GeoArabia, Vol. 6, No. 4, 2001
Gulf PetroLink, Bahrain

Exploration Strategy Development and Performance Management: a Portfolio-based Approach

Michael A. Naylor and Laurent Y. Spring
Petroleum Development Oman

ABSTRACT

In Petroleum Development Oman (PDO), the exploration opportunity portfolio is managed by a dedicated team responsible for its integrity and analysis. The team uses a customized suite of tools for volumetric and economic assessment that has been developed since 1997. In addition to their application in quality control, regular performance monitoring and reporting, the tools are used to determine annual finding targets and formulate exploration strategies.

The portfolio management process in PDO has made a major contribution to the quality of prospects that are selected for drilling. Thanks to new evaluation processes and a robust suite of tools, the company has a better understanding of the composition and quality of the prospect portfolio, and is explicitly aware of the challenges and issues facing exploration. Portfolio management tools enable objective target setting and communication, thereby achieving shared ownership. The clarity brought by portfolio analyses provides a powerful focus to the asset teams' efforts to improve prospect quality.

PDO is also able to quantify the consequences of changing activity levels and balance in the program, and of the limitations imposed by the portfolio. These provide the basis for ongoing dialogue with shareholders and justify the strategy shift towards frontier exploration enacted since 1998. Exploration in PDO has shifted from being opportunity-driven to being led by a portfolio-based strategy. A similar approach may be suited to other exploration ventures with sizeable portfolios.

INTRODUCTION

This paper begins by describing the process and tools of portfolio management employed in Petroleum Development Oman (PDO). We then show how these are used to screen and select prospects for drilling, set exploration targets, contribute to strategy development, and define goals for portfolio improvement. We conclude with an assessment of the long-term viability of exploration and future portfolio management challenges. Although the tools used in PDO are proprietary, we suggest that the approach followed may be suitable for other exploration ventures with sizeable portfolios. All technical terms and abbreviations are defined in a glossary at the end of the paper.

THE ROLE OF PETROLEUM DEVELOPMENT OMAN

Petroleum Development Oman LLC is the operator on behalf of the Government (60 percent) and private shareholders (Shell 34 percent, TotalFinaElf 4 percent, Partex 2 percent) of a large concession area in Oman, about 114,000 sq km (Figure 1). The company has produced more than 5.5 billion barrels of crude oil and condensate since oil exports began in July 1967. Oman's remaining liquids reserves amount to some 5.5 billion barrels.

PDO's production system is sizeable, extending some 750 km from the southernmost Dhiab oilfield to the coastal tank farm installations in Mina Al Fahal, near Muscat. Currently, 98 fields are on stream with oil being produced from more than 2,200 wells and evacuated through a system of 46 gathering stations, 14 production stations and a pipeline network of 2,700 km with four main booster stations. The current level of oil production is approximately 850,000 barrels per day black oil and 65,000 barrels per day of condensate.

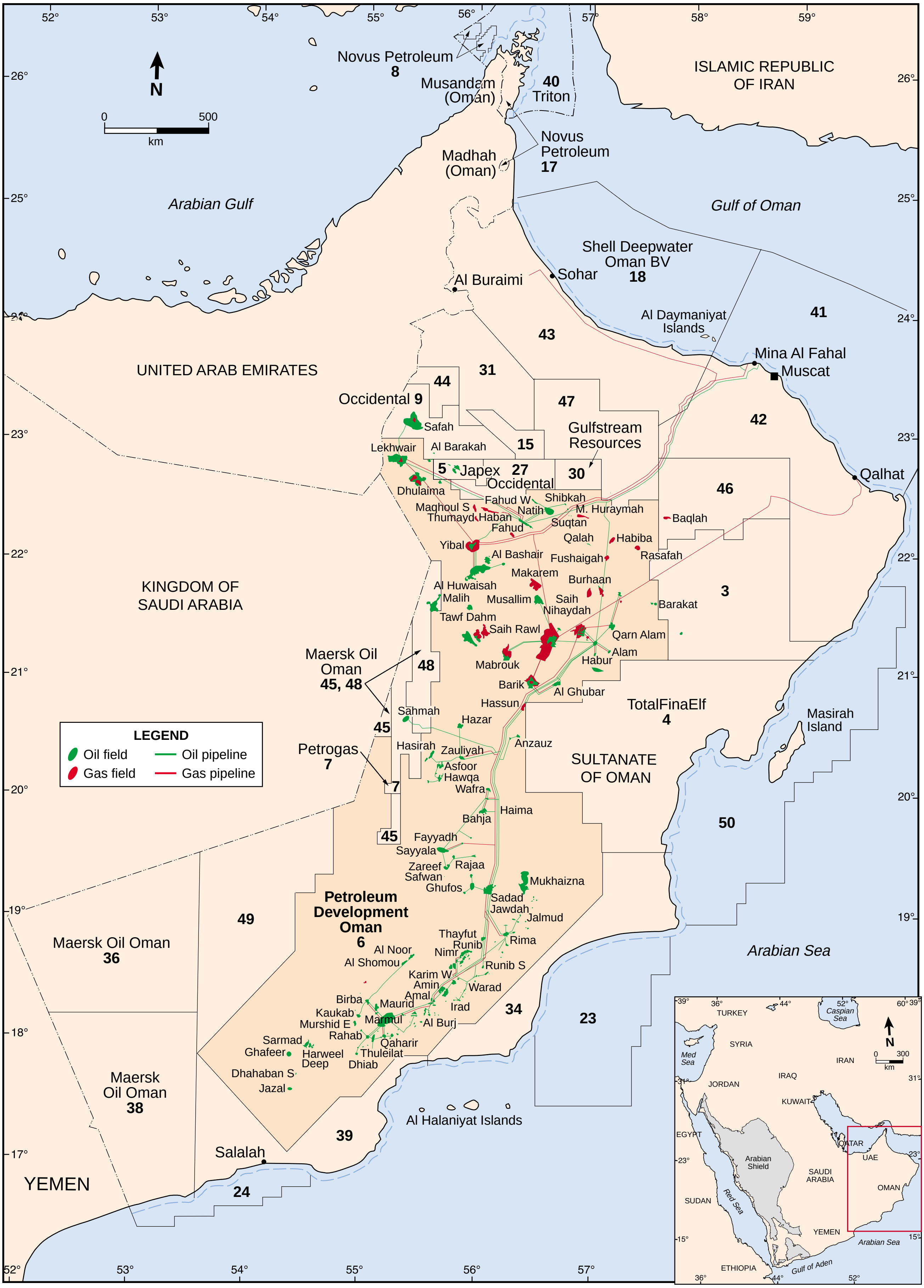


Figure 1: PDO concession map indicating location of producing fields and pipeline infrastructure.

