Elements of the Frontier Exploration Workflow

By: Mike Simmons

Modern frontier exploration workflows for conventional resources (Figure 1) are focused around:

(i) The development of play concepts, drawing on the creativity of the exploration geoscientist, informed by appropriate geological analogues

(ii) The mapping of various play elements within a play concept using common risk segment (CRS) mapping techniques (Grant et al., 1996; Longley and Brown, 2016). At their most basic, these are 'traffic light' assessments of risk based on: reservoir presence and effectiveness; source rock presence and maturity; the migration limits of the hydrocarbons generated; and seal presence and effectiveness (Figure 2). They can be informed by analysis of successful and dry wells in the basin being assessed, and the likely limits of trap distribution.

(iii) The definition of a high-graded play fairway in which prospects can be sought.

(iv) The calculation of the likely yet-to-find volumes of hydrocarbons within a play within a basin. This can be predicted from the size and number of prospects, allowing prospective plays and basins to be ranked.

Exploration for unconventional resources follows a similar type of screening process.

The workflow requires the exploration geoscientist to evaluate the geological history of the basin or region they are studying, beginning with tectonostratigraphy, and culminating in a detailed understanding of depositional history and the subsequent burial history of the sediments deposited.

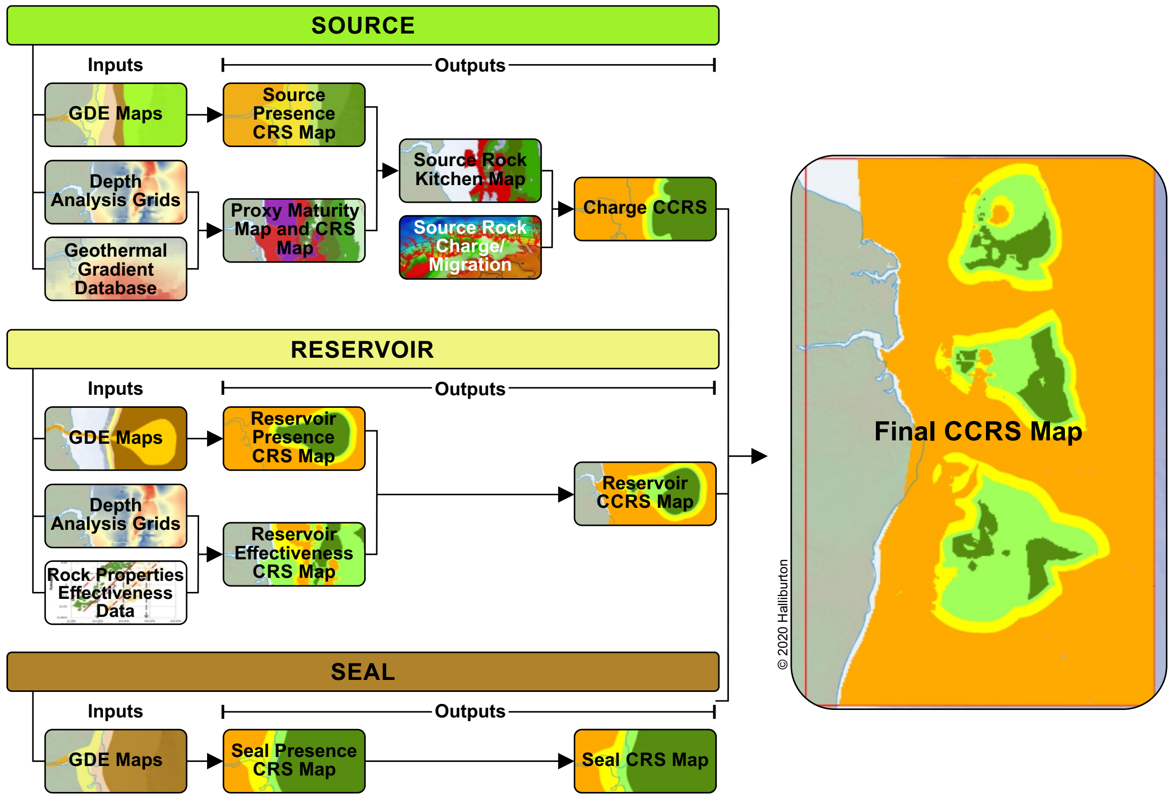

Figure 2 > Common risk segment mapping. Converting geological data and interpretations into an assessment of risk, ultimately high-grading a region in which a play is thought more likely to work — the play fairway.

