisal wells (W-2, W-3, W-4 and W-5) were drilled to collect the additional data (logs, cores, fluid samples, well testing) with different objectives. Only Lowest Known Gas (LKG) has been encountered for different reservoir units in the drilled wells (Unit-A: 3580, Unit-B: 3650 and unit-C: 3740 m) and the structure is assumed to be filled to the spill point (unit-A: 3850 m, unit-B: 3950 m and unit-C: 4050 m). Different reservoir units (Unit-A, Unit-B and Unit-C) and fluid parameters obtained from each well are summarized in Table 3.

The estimated Original-Gas-In-Place volume was reduced as some wells encountered relatively poor reservoir properties and lower net pay than expected. The unit-B tested in W-2 well did not flow and two units (A and C) were not tested as reservoir characteristics were not very encouraging. The W-4 well logs showed that unit-B was completely absent and well tests performed for unit-A and unit-C showed lower productivity than assumed prior to drilling. Due to post depositional changes mainly because of diagenesis, the well test, performed for short duration in different appraisal wells, show a severe variability in well performance in the discovered reservoirs (Table 4). The well test results show good productivity in Unit-B (2 out of 4 wells tested) and in Unit-C (2 out of 3 wells tested) reservoirs. However, tests showed very low productivity (2 out of 5 drilled wells tested) for Unit-A reservoir. Considering the well test results, the discovered field still carries a high uncertainty on the long term production performance in order to sustain the production.

All the drilled appraisal wells were found hydrocarbon bearing in one or the other reservoir (appraisal targeted specific reservoir unit as primary but encountered other unit which was secondary and vice versa). Some tested wells for unit-A indicated the productivity below economic threshold which does not recover well cost. Therefore, in spite of the positive well results, the volumetric and well productivity uncertainties could not be reduced for this field. The available data analysis has indicated that there are still significant reservoir uncertainties due to limited and sparse data, short duration of well tests performed, inconsistency and measurement limitations in each reservoir unit.