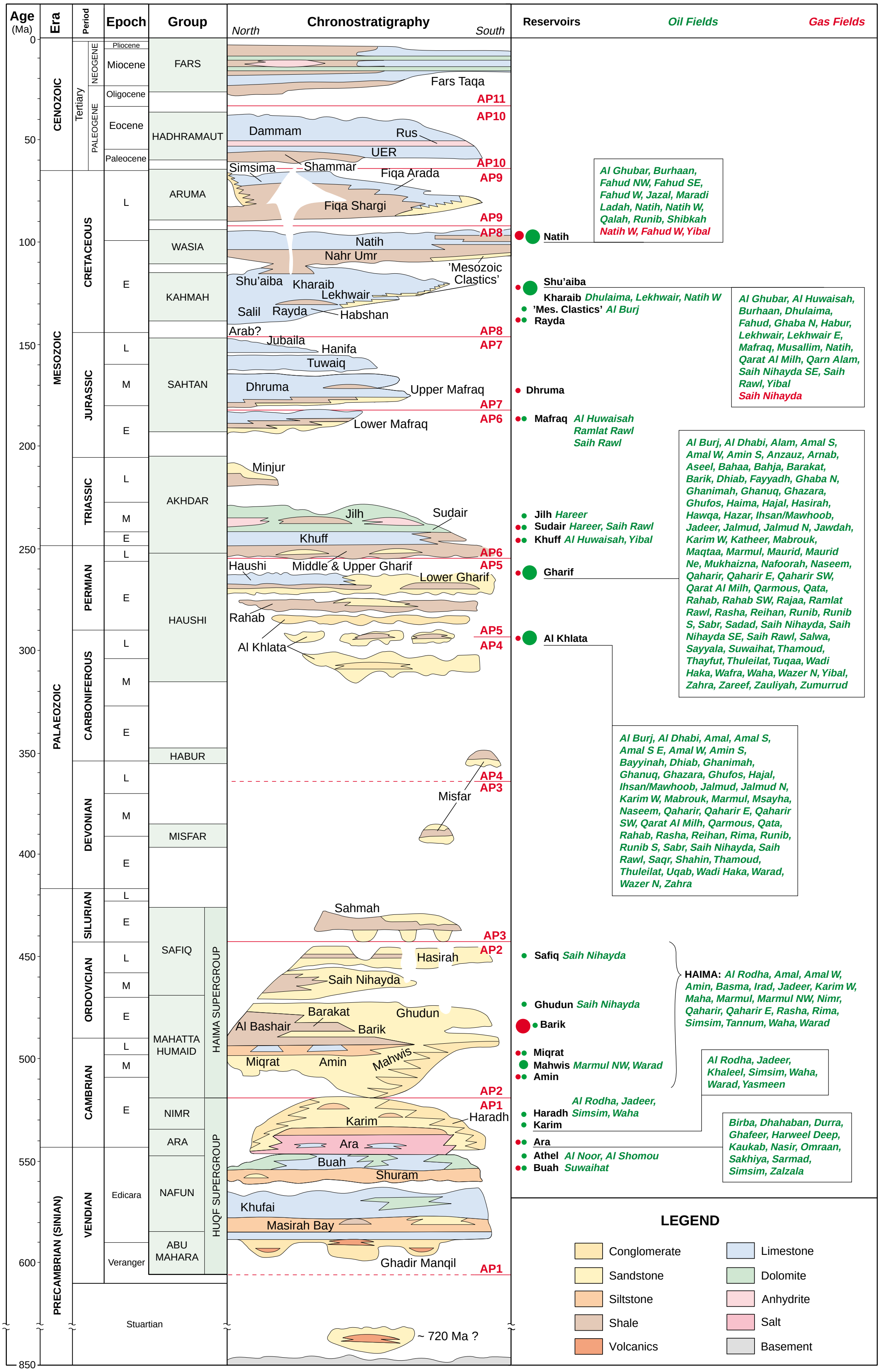


Figure 2: Simplified chronostratigraphy of Oman (H.H.J. Droste, written communication, 2001) with the Arabian Plate (AP) megasequence boundaries (after Sharland et al., 2001), and oil and gas fields.

Field development activity levels are high, with more than 20 drilling rigs dedicated to maintaining oil production. In addition, four-rig-years of activity is devoted to oil and gas exploration, and two dedicated rigs drill development wells for the upstream liquefied natural gas (LNG) project. Two full-time seismic crews support these activities.

PORTFOLIO MANAGEMENT IN EXPLORATION

Exploration in PDO takes place in five asset teams. The frontier exploration asset pursues novel geological concepts, whilst each of the four area-based production asset teams addresses its own near-field exploration potential. The portfolio management team provides corporate exploration planning and exploration coordination across the company.

In Oman, oil and gas have been produced from reservoirs ranging in age from Infracambrian to Cretaceous, and the large diversity of reservoirs and traps (Figure 2) poses unique challenges. PDO's prospect portfolio (Figure 3) consists of several hundred prospects. The portfolio is split between oil and gas, and each of these is further subdivided into 'frontier', 'exploratory-appraisal scope-for-recovery' and 'undefined geological potential'. Oil has an additional 'near-field exploration' portfolio subdivision. The exploration prospect portfolio is smaller than, but of a similar order of magnitude to, the present proven reserves base.

The hydrocarbon plays of Oman are many and varied (e.g. Boserio et al., 1995; Guit et al., 1995; Loosveld et al.,1996; Droste, 1997; Amthor et al., 1998; Richard et al., 1998; Oterdoom et al., 1999; Reinhardt et al., 1999; and Terken, 1999. PDO's extensive prospect portfolio is a consequence of the large concession size, the long and varied stratigraphic record, and a range of structural styles and deformation episodes. It is the product of a long and active history of evaluation and drilling. The size and diversity of the portfolio demands a consistent approach to its assessment, and regular reviews of the quality and quantity of the prospects.

Process Management

The exploration work-flow is illustrated in Figure 4. Key elements include the early generation and selection of new concepts and opportunities, followed by the development of prospects using existing and newly acquired well, seismic, and geological data. Prospects that pass geological and economic screening are candidates for drilling. A rigorous reserves-booking process follows in the case of success. All well outcomes are the subject of a post-drilling review in order to ensure that geological and

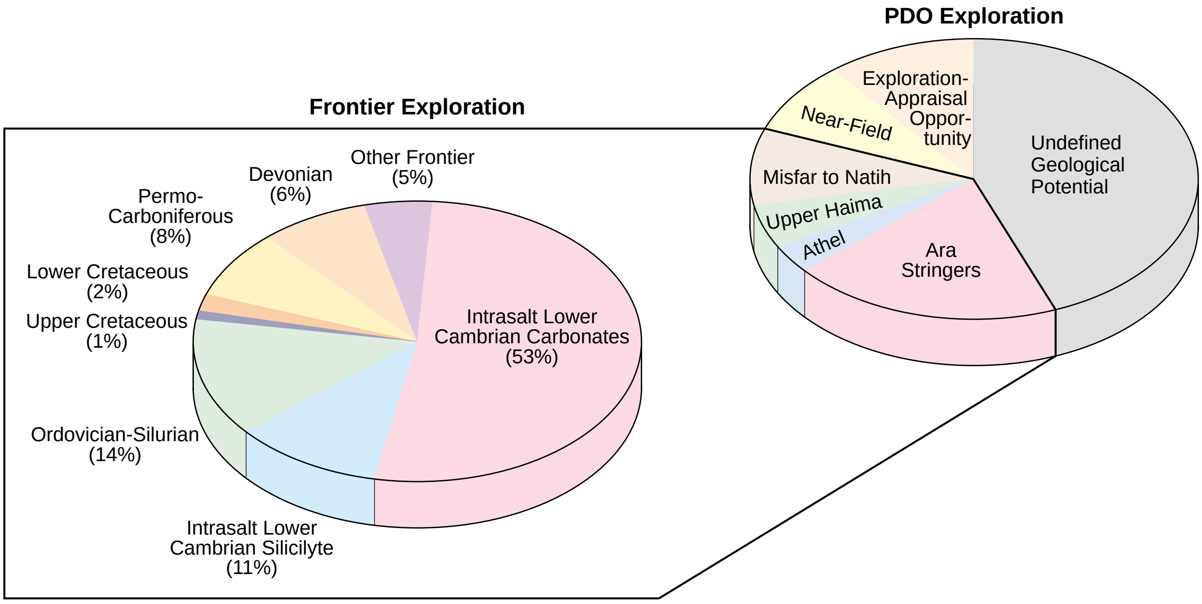


Figure 3: PDO's oil prospect portfolio. For planning purposes the several hundred PDO exploration prospects are grouped into 'frontier exploration', 'near-field', 'exploration-appraisal opportunity' and 'undefined geological potential'.

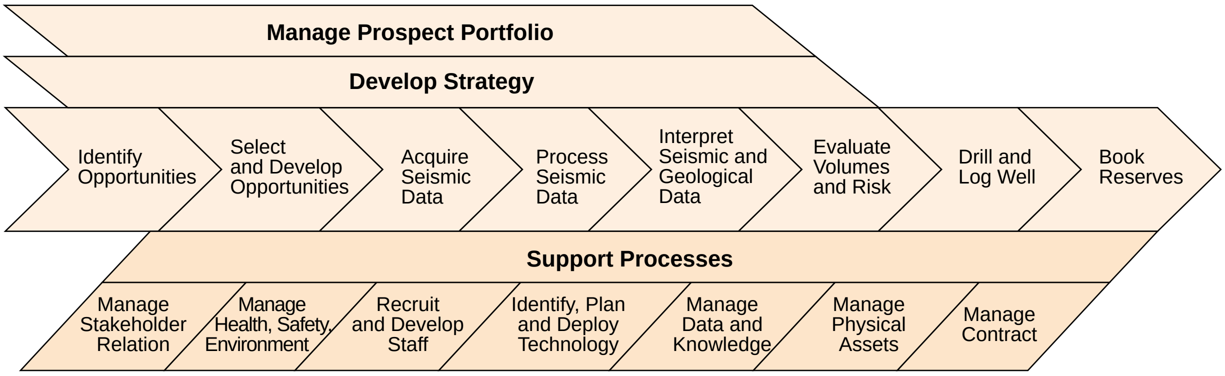


Figure 4: This exploration work-flow allows for early generation and selection of new play concepts and opportunities, utilizing existing and newly acquired seismic, well and geological data.

operational learning points are captured, and subsequently fed back into the future evaluation of prospects. Technology implementation, staff development, and portfolio management underpin and enable the evaluation process.

Since April 1998, management of the exploration portfolio, and related activity planning, has been the responsibility of a small, dedicated team of senior professionals. The responsibilities of the portfolio team are as follows: (1) evaluation consistency checks; (2) leading the prospect appraisal challenge team; (3) review of prospect appraisal performance; (4) portfolio integrity and quarterly reporting; (5) identification and development of tools; (6) methods of basin potential assessment; (7) build annual program; and (8) strategy development.

Play and prospect maturation takes place within projects or 'themes' that consist of geographic- or play-based opportunity groupings. Periodic formal reviews of theme activities take place against pre-agreed milestones, deliverables, and portfolio improvement targets. The outcome of a theme milestone review may be endorsement of further work, agreement to drill a key well test, or the decision to 'mothball' the theme. Factors likely to terminate work on a theme include inadequate reward potential when compared against other opportunities, or the need to mature and apply new technologies before proceeding further. In all cases, thorough—but fit-for-purpose—documentation of the work is required, to ensure that corporate knowledge is retained.