To do so, the explorationist needs to draw on a variety of data types and specialist interpretation techniques (see previous aticles in the Exploration Handbook series). In this article we highlight how these techniques come together to provide an assessment of exploration potential, prior to prospect definition and drilling of wildcat wells.

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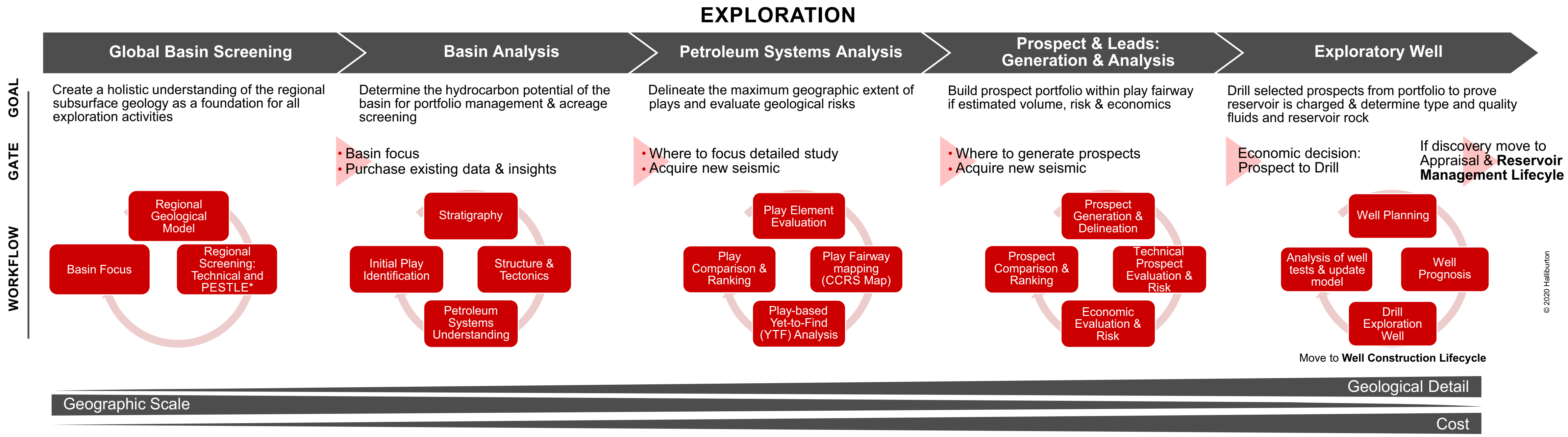

Figure 1 > The generalized frontier exploration workflow.
*Political, Economic, Social, Technological, Legal and Environmental

WHERE TO EXPLORE

Most oil companies engaged in exploration have a new ventures team. The role of this team is to identify the areas in which the company should focus its exploration efforts. Several approaches, some proactive, others reactive, may guide the work of this team:

(i) Creating completely new concepts

- Are there new combinations of source rock, reservoir, seal, and trap (plays) that can be envisaged for a basin?

(ii) Building on success

- Can play concepts that have been successful in a basin be applied to other basins?
- Can a successful play concept in a basin be extended to other parts of that basin?

(iii) Understanding past failure

- Should a play concept be written off because of previous failures?
- Will re-examining aspects of the play (e.g. migration) open up the possibility of the play working in other parts of the basin, or in other regions?

(iv) Being driven by opportunity

- Availability of a licensing round. Not all potentially prospective basins have acreage available to license. A licensing round may require rapid evaluation of the opportunities available.
- Farm-in offers from another company. Most large companies will keep a running inventory of their view of the potential of basins. Even so, an invitation from another company to participate in an exploration venture may require reassessment of that potential.
- Geopolitical considerations. Changing political circumstances may open up basins for assessment, or, especially for government-owned companies, exploration focus may be driven by wider considerations of that company or nation’s activities.
- Technological considerations. The ability to drill wells in deeper water, in challenging environments, or to greater depths, may open up new basins, or parts of basins for assessment.