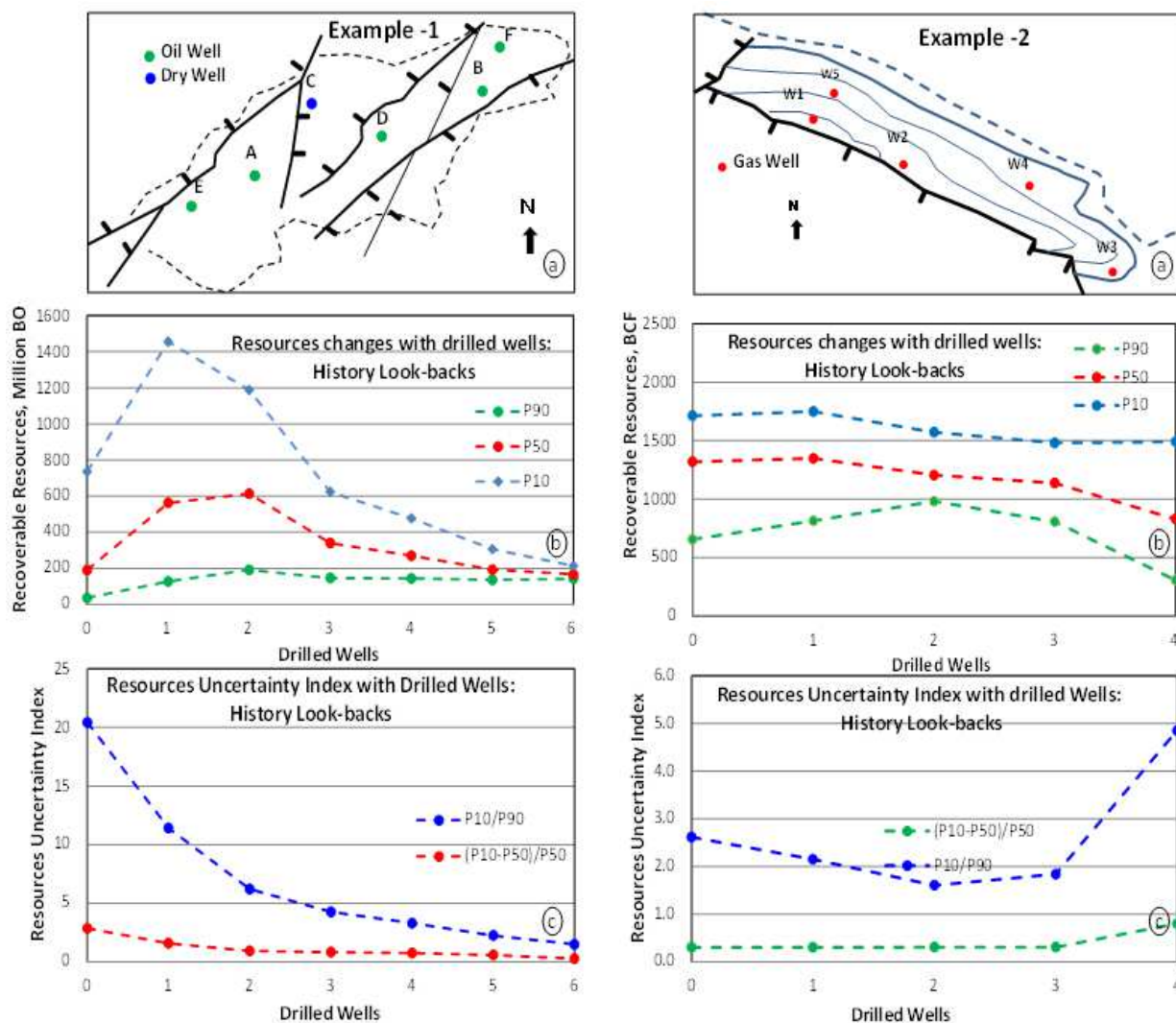


Fig. 4. Uncertainty Variation in Relative Resources for two unnamed Fields (From discovery to end of appraisal). The operators for both discoveries were different. Example-1 is a carbonate oil reservoir where appraisal has been effective and has helped in narrowing down the distribution range and optimized the field development plan. Example-2 is a clastic gas field where multiple reservoirs were discovered which have net pay below seismic resolution (0-12m). Appraisal wells in this case were planned to appraise specific unit with multiple objectives to reduce reservoir uncertainties. The results of these wells were highly variable and were unable to reduce the static and dynamic uncertainties of reservoirs. Therefore, even after drilling 4 appraisal wells distribution range could not be narrowed down as results were significantly different in terms of reservoir characteristics and well deliverability than assumed before drilling. The geological complexity of reservoirs was confirmed by the appraisal drilling which helped to avoid capital intensive final investment decision of field development and the field declared uncommercial

Therefore, due to extreme reservoir complexities (e.g., structure evolution, sedimentology and stratigraphy, diagenesis, complex rock matrix and variable reservoir pressure), the existing data was not enough to provide higher confidence on the 3D reservoir model outcomes (e.g., volumetric estimates, reliable production forecasts and development wells planning) and to support the field development plan. The well results indicated that if field goes into development phase, more number of

development wells may be required which makes the field economically unattractive. Given the large appraisal area and multiple objectives, although highly variable well results have not allowed to terminate the appraisal plan but the whole appraisal campaign information has successfully demonstrated the geological complexities of discovered reservoirs which has helped the company to stop the field development plan (FDP) requiring several billions US\$ of capital investment.

Table 2. Summary of average reservoir and fluid parameters estimated after drilling of each well.

Key parameters	Predrill	Well A	Well B	Well C	Well D	Well E	Well F
Reservoir top (m)	4350	4404	4363	4456	4414	4394	4497
Gross interval (m)	80.0	128.0	242.0	24.0	120.0	138.0	189.0
Net pay (m)	56.0	72.0	190.0	0.0	81.5	76.0	87.0
N/G	0.70	0.56	0.78	0.000	0.68	0.55	0.46
Porosity (average)	10%	9.50%	12.90%	6%	12%	10%	13%
Water saturation	36%	18.30%	27%	39%	36%	22%	25%
Formation volume factor	1.38	1.37	1.25	1.25	1.25	1.25	1.25
Oil-water contact (m)	----	4532	4572	None	4505	4532	4572
Cutoffs (Vcl/Phi/Sw)	0.5/0.05/0.5	0.5/0.05/0.6	0.5/0.05/0.6	0.5/0.05/0.6	0.5/0.05/0.6	0.5/0.05/0.6	0.5/0.05/0.6
API gravity	25-30°	30°	30°	30°	30°	30°	30°
GOR (SCF/b)	500	750	670	----	700	740	740
CO <sub>2</sub> /H <sub>2</sub> S content (%)	2-5%/none	2-5%/none	2-5%/none	2-5%/none	2-5%/none	2-5%/none	2-5%/none
Gas gravity	0.90-1.06	0.90-1.06	0.90-1.06	0.90-1.06	0.90-1.06	0.90-1.06	0.90-1.06
Reservoir pressure (psi)	6800-7648	7225	7310	----	7268	7242	7344
OOIP (P90/P50/ P10)	120/635	425/1874	765/2450	810/1890	800/1503	756/1070	789/926
	/2450	/4850	/4750	/3458	/2650	/1700	/1185
RF	30%	30%	25%	18%	18%	18%	18%
P50 RR (Millions of barrels)	190	562	613	340	270	193	167
Uncertainty index 1 (P10/P90)	20.42	11.41	6.21	4.27	3.31	2.25	1.5
Uncertainty index 2 (P10-P50)/P50	2.86	1.59	0.94	0.83	0.76	0.59	0.28

Table 3. Summary of reservoir and fluid parameters estimated after drilling each well