Scrutiny of individual prospects begins with early peer reviews and appraisal by the evaluation team leader. Regular senior management walkabouts provide a further level of review, ensuring consistency of approach and cross-fertilization of good practices. A formal, minuted peer review is mandatory prior to drilling a prospect, in order to review and endorse the risks and volumetrics of a prospect. The risk framework and parameter sets, or 'play recipes', of individual plays are also reviewed by peers. An external assessment of the prospect portfolio is conducted annually to provide an independent audit of portfolio integrity.

Portfolio Ownership

The prospect portfolio is owned by the asset managers, who delegate responsibility for portfolio segments to their exploration evaluation teams. This ensures accountability for prospect quality, and ownership of portfolio targets.

The dedicated portfolio team plays the role of trustee and advisor, and reports quarterly on the progress of the oil, gas, and condensate portfolios. Focus on the portfolio is maintained by defining numerical targets for both the expectation volumes [defined as product of Probability Of Success (POS) and Mean Success Volume (MSV)] added to the portfolio, and the number of drillable prospects generated. These targets form an element in the annual assessment of exploration performance, which also includes expenditure (against budget), the reserves found, and measures of the professionalism of the staff and operational excellence.

Tools for Planning and Analysis

To assess the full life-cycle attractiveness of exploration opportunities, the portfolio management team makes use of a series of in-house PDO and Shell Group tools (Figure 5). The portfolio analyst evaluates the undrilled opportunities through the following four-step process flow:

(1) assessment of the in-place volumes and geological risks of the prospects using a *risk/volume calculator*, employing Monte Carlo techniques, developed by Shell;
(2) evaluation of the development options and economic viability of the recoverable volumes, using an in-house *field-development expert system;*
(3) modeling the strategic long-term value of the economic prospect portfolio, using an Excel-based *program modeler* that simulates the drilling of a sequence of prospects; and
(4) assessment of key economic parameters, using an *economic model* specific to PDO's own operations.

Volumetrics and Risk

Quantitative assessment of prospect volumetrics and risk starts by using a *risk/volume calculator,* which is Shell proprietary software. The inputs are a full assessment of risks, rock properties, and uncertainties for charge, reservoir, trap and seal, from which in-place volumetrics are calculated using Monte Carlo simulation techniques. The inputs are assessed at three levels as follows:

(1) **Oman-wide:** for example, structural uncertainty as a function of seismic data quality and coverage;
(2) **play- and area-specific:** for example, charge risk for the play; representative reservoir parameters and hydrocarbon properties; and
(3) **prospect-specific:** for example, trap size; local seal risk; update to charge risks, hydrocarbon column length according to the prospect's location and structural history; reservoir properties according to position in facies belt and depth.

The volumetric and risk outputs are stored in an Oracle database. Four additional in-house tools take the analysis further. An Excel tool is used to generate a simple, one-page graphical prospect summary of the input and output data (Figure 6). This summary sheet enables the prospect review team to grasp the main elements of the prospect at a glance, and to compare the input with Common Risk Segment (CRS) and Gross Depositional Environment (GDE) maps for the play, ensuring consistency of evaluations.

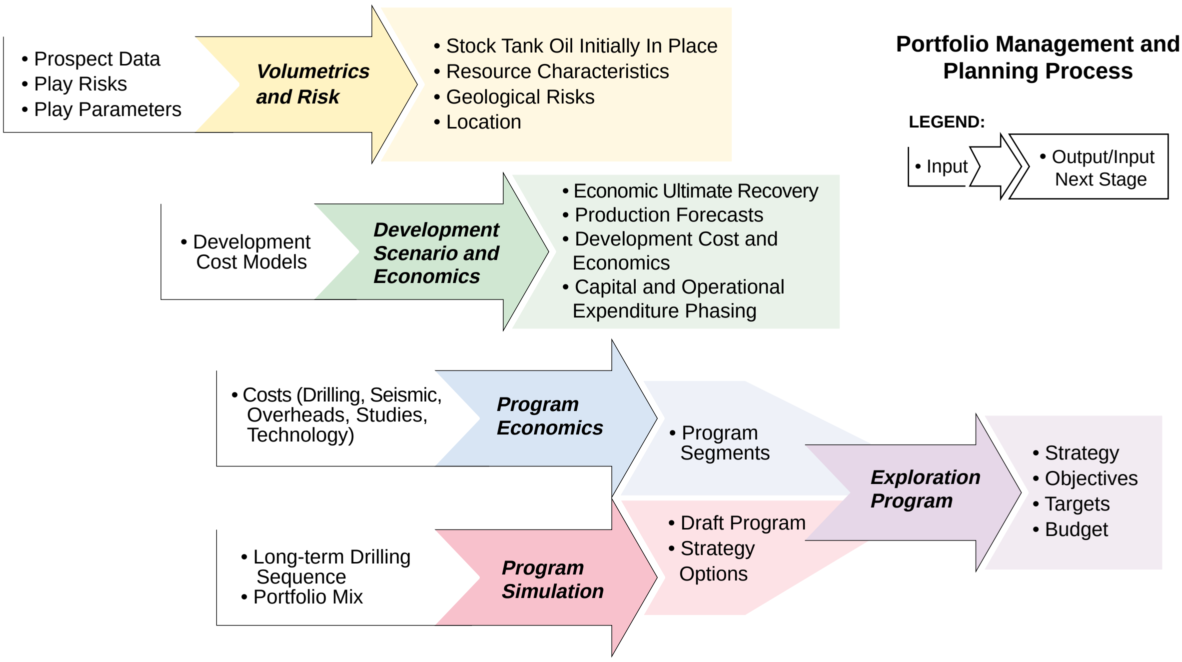


Figure 5: The sequence of tools used in the process flow from volume to value assessments. Tools are shown as colored arrows, adjacent to the key input and output parameters.

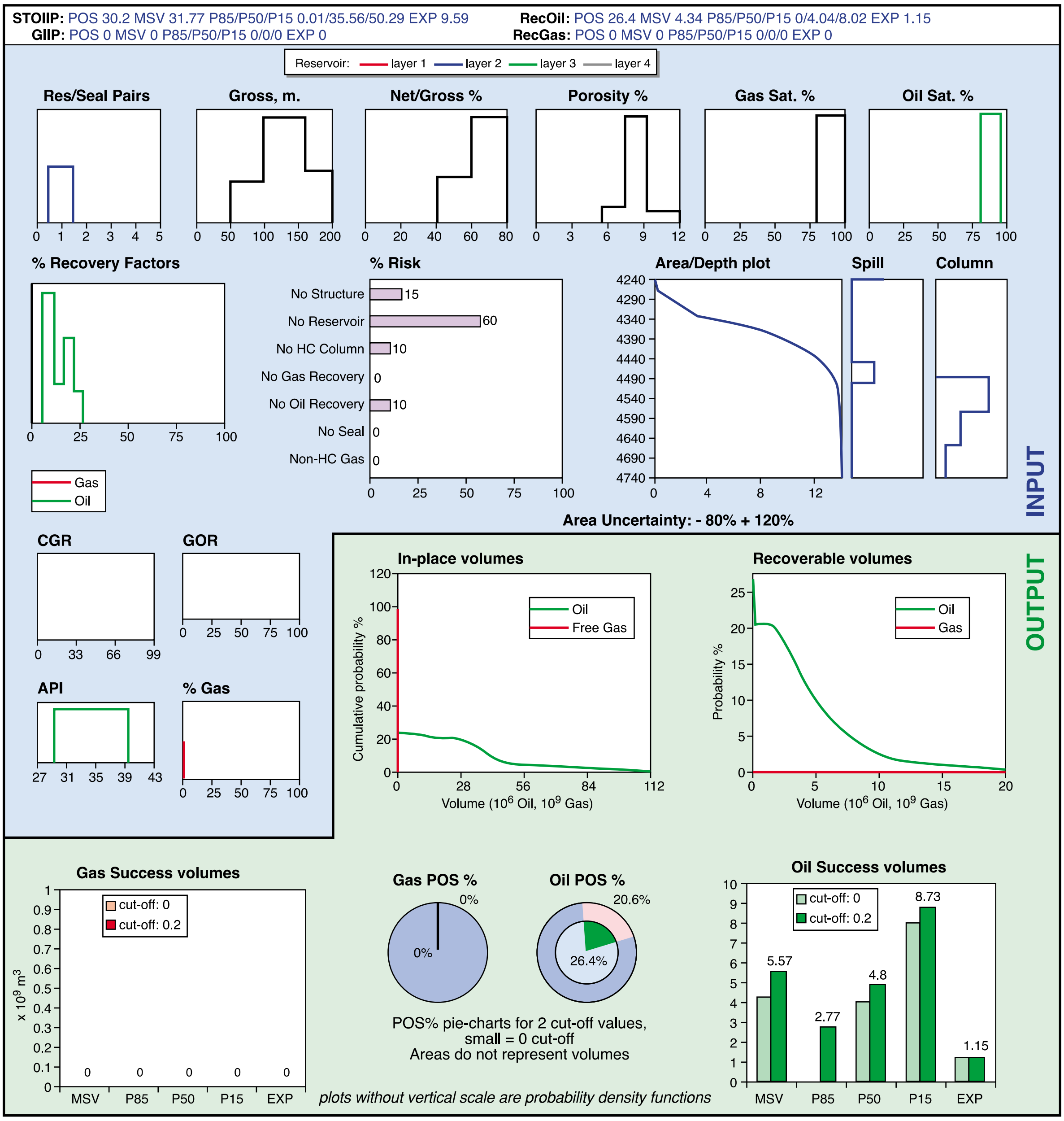


Figure 6: Screen display example of Excel summary sheet displaying prospect characteristics input and volumetric output. This kind of summary enables a quick quantitative assessment of the volumetrics and risk of an exploration opportunity. Input is shown in blue and output in green.