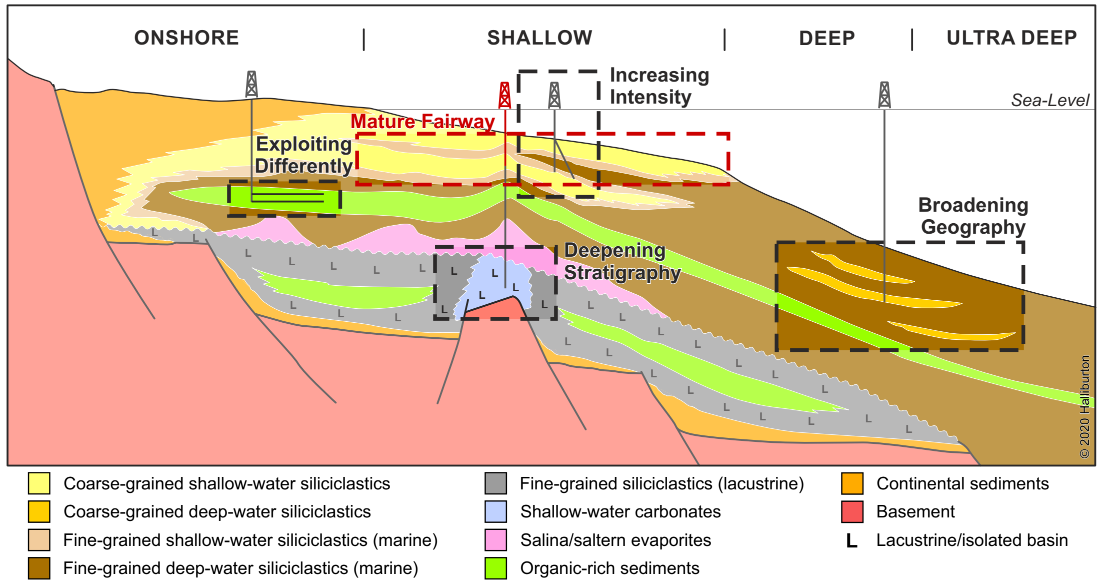

Figure 3 > Evolution of play concepts in a hypothetical basin.

Given all the possible reasons to review exploration, it is not surprising that the work of a new ventures team never ends! There are always play concepts to generate or revisit, and new geography or stratigraphy to consider (Figure 3).

Although there are few completely unexplored basins on Earth, some are relatively underexplored (“frontier basins”). For example, the Black Sea Basin occupies c. 423,000 km^2, yet only 20 or so deep-water wells have been drilled there (Simmons et al., 2018).

There are many basins that have been extensively drilled in shallow stratigraphy, but deeper stratigraphy remains relatively unexplored (“frontier plays”). Stratigraphic traps, such as subcrops, pinch-outs, and isolated reefs, are relatively underexplored, and plays associated with these are likely grown in importance.

Even in the Middle East, where simple structural closures have yielded immense volumes of hydrocarbons, attention is now turning to stratigraphic traps (Cousins et al., 2019). Put simply, there is a still a great deal of the subsurface to be fully evaluated for its hydrocarbon potential (Figure 4). How then, do geologists evaluate this potential?