Key parameters	Predrill	Well-1	Well-2	Well-3	Well-4	Well-5
<b>Unit-A</b>						
Reservoir top (m)	2860	2759	2790	3366	3332	2927
Gross interval (m)	33.3	27.4	29.4	57.8	57.2	56.9
N/G	0.30	0.07	0.03	0.12	0.02	0.13
Net pay (m)	10.00	1.98	0.78	6.71	1.07	7.32
Porosity (average)	14%	10%	9%	11%	8%	12%
Water saturation	20%	11%	10%	11%	23%	13%
<b>Unit-B</b>						
Reservoir top (m)	2940	2840	2872	3453	3390	3011
Gross interval (m)	66.7	95.0	93.6	94.3	91.4	88.4
N/G	0.30	0.12	0.13	0.03	0	0.04
Net pay (m)	20.0	11.13	11.73	2.59	0	3.51
Porosity (average)	14%	16%	16%	9%	0	9%
Water saturation	20%	14%	8%	16%	0	25%
<b>Unit-C</b>						
Reservoir top (m)	3020	2935	2966.0	3548.0	3481	3100.0
Gross interval (m)	50.00	26.80	26.10	25.30	25.4	23.30
N/G	0.30	0.47	0.30	0.32	0.06	0.49
Net pay (m)	15.00	12.50	7.92	8.08	1.52	11.28
Porosity (average)	14%	12%	11%	15%	10%	11%
Water saturation	20%	15%	8%	6%	19%	23%
<b>Total</b>						
Cutoffs (Vcl/Phi/Sw)	30%/7%/60%	30%/7%/60%	30%/7%/60%	30%/7%/60%	30%/7%/60%	30%/7%/60%
CO <sub>2</sub> /H <sub>2</sub> S content (%)	<2 /none	<2 /none	<2 /none	<2 /none	<2 /none	<2 /none
Reservoir pressure (psi)	5160	5695	5695	5695	5695	5695
OGIP (P90/P50/ P10), TCF	0.9/1.9/2.4	1.2/1.96/2.5	1.4/1.7/2.2	1.2/1.6/2.1	0.5/1.2/2.1	0.5/1.2/2.1
<b>RF</b>						
P50 RR (BCF)	1331	1372	1179	1146	863	780
Uncertainty index 1(P10/P90)	2.6	2.1	1.6	1.8	4.8	4.2
Uncertainty index 2 (P10-P50)/P50	0.27	0.26	0.29	0.29	0.74	0.75

Table 4. Summary of the field-2 well test results (Million SCF/day gas)

	W-1 (Discovery)	W-2	W-3	W-4	W-5
Unit-A	No tested	No tested	1.0	2.0	No tested
Unit-B	26.0	Dry	35.0	No sand	0.5
Unit-C	No tested	No tested	50.0	1	28.0

Figure 4 (Example 1 and 2) shows the recoverable resources and uncertainty changes over the appraisal and early development period for both unnamed fields (Table 2 and 3) which was estimated using history look-back approach. This look-back approach clearly demonstrates the effective value added by each well, the evolution of the estimation of RR and recoverable resources and the reduction in RR uncertainty.

## Concluding Remarks

The capital intensiveness of E&P business and emerging low oil price scenarios have necessitated the scrutiny on every dollar spent on data gathering. A well-developed appraisal strategy developed using multi-disciplinary team of geoscientists, engineers and economics specialists, ensures that data/information collection is focused on the data that allows uncertainty reduction and create value by affecting the future decision makings and helps to avoid situations where data is acquired for uncertainty reduction but does not add value.

The evaluation and justification of individual appraisal activity, based on identified key uncertainties, geologic risks and added VOI, helps in minimizing appraisal and capital expenses. This workflow also emphasizes that the value is not only simply a function of cost and reward but is also created by learning through use of early drilled wells data/information to optimize (reduce cost and maximize reward) the subsequently planned appraisal activities. Furthermore, successful appraisal also sets the stage for success of the development project by helping in concept selection, detailed design and execution for maximized whole cycle project economics under acceptable residual risks, allows smarter decision making by focusing on decisions that add value and guards against overcapitalization or loss of opportunity.

To have a complete knowledge on all the geological characteristics is almost impossible based on a single discovery well. Therefore, there is always a possibility for residual risk and resources loss on appraisal drilling. Defining the post discovery resource uncertainty and risks are the fundamental concepts that are imperative for optimal and informed decision making and formulation of the appraisal strategy. This has been illustrated through two real field examples. These examples have clearly illustrated that how a holistic appraisal campaign has helped to support the future development decision for carbonate reservoir field and to avoid the development investment for clastic reservoir field.

Finally, it is emphasized that there is no straight forward and unique process for appraisal activities visualization, planning and execution. Each discovery will have its own complexities, associated key uncertainties depending upon the available data/information and offset analogues, schedule drivers and will require a specific appraisal plan to assess its

potential to support the project way forward such as continue appraisal activity, exit option or transfer project to development, Farm-out, etc. and to arrive at the optimal development scenario. The appraisal results, including the project way forward recommendations, should be critically analyzed following look-back approach and documented carefully to support the upcoming investment decisions.

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## Author's Contributions

Author's contributions briefly describe the different components of appraisal strategy necessary for appraisal framing and evaluation workflow. Methodology suggested for the appraisal locations selection and their sequencing combines uncertainty reduction, probability of success with VOI technique to determine the number of appraisal wells, their sequence of drilling and their justification that is based on economic merit. The effectiveness of this systematic approach has been illustrated through some real.

## Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues are involved.

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