A query / interface tool is used for direct interrogation of the prospect database. A series of windows and screen-views are used to quality-control input and output data, and to generate portfolio reports by hydrocarbon type, play and area. The input and risks can be queried for any play, and can be subsequently compared with the Common Risk Segment (CRS) and Gross Depositional Environment (GDE) maps, ensuring the robustness and internal consistency of each prospect within the play.

Field Development Models and Prospect Economics

Rapid screening of full life-cycle oil-prospect economics is conducted with a comprehensive *field-development expert system* programed in Visual Basic. It can be applied in batch mode to the entire portfolio, or on individual prospects. Data are imported from the prospect database. Key inputs include the Stock Tank Oil Initially In Place (STOIIP), geological POS, 'resource characteristics', and

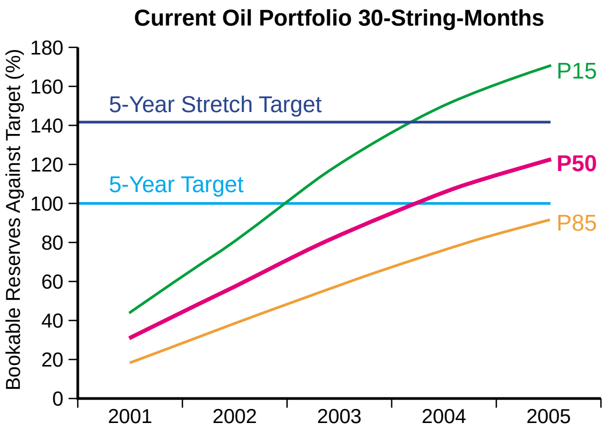


Figure 7: A 5-year reserves delivery model, from which reserves targets can be derived.

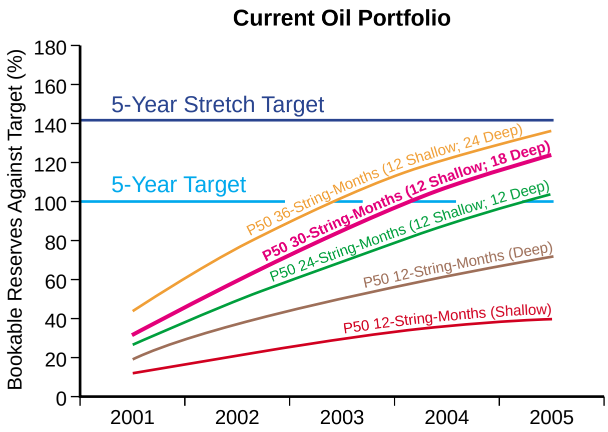


Figure 8: Simulation results used to assess the optimum drilling intensity and rig composition.

locations of current and future gathering stations. The 'resource characteristics' typically include (1) reservoir depth; (2) pressure regime; (3) hydrocarbon column length; (4) oil gravity / viscosity; (5) relative proportion of oil and gas; (6) permeability, connectivity, heterogeneity of the reservoir; and (7) degree of fracturing of the reservoir.

The system contains an extensive range of PDO-designed notional field-development scenarios and cost-engineering functions for each reservoir in Oman. These capture an extensive body of reservoir engineering knowledge, including the actual field development, drive mechanisms, and performance of more than 90 fields. The 'resource characteristics' of the prospects are matched against the development scenarios, in order to automatically determine the optimal primary and life-cycle development options. The system then returns the relevant economic and technical parameters, such as the economic POS, recovery factors, P85, P50 and P15 recoverable reserves, production forecasts, capital expenditure phasing, Unit Technical Cost (UTC), Net Present Value (NPV) of the prospects, and Value-Investment-Ratio (VIR).

Outcomes of the Drilling Sequence

The final step is to simulate the drilling of a sequence of prospects, for which a *program modeler*, employing Monte Carlo techniques, was written in Excel. The prospects are characterized by the outputs described above (e.g. combined geological and commercial POSs, reserves, and reservoir depth). The tool predicts the volume of hydrocarbons to be discovered and the production profile that would result when the discoveries are developed (Figure 7).

The user assembles his choice of prospects, such as a single theme (i.e. geographic- or play-based grouping of opportunities), a drilling program or the entire portfolio. Variables under user control include the amount of drilling string-time available, duration of the drilling campaign, degree of dependency amongst prospects, and the number of appraisal wells required in the case of success. The user may choose an explicit sequence of prospects, reflecting a specific activity plan or strategy, and the time at which prospects are ready to drill. Alternatively, he may simply rank-order the prospects by one of their many characteristics (e.g. risks, volumes, or value).

The modeling capabilities enable the analyst to generate scenarios where only selected portions of the portfolio are drilled, or to assess the impact of rig-fleet composition (shallow versus deep rigs) and drilling intensity (number of rigs) on discovery targets.

Outputs from the *program modeler* simulations (e.g. yearly bookings or production profile) can be fed into an economic model that calculates more rigorous cash-flow forecasts. A range of economic indicators can then be used for allocation of exploration capital and project-ranking purposes.

In the hypothetical example (Figure 7), a 5-year target was set and an annual budget for 30-string-months of drilling activity was available. This was split into 18-string-months on deep rigs, capable of reaching 6-km deep targets and 12-string-months on a standard rig, capable of reaching 3-km deep targets.

The prospect portfolio was run through the simulator, and 500 equally probable outcomes were computed. The P85, P50, and P15 lines represent computed outcomes numbering 75, 250, and 425, respectively, sorted in increasing order. This graphical representation enables management to assess the possible low and high sides of a given drilling campaign. By interpolating between the P85, P50 and P15 lines, we can estimate the probability of meeting the assigned target as 70 percent, whereas there is a 33 percent chance of achieving the stretch-target.

The same portfolio was modeled (Figure 8) with different allocations of total rig time, and different mixes of 'deep' and 'shallow' rigs. Based on the forward modeling, we conclude that a yearly drill time of 24- to 30-string-months will achieve the 5-year target. Note the law of diminishing returns on the 36-string-month option, where the deep-objective portfolio displays a distinct creaming pattern.

Prospect Screening

The output from the *field-development expert system* provides the basis for screening and ranking prospects in the annual exploration program build. The primary screening criteria ensure that the prospect exceeds minimum expectation reserves, and minimum Probability Of Success (POS), and does not exceed maximum Unit Technical Cost (UTC). The criteria for drillability are POS (above a play dependent threshold), Expected Monetary Value (EMV) above a predefined limit, and expectation reserves.

Primary screening and drillability criteria are applied to individual prospects. Prospects that do not pass primary screening—typically very high risk or low reward—are retained in the portfolio, to be improved or eliminated, but do not contribute to portfolio volumes. POS thresholds for drilling vary, being relatively low for play-opening prospects and higher for conventional, well-understood plays.

The sum of risked volumes of prospects on the exploration drilling sequence must meet, or exceed, the agreed reserves target. However, additional objectives must also be met. These include finding costs, and—in the case of near-field exploration—the potential to contribute immediate production, and optimize the use of existing facilities and surplus production capacity (Figure 9). Resource optimization (i.e. optimum rig type for the current portfolio composition) and strategic requirements—for example, drilling play-opening wells and maximizing the Value Of Information (VOI) gathered—are also considered.

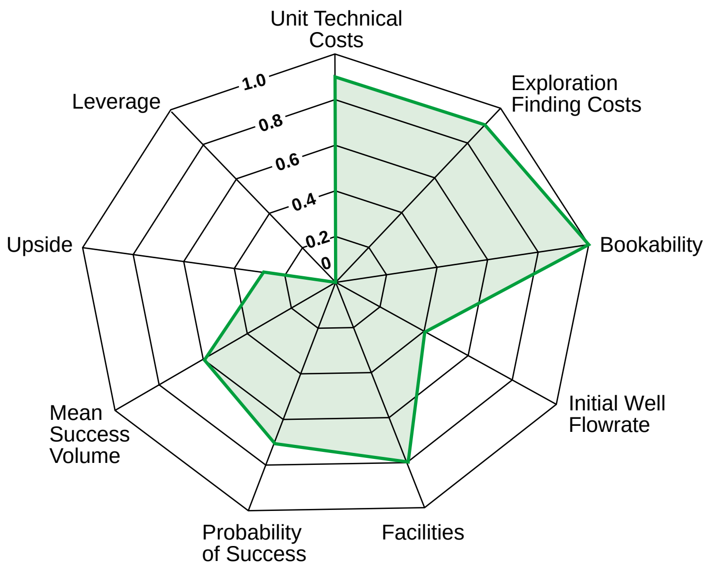


Figure 9: Example of a multicriteria tool used to select drilling sequence candidates. By itself, the tool does not replace decision making on what should be incorporated in the drilling sequence. However, the radar-plot representation enables the analyst to characterize different prospects and identify the merits or weak points of drilling sequence candidates. For example, if the current strategy is to open up a new play, management may preferentially select prospects that have high volume upside even though they have relatively low probability of success. Conversely, if the imperative is to deliver immediate production to fill under-utilized facilities capacity, considerations of reserves bookability, initial well flowrate, high Probability Of Success (POS) and cost will tend to predominate.