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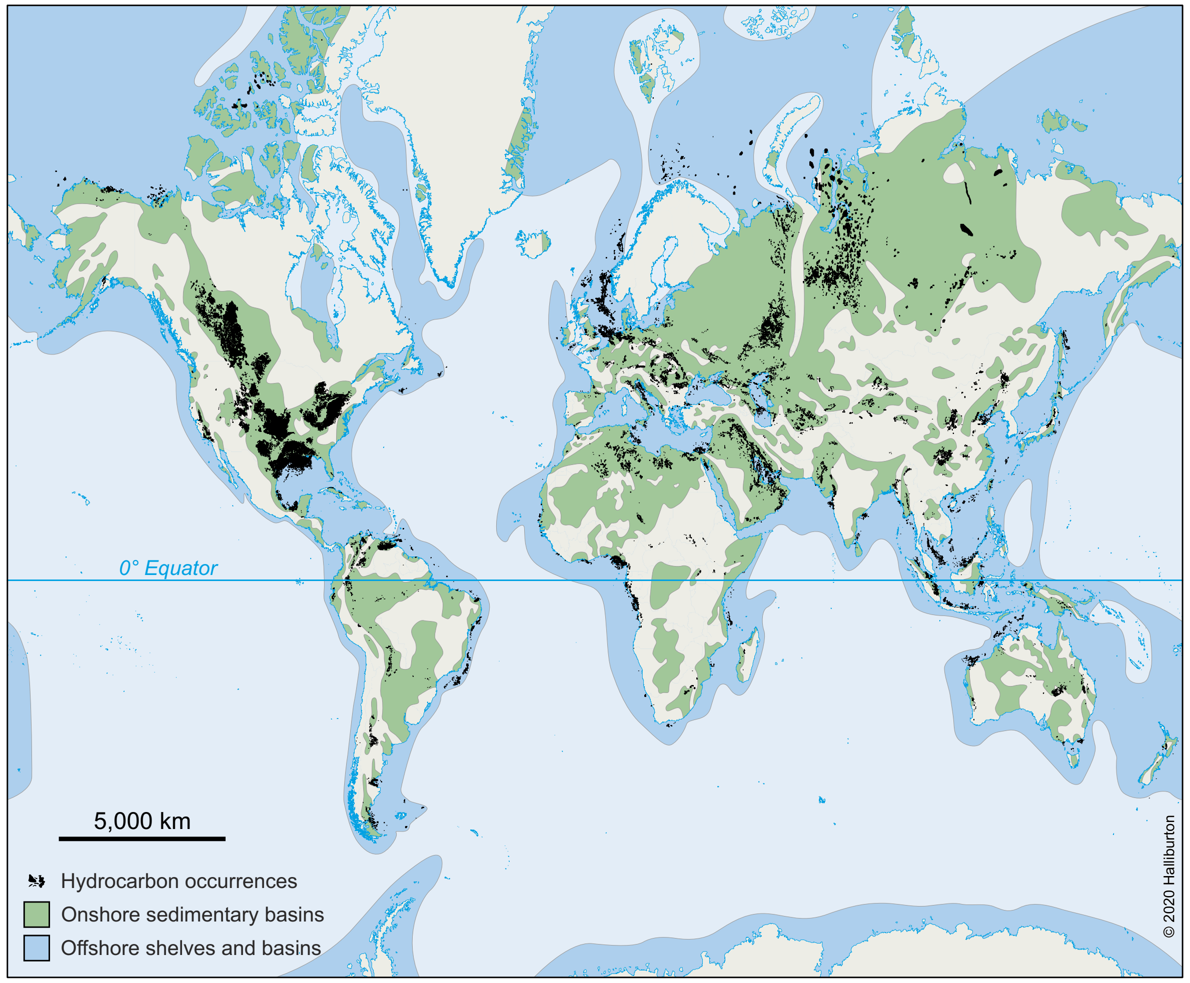

Figure 4 > Onshore and offshore sedimentary basins that are the focus for hydrocarbon exploration. A number of basins are relatively unexplored.

HOW TO EXPLORE

Fundamentals

Successful exploration requires a good understanding of geological risk. This in turn requires an understanding of the geological history of the basin or region being evaluated, the likely sedimentary succession present, and its hydrocarbon potential. Predictions of the subsurface need to be made away from data constraint. To carry out these predictions effectively, the geologist will need to utilize a number of fundamental techniques:

- Data search and capture. In frontier basins, every piece of data a geologist can find may prove important. Access to available wells and seismic data is vital, but outcrops on the margin of the basin may also prove insightful. Likewise, the results of specialist analysis such as organic geochemistry, sedimentology and biostratigraphy can be invaluable and need to be sought out. The value of published literature should not be underestimated and an effort should be made to "look under every stone" in order to find data that may affect geological risk assessment.
- Sequence stratigraphy. Sequence stratigraphy considers the sedimentary response to changes in relative sea level. It is, therefore, powerful in predicting subsurface sedimentary architecture and the likely facies present in a given location.

Geological age is key to integrating data; sequence stratigraphy, as a proxy for age, provides a framework in which to standardize and integrate disparate geological data. Wells, outcrops, seismic data, and specialist data can be attributed with sequence stratigraphic surfaces, and thereby integrated into insightful interpretations such as gross depositional environment maps.

Recognition of globally significant sequences (the results of eustasy) provides additional predictive capabilities in determining the likely sedimentary fill of a basin and its hydrocarbon potential (e.g. major eustatic falls associated with lowstand fan deposition).