A generic list of criteria for prospect selection and assembling the drilling sequence would typically include: (1) expectation reserves bookable in million barrels of oil; (2) commercial value added (NPV in millions US$); (3) contribution to immediate production (in barrels / day); (4) finding cost (in $ per barrel of oil equivalent); (5) potential to test multiple objectives with a single well; (6) data-gathering / Value Of Information (VOI) considerations; (7) strategic portfolio impact (e.g. ability to make-or-break a play, impact on the Probability Of Success (POS) of related prospects and hence its impact on upside volumes); and (8) Unit Technical Cost (UTC) mix of prospects chosen.

IMPACT ON EXPLORATION STRATEGY

One of the most exciting applications of portfolio management tools is in the building of future strategies for oil and gas exploration. A suite of tools and processes such as those described here can be invaluable, as we will illustrate with a number of examples from 1998, 1999, and 2000.

A portfolio-based approach has proved its merit in responding to both high and low oil prices. When oil prices are high, exploration activities may increase to seek growth opportunities and inventorize future potential. When oil prices are low, an exploration strategy has to satisfy diverse demands, such as cost saving, whilst still delivering low-cost reserves that can contribute to immediate production. A portfolio view helps balance the diverse pressures on the exploration program, such as: (1) drive for cost-leadership; (2) budget reductions as a consequence of low oil prices; (3) imperatives of meeting annual targets; (4) devolution of near field exploration to area-based asset teams; (5) strong creaming of older plays; (6) drive for new play development; (7) need to inventorize future potential of the concession; (8) need to compete with alternative investment opportunities (e.g. field development and the maturation of known reserves); and (9) staff resource constraints.

Reserves Targets

Target setting is an important aspect of the exploration business. Targets may be quantitative measures, such as volumes to be discovered, finding costs, and volumes added to the undrilled portfolio. Newly discovered hydrocarbon reserves represent an immediate return on the drilling investment, whereas portfolio volume targets ensure that appropriate resources are invested in data gathering, studies, and prospect generation to support future drilling discoveries. Targets may also include strategic objectives, such as proving a new play concept, or commercializing the oil found in a recent discovery. These targets are frequently embodied in a scorecard, which states the above-target, on-target, and below-target ranges for each objective. The team's performance is then the weighted sum of its performance against the individual scorecard elements.

In large, established companies, exploration targets are generally based on past performance and historic activity levels. In mature basins, as plays become more complex and traditional plays become creamed, such methods will sooner or later become inappropriate. In high-risk ventures, especially if drilling activity is limited, an annual finding target may not be suitable: emerging plays usually require a substantial up-front exploration investment before being rewarded by a reliable series of discoveries. Nonetheless, management requires a clear projection of the size, timing, and uncertainty in future reserves delivery. It is our contention that this projection should be based on the assets which will deliver the required performance, that is, the prospects in the portfolio. The tools and processes described here allow targets and future expectations to be defined objectively. One such example is shown in Figure 7.

Drilling Strategies

In developing options for a future exploration program, several key questions must be addressed, for example: (1) What is the optimum level of exploration drilling?; (2) How should string time be allocated to deep and shallow (or frontier and conventional) objectives?; (3) What is the consequence of very limited drilling?; and (4) What is the minimum number, size, and Probability Of Success (POS) of the prospect to be drilled in order to fulfill the target?

Optimum Activity Levels

Selecting the right activity level is a key to containing finding costs. Simulations with our *program modeler* indicate that around 2.5-rig-years (30-string-months) drilling yields the best value for money, with approximately 30 million barrels of oil reserves added by each rig-year (Figure 8). At higher activity levels, the returns per rig-year gradually diminish. This is a consequence of the size and quality of the prospects presently available in the portfolio; about 50 percent of the portfolio contains both very high risk (POS <10 percent) and low success-volume prospects. If high activity levels were to be pursued, one would require confidence that today's high-risk prospects can indeed be improved before drilling, or that they will be replaced with better quality new prospects. This would have implications for providing the organization with appropriately skilled staff and the necessary technologies to be employed in prospect generation and maturation.

Balancing Frontier Versus Conventional

In a diverse portfolio, such as the one in Oman, the mix of frontier (deep) and conventional (relatively shallow) prospects and employed string-time has a dramatic effect on the optimum activity level, and on the targets that can be met.

We see that—for this portfolio—optimum performance is achieved with a dominance of frontier string-time (Figure 10). This is a consequence of the strong creaming and small size or number of the remaining conventional prospects (Figure 11). Without new portfolio additions, the conventional portfolio segment can sustain 12-string- months drilling for only 2 to 3 years.

These types of models helped drive, and subsequently validated, PDO's exploration strategy shift since 1998, in which frontier prospect generation and drilling deep objectives, such as the intrasalt Carbonate Stringers (Reinhardt et al., 1999), have been emphasized.

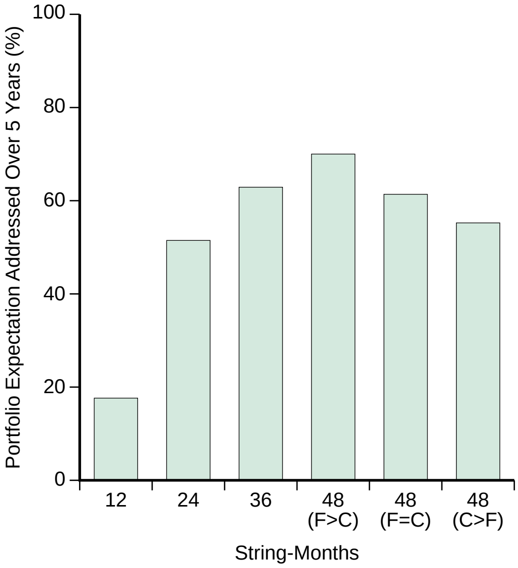


Figure 10: Output from the program modeler—a bar chart of activity level versus reserves booked. A 48-string-months with dominance assigned to deep frontier drilling results in an optimum activity level. Legend: F = Frontier (deep) exploration; C = Conventional (shallow) exploration.

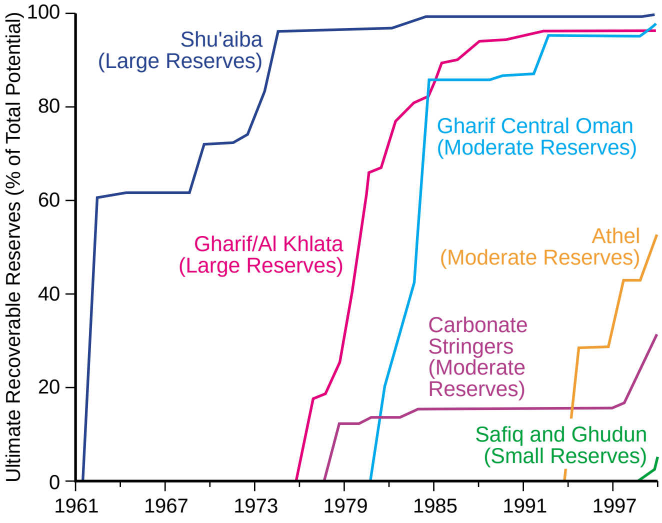


Figure 11: Portfolio composition and creaming. The Shu'aiba, Gharif/Al Khlata and Gharif Central Oman plays show strong creaming, whereas the Carbonate stringers, Athel and Safiq-Ghudun plays suggest that substantial volumes may still be found. The potential of each play is indicated by its relative size: large—more than 1 billion barrels of oil reserves; moderate—approximately 500 million barrels of oil reserves; and small—less than 200 million barrels of oil reserves.

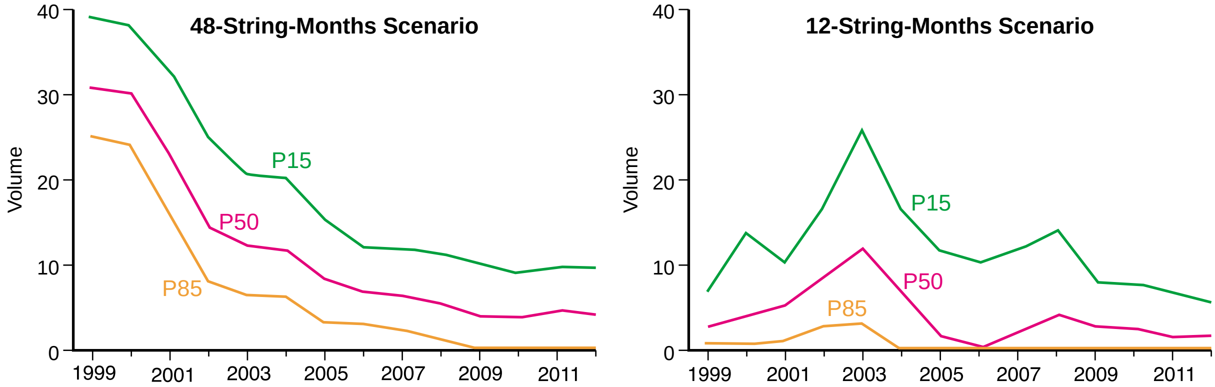


Figure 12: Reserves booking profile for 48- and 12-string-months drilling of a hypothetical portfolio of high-risk prospects. A 48-string-months activity level assures a predictable success rate (left), whereas the 12-string-months scenario would result in an erratic reserve booking performance (right).

The Consequence of Limited Drilling

Apart from necessitating lower finding targets, limited drilling activity exposes an exploration campaign to the statistical vagaries of drilling low POS prospects. At high activity levels, exploration shows a steady performance, albeit declining as the best prospects are creamed (Figure 12, left). At low activity levels, there is a substantial risk of making no, or minimal, discoveries for several consecutive years (Figure 12, right), which would damage stakeholder confidence in exploration. For PDO's oil portfolio, simulations suggest that the minimum level of drilling for credible and consistent performance against targets is about 24-string-months annually.

Other considerations also suggest that very low activity levels are undesirable. Reduction in drilling would likely be accompanied by staff reductions, for example, leading to loss of critical mass of expertise. Besides seeking to prove new oil reserves, exploration wells are the key tool for obtaining subsurface data for improved understanding of plays and petroleum systems. Low drilling levels would limit new data gathering, severely restrict the testing of new concepts, and thereby compromise future exploration programs.

Improving Performance

Historically, exploration in PDO initially booked an average of 50 to 65 percent of the mean discovery volume in a prospect, on the basis of primary—as opposed to full-life cycle—reserves. We are actively seeking to improve on this in three ways.

The first approach is organizational—we incorporate a commercialization team in the exploration organization. Its role is to focus on key data-gathering to maximize reserves bookings in new discoveries. It fulfils a second role in systematically evaluating and maturing STOIIP conversion opportunities, that is, working up previous discoveries, which for reasons of economics or resource limitations, have not been booked or developed.

The second approach is technology driven, making greater use of *smarter appraisal*, in which, for example, modeling studies and seismic inversion techniques are used to support reserves bookings on the basis of fewer appraisal wells. Replacing a realistic part of our appraisal drilling with technology and studies could increase reserves delivery by 15 to 20 percent.

The third is a portfolio-management based approach: the concept of *POS polarization*. The concept entails using technology and good evaluation practice, to turn the 'gray middle-ground' prospects, with average POSs, into high-POS (drillable), or low POS (non-drillable) prospects.

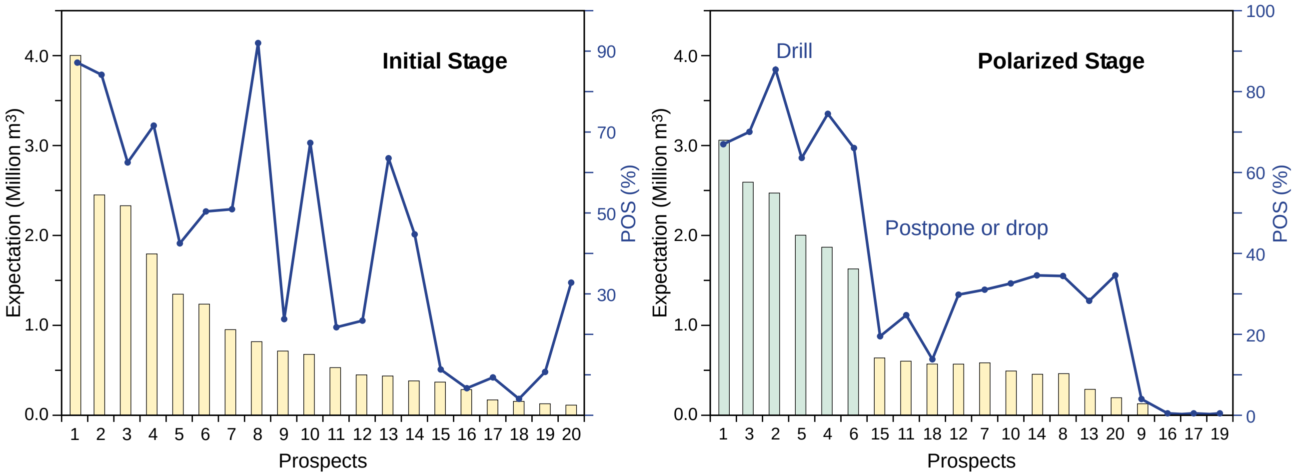


Figure 13: Probability Of Success (POS) polarization concept and example. After POS polarization, the prospect sequence is re-sorted and falls into two groups, 'Drill' and 'Postpone or drop'. In the Initial Stage (left) there are a few high expectation prospects and a large number of equally drillable prospects with an expected total voume of 19.8 million m^3 (124.5 million barrels). After the POS-polarization (right) drillable prospects are evident, and it is possible to identify prospects to be dropped or postponed, realizing an expected total volume of 18.9 million m^3 (119 million barrels).

We can use the *program modeler* to demonstrate the potential of POS polarization. The approach taken is to change individual prospect POSs by +20 percent or -20 percent at random, within reasonable boundaries (e.g. not less than 0 percent POS, and not more than 70 percent POS), according to play type and maturity. The expectation of each prospect is then recalculated and the drilling sequence is reordered according to the new expectations (Figure 13). Simulations on PDO's portfolio after a nominal ±20 percent POS polarization shows that some 30 to 40 percent extra reserves can be achieved (Figure 14). The models have driven home to the organization the importance of this concept, and engendered its ownership. POS polarization is focused on the following five main risks affecting prospects:

(1) **Structural risk:** depth conversion, acquiring new seismic data, use of pre-stack depth migration and post-stack imaging processing techniques. Added benefit: reduce the uncertainty in gross rock volume, allowing more accurate economic calculations by right-sizing the field development plan. In some plays, better structural definition may increase the size of the prospect by resolving structural complexity and providing a clearer basis for assessing the presence/absence of fault compartmentalization.

(2) **Charge risk:** basin modeling is used to tackle timing of charge relative to structure development, hydrocarbon type, and the definition of migration paths and potential charge shadows. Seismic data are used to assess the presence of oil/gas.

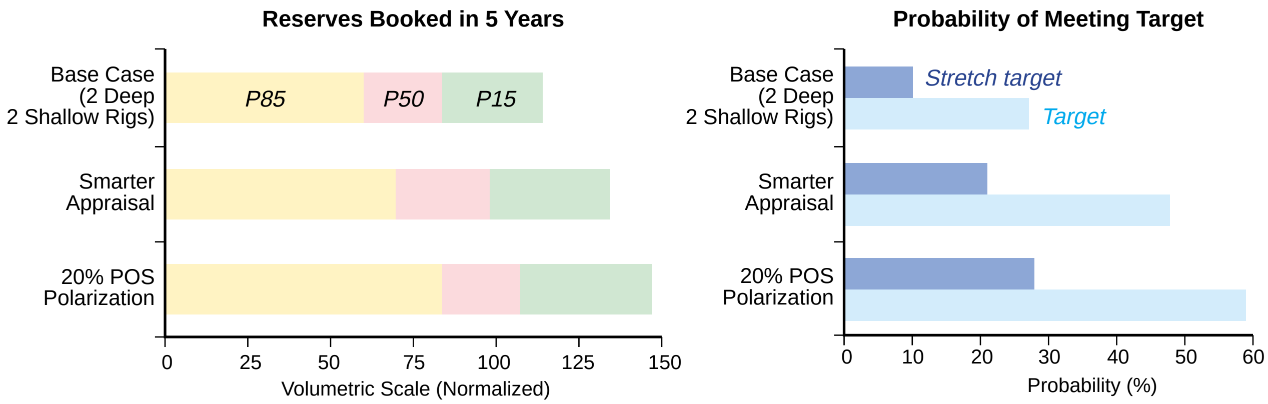


Figure 14: Probability of achieving stretching targets for different scenarios.

(3) **Seal risk:** Gross Depositional Environment (GDE) maps (thickness, shale brittleness, and fault and fracture intensity) lead to the creation of Common Risk Segment (CRS) maps at a play level. This will ensure prospect evaluation consistency within the play by standardizing the risk of seal failure.

(4) **Reservoir risk:** Gross depositional environment maps are used to generate CRS maps at a play level; typical considerations include facies, gross thickness, and net-to-gross ratio. Additional considerations for reservoir risks include porosity, horizontal permeability, and vertical permeability, which may include depositional and diagenetic factors. An added benefit is the introduction of prospect evaluation consistency within a given play by well-calibrated reservoir input parameters. Seismic data are used to estimate presence / absence of porosity.