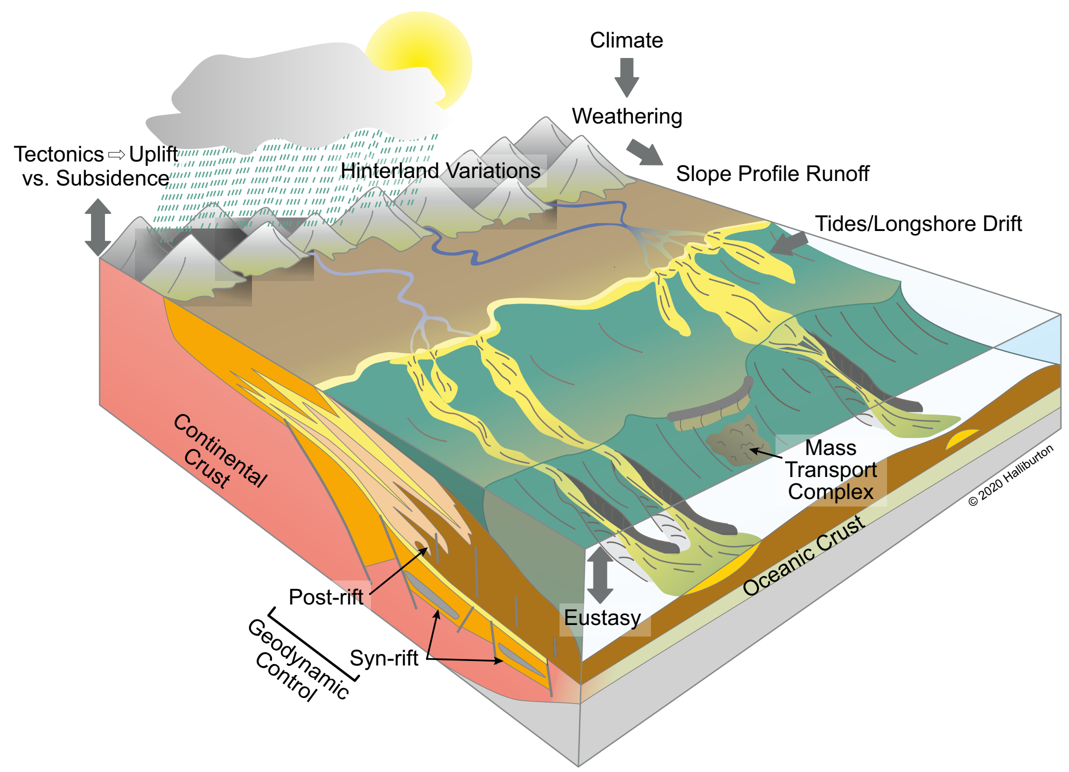

Figure 5 > Schematic representation of Earth systems science elements. This is a holistic approach that considers the key factors that govern erosion, transportation, and ultimately the deposition of sedimentary rocks. The interplay of tectonics, climate and eustasy can be used to aid in the prediction of petroleum systems elements.

- Geodynamics. High-resolution plate tectonic models are now available without the need for specialist software or powerful computing facilities (e.g. QuickPlates®). They allow the tectonic history of a basin to be evaluated and conjugate margins to be located, facilitating the selection of play analogues.
- Earth systems science. Developments in geodynamics have facilitated the use of the broader discipline of Earth systems science in exploration. The complete geological tectono-sedimentary system is considered from sediment source to its ultimate destination in a basin, with a variety of Earth systems factors such as eustasy, uplift, subsidence, and climate controlling this (Figure 5). This can be highly predictive and used to de-risk play concepts.
- Depth mapping. Reservoir, source rock, and seal presence need to be considered within a depth framework to evaluate the effectiveness of these petroleum systems elements. Dynamically updatable structure contour maps and grids are now relatively easy to construct in many exploration software packages (e.g. DecisionSpace®) and provide a vital perquisite to basin screening.
- Basin modeling. Basin modeling is essential to predict source rock maturity through geological time, and thus assess if, when, and how hydrocarbons were generated and migrated. Subsurface pressure and reservoir quality can also be modeled. Modeling may be performed in 1D, 2D, or 3D, plus the extra dimension of time, but should begin with the calibration of a data-rich well in 1D. A program of 1D modeling of wells and pseudo wells (predicted lithological columns) can give a quick, but necessarily rough, view of a petroleum system. Such modeling can now be performed by generalists as well as specialists in software such as Permedia®.

The application of these fundamental techniques within frontier exploration lies at the heart of the Neftex®.

Tectonic History

Today, few sedimentary basins are completely unknown entities. Data have been collected for decades by industrial and academic seismic programs, drilling initiatives such as the International Ocean Discovery Programme (IODP) and its predecessors, and by the study of outcrops in and on the margins of basins. Thus, even basins that have experienced limited efforts to explore for hydrocarbons are reasonably well understood, at least in terms of their basic tectono-stratigraphy.

"Recognition of globally significant sequences ... provides additional predictive capabilities in determining the likely sedimentary fill of a basin and its hydrocarbon potential..."