(5) **Reservoir engineering related risks:** The reservoir engineering community advises the exploration team with updated field development concepts, and the commercial attractiveness of prospects. This involves the following key parameters: minimum well delivery rates; type of pressure support; minimum economic reserves; reservoir heterogeneity and continuity; and risk of no hydrocarbon recovery.

The current level of risk, and the extent to which technology can be used to assess and reduce that risk, is assessed in each play, theme, or prospect. This allows evaluators to focus on the critical risks and those where a significant risk reduction can be obtained, rather than expending staff resources on risks that are for all practical purposes irreducible (Figure 15). The outcome is a minimum POS criterion that prospects have to pass in order to be drilled. This criterion naturally varies according to the type of play being pursued.

Long-term Viability of Exploration

In a concession that has been actively explored for some years, it is prudent to ask how long the potential of the basin will support continued exploration. PDO faces such questions as it approaches the last decade of a 75-year concession.

Portfolio Rejuvenation

The program simulations show that whilst for the next five years we can meet our targets (Figures 8 and 9), thereafter the reserves finding rate—based on today's portfolio—would fall, and finding costs would rise dramatically as smaller and riskier prospects are drilled (Figure 16). However, the concession has a substantial undefined potential. This potential has been calculated from a variety of independent basin-scale estimates and statistical analyses of discoveries and field sizes. The challenge is to transform this potential into specific prospects. It becomes imperative to do this in the next five years, in order to be able to continue exploration and realize the bulk of the concession potential before 2012. Whilst the models do not tell us how to do it, they make it very clear what the prize is, and on what time-scale we have to act.

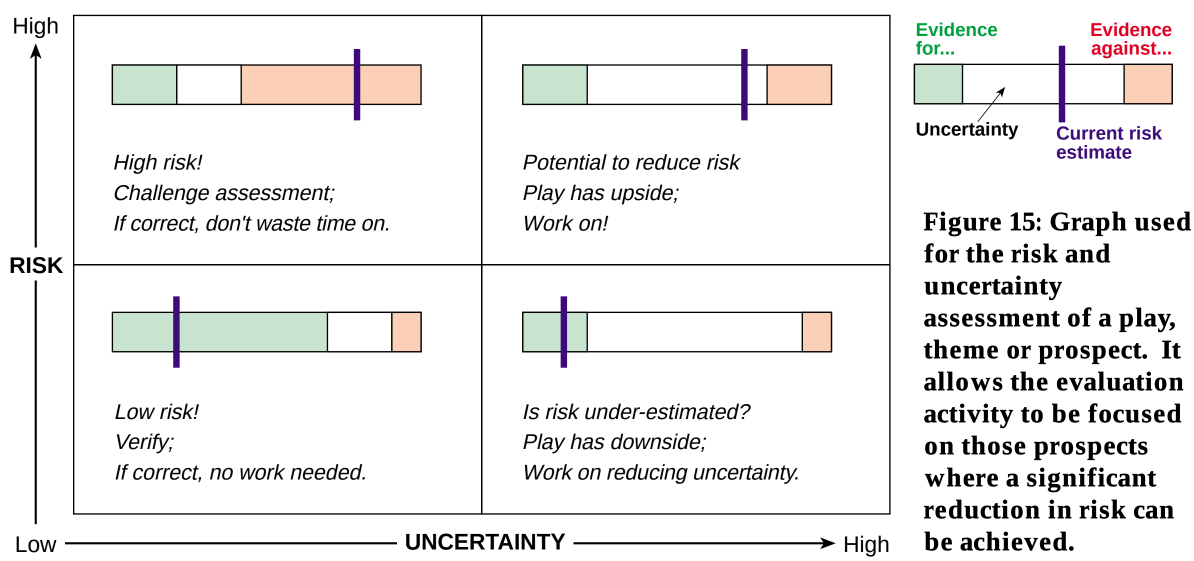
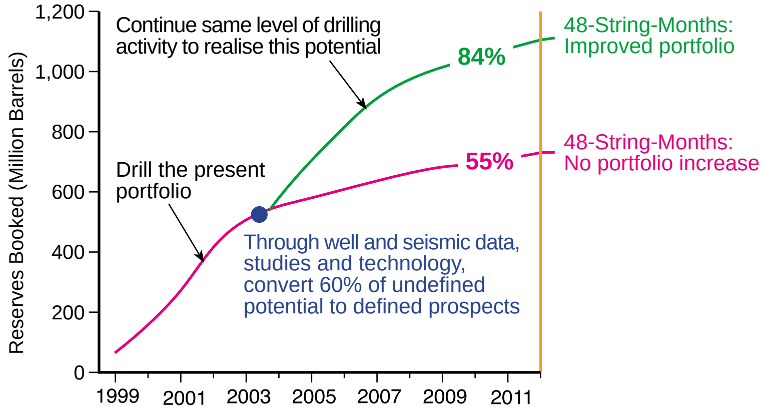


Figure 15: Graph used for the risk and uncertainty assessment of a play, theme or prospect. It allows the evaluation activity to be focused on those prospects where a significant reduction in risk can be achieved.

Figure 16: The prize inherent in portfolio rejuvenation with a portfolio breakdown of 34% for deep frontier exploration, 9% for shallow conventional exploration, 10% for 'exploratory appraisal scope-for-recovery', and 47% into 'undefined geological potential'.



Portfolio Trends

Portfolio quality is moving in the right direction to support the above strategies. The average prospect expectation is increasing, and the top 50 percent of the portfolio volume is contained in fewer prospects (Figure 17). The spread between upside and downside volumes is widening, which enables management to select high-value prospects for drilling. The high drilling intensity (approximately 25 exploration wells / year) means that the better prospects generated by POS polarization are quickly drilled. Prospects remaining in the portfolio tend to be the more risky ones and, as a result, the average POS of the portfolio has not changed substantially. This clearly underlines the need to invest in skills and technologies that can further address prospect risk.

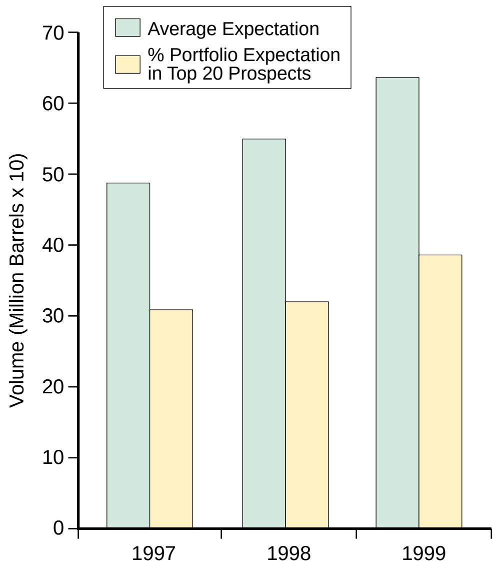


Figure 17: Three-year portfolio trends and portfolio composition.

Portfolio Diversification

Currently the portfolio comprises various themes with different risk attributes. Since half of the current frontier prospect portfolio lies within the intrasalt Athel and carbonate stringer plays of South Oman, there is a clear need to diversify the portfolio further. Recent modest success in the Haima Safiq-Ghudun sandstone play in central Oman was followed up by a year of intensive prospect maturation. This has doubled the size of this portfolio segment. Focused activities to generate other plays are ongoing throughout the concession.

NEXT STEPS

PDO's portfolio management team has three short-term goals. Firstly, there is a need to rigorously and systematically re-examine the undefined potential of the concession. For established plays (such as the Natih, Shu'aiba, and Gharif), the methods for this include field-size distributions (Davis and Chang, 1989; Houghton et al., 1993), and creaming-curve analyses (Meisner and Demirmen, 1981). This work must also recognize the substantial uncertainty inherent in such methods.

Secondly, we need to assess our vulnerability to the dependencies within a play or theme. If the three key wells in a new play fail, how does that impact our portfolio and long-term performance? Conversely, if they succeed, how much does the portfolio value increase, and what are the implications for exploration strategy? Both interplay and interprospect dependencies are being examined. The aim is to quantify the consequences of positive or negative outcomes of linked prospects, and optimize the exploration strategy in prospect clusters through smart-prospect sequencing. Algorithms to do this will be integrated into our program modeler.

Thirdly, we are building a stock of drillable prospects, to demonstrate to stakeholders the tangible fruits of our efforts in POS polarization and portfolio rejuvenation.

CONCLUSIONS

The portfolio management process has made a major contribution to the quality of prospects drilled in Oman. Every exploration department aspires to continuously optimize its exploration program; the tools described allow dynamic and auditable portfolio management.

Thanks to new processes and a robust suite of tools, the company has a better grip on the prospect portfolio, and is explicitly aware of the challenges and issues. The exploration directorate has been able to demonstrate the fairness and credibility of targets, and communicate them amongst all those concerned with the exploration process. The clarity brought by these portfolio analyses provides a powerful focus to the asset teams' efforts to improve prospect quality.

Portfolio management provides data with which the consequences of changing activity levels and balance in the program can be assessed. It also makes explicit the limitations imposed upon us by the portfolio. These provide the basis for ongoing dialogue and vindicate the strategy shift towards frontier exploration enacted since 1998. As a result, PDO has been able to maintain a drilling success rate in excess of 40 percent and hold finding costs at US$ 1 per barrel of oil equivalent or less.

Exploration in Oman has shifted from being opportunity-driven to being led by a portfolio-based strategy. A similar approach may be suited for other brown-field settings with sizeable portfolios.

ACKNOWLEDGMENTS

We thank the Ministry of Oil and Gas and Petroleum Development Oman (PDO) for permission to publish this paper. We acknowledge the many colleagues in PDO who have contributed to the ideas presented here and whose work has contributed to the healthy prospect portfolio that we have today. In particular, we would like to thank Alastair Milne, Mark Doyle, and Harry Gielen who began the development of the in-house tools that we describe. We also thank present and former colleagues in PDO's exploration leadership team for their support and encouragement, and in particular Matthias Bichsel, Gavin Graham, and Bruce Levell. The comments and suggestions of the two anonymous reviewers and Geo*Arabia's* editors are acknowledged. The design and drafting of the final graphics was by Gulf PetroLink.

GLOSSARY

Booking Action of formally endorsing a reserves volume of an exploration discovery. The booking must have a notional field development plan and economics attached to it.

Cut-off Volumetric limit, below which relatively small volumes are deemed uneconomic. Discovery of a volume below the economic cut-off is therefore regarded as a commercial failure.

CRS Common Risk Segment

EMV Expected Monetary Value: the value of the cash flow of a project, risked to take account of all possible outcomes, favorable and unfavorable, that may result.

Expectation The product of the Mean Success Volume (MSV) and Probability Of Success (POS). This is used for (1) comparison and ranking of prospects with different degrees of uncertainty or probability; and (2) for estimating the most likely volumetric outcome of a statistically large number of drilled prospects.

Expectation curve An expectation curve is defined as a set of equally likely outcomes of an uncertain situation arranged in terms of increasing size against cumulative probability.

GDE Gross Depositional Environment.

L/M/HSV Low, Mid, and High Success Volumes. In volumetric appraisal, the success volumes (after cut-off) are classified into three equal-sized probability classes. The means of the three classes are the low, mid and high success volumes. These correspond almost exactly to the P85, P50 and P15 values of the success cases. The HSV or P15 is often quoted as the upside of the prospect.

MSV Mean Success Volume: the probability-weighted average of all possible successful outcomes on the expectation curve. This is normally calculated after applying a non-zero cut-off. An MSV is associated with a probability of success (POS).
The MSVs and their POSs will vary according to the cut-off used. The highest POS, and lowest MSV, is associated with a zero cut-off.

NPV Discounted Net Present Value of a project. The value of a project (e.g. oilfield development), calculated from the sum of the cash flows from first project expenditure to abandonment. These cash flows are expressed in real-term money and further discounted to Present Value (PV) money. The effect of discounting on cumulative cash flow reduces the value of the future income in comparison to the cost of early expenditure, reflecting the time-value of money.

POS Probability Of Success. Probability that a prospect comes in successfully; that is, the discovered volumes exceed the minimum economic cut-off. The POS is basically 1 minus the sum of all risks.

Prospect Subsurface feature with the potential to have entrapped oil or gas, and which has a relatively well-defined geometry from the available data.

Reserves Oil or gas resources that have been demonstrated to be producible and for which a development plan or concept can be shown to generate an acceptable economic return based on the expectation volumes.

Risks In prospect appraisal, the following five main risks are recognized:
(1) Trap risk: absence of hydrocarbon trapping structure; can result from poor seismic coverage, unfavorable fault juxtaposition, and unforeseen velocity variations in the overburden.
(2) Top seal risk: absence of a caprock (e.g. shale or salt) over part or the whole structure.
(3) Reservoir risk: absence of a porous and permeable rock where hydrocarbons not only can enter the intergranular space, but can also be extracted.
(4) Charge risk: absence of an active hydrocarbon-generating kitchen or lack of access to the source of charge.
(5) Recovery risk: in case of tight, or hydrocarbon saturation reservoirs, the hydrocarbons cannot be brought to the surface.

STOIIP Stock Tank Oil Initially In Place: the total volume of oil present in a subsurface accumulation, but converted to standard surface conditions. STOIIP includes both recoverable (producible) oil, and oil which cannot be economically recovered (residual oil).

UTC Unit Technical Cost of a project, in US$ per barrel of oil produced in the future. Calculated as the sum of the capital and operating costs (expressed in real terms money) divided by the total discounted production from start-up to abandonment.

VIR Value Investment Ratio; a measure of the investment attractiveness of a project. Essentially the ratio of the Net Present Value (NPV) cash 'profit' generated by a project, divided by the capital invested to generate that profit.

REFERENCES

Amthor, J.E., W. Smits, P. Nederlof, N. Frewin and S. Lake 1998. Prolific oil production from a source rock—the Athel silicilyte source-rock play in South Oman. American Association of Petroleum Geologists 1998 Annual Convention, Program with Abstracts.

Davis, J.C. and T. Chang 1989. Estimating potential for small fields in mature petroleum province. American Association of Petroleum Bulletin, v. 73, no. 8, p. 967–976.

Boserio, I.M., C. Kapellos and H. Priebe 1995. Cambro-Ordovician tectonostratigraphy and plays in the South Oman Salt Basin. In, M.I. Al-Husseini (Ed.), GEO'94. Gulf PetroLink, Bahrain, v. 1, p. 203–213.

Droste, H. 1997. Stratigraphy of the lower Palaeozoic Haima Supergroup of Oman. *GeoArabia*, v. 2, no. 4, p. 419–472.

Guit, F.A., M.H. Al-Lawati and P.J.R. Nederlof 1995. Seeking new potential in the early-late Permian Gharif play, West Central Oman. In, M.I. Al-Husseini (Ed.), GEO'94. Gulf PetroLink, Bahrain, v. 1, p. 447–462.

Houghton, J.C., G.I. Dolton, R.F. Mast, C.D. Masters and D.H. Root 1993. U.S. Geological Survey estimation procedure for accumulation size distribution by play. American Association of Petroleum Geologists Bulletin, v. 77, no. 3, p. 454–466.

Loosveld, R.J.H., A. Bell and J.M.J. Terken 1996. The tectonic evolution of interior Oman. *GeoArabia*, v. 1, no. 1, p. 28–51.
Meisner, J. and F. Demirmen 1981. The creaming method: a Bayesian procedure to forecast future oil and gas discoveries in mature exploration provinces. Journal of the Royal Statistical Society, Series A, v. 144, no. 1, p. 131.
Oterdoom, W.H., M.A. Worthing and M. Partington 1999. Petrological and tectonostratigraphic evidence for a mid Ordovician rift pulse in the Arabian peninsula. *GeoArabia*, v. 4, no. 4, p. 467–500.
Reinhardt, J.W., J.E. Amthor and F. Hoogendijk 1999. Deep oil exploration in an unconventional reservoir—the Pre-Cambrian intra-salt carbonate play of Oman. American Association of Petroleum Geologists 1999 Annual Convention, Program with Abstracts, p. A115.
Richard, P.D., P.J.R. Nederlof, J.M.J. Terken and N. Al-Ruwehy 1998. Generation and retention of hydrocarbon in the Haushi play, North Oman. *GeoArabia*, v. 3, no. 4, p. 493–506.
Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate sequence stratigraphy. *GeoArabia* Special Publication 2, Gulf PetroLink, Bahrain, 371 p, with 3 charts.
Terken, J.M.J. 1999. The Natih petroleum system of north Oman. *GeoArabia*, v. 4, no. 2, p. 157–180.

ABOUT THE AUTHORS

Michael (Mike) Naylor *became Exploration Planning Manager for Petroleum Development Oman (PDO) in Muscat in 1998, after serving as Manager of Geological Services in PDO for 3 years. He is also PDO's discipline head for exploration geology, with responsibilities for process integrity, staff development and technology management. He has an MA in Natural Sciences and a PhD in Structural Geology from Cambridge University. He worked as a Structural Geologist with Shell Research from 1979 to 1983, as a Seismic Interpreter/ Geologist in PDO (1983–86), a Senior Explorer with Shell Egypt (1986–91), and was a Research Manager in Shell Research from 1991 to 1995. Mike is a Fellow of the Geological Society of London, and a member of the Editorial Board of GeoArabia.* *E-mail: Michael.MA.Naylor@PDO.co.om*

Laurent Spring *is Portfolio Manager in Petroleum Development Oman. He has a PhD in Geology from Lausanne University, Switzerland, and an MBA from Henley Management College, Great Britain. He joined Shell in 1993, and spent two years as a Geologist in greenfield exploration in The Hague, before joining the Kuwait Oil Company-Shell joint study team. Laurent then moved to Thai Shell, first as Senior Production Geologist, thereafter as Manager of Exploration and New Opportunities.*
E-mail: Laurent.Y.Spring@PDO.co.om

Manuscript Received March 18, 2001

Revised May 26, 2001

Accepted May 31, 2001