The evaluation of a basin usually begins with an understanding of its tectonic history through the definition of tectonic megasequences. Such an understanding can provide insight into key issues that govern prospectivity:

- » **Timing of basin formation.** Very young basins lack mature source rocks, while very old basins may only possess over-mature source rocks, at least at depth.
- » **Phases of tectonic history.** These include pre-rift, syn-rift and post-rift. Petroleum system elements are often related to discrete phases in the history of a basin, and an overly complex basin history can destroy petroleum systems elements, for example by inducing breach of traps.
- » **Past and present geothermal gradients.** These impact source rock maturity, timing of migration, and reservoir effectiveness.

The tectonic history of a basin can be determined from the geodynamic context derived from plate tectonic models, coupled with large-scale basin architecture as imaged on deep seismic data. Some initial basin modeling can be helpful in generating basic notions of the likely possibilities of hydrocarbon generation, reservoir effectiveness and seal integrity. Such initial work can be followed up with more detailed studies as the play concepts develop, and the likely locations of the play fairway and any prospects within it become clearer.

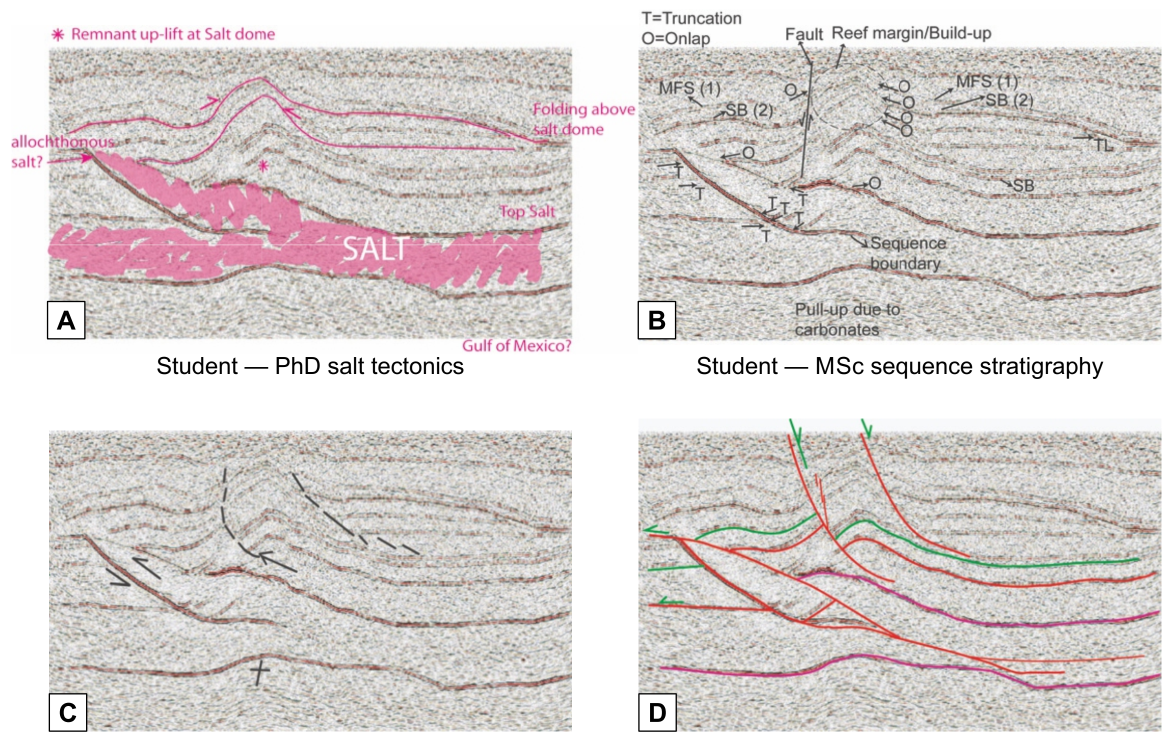

Figure 6 > Different interpretations of the same seismic data reveal bias in interpretation relating to the experience of the interpreter. After Bond et al. (2007).

Sedimentary Fill

If a basin has a tectonic history that suggests potential for prospectivity, the next task is to evaluate its likely sedimentary fill, usually megasequence by megasequence, as determined from the tectonic history of the basin.

An initial assessment is made using seismic data. These data are usually speculative, gathered to promote the prospectivity of a basin or region. Seismic character and facies are useful indicators of sedimentary fill, and can be integrated with well and/or outcrop information to determine lithology.

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In the absence of well and/or outcrop data, regional geological understanding, such as tectonic history, sea-level change, and conjugate or analogue basins can be used. These are important because interpretation of seismic data can easily be susceptible to bias derived from the experience of the interpreter, as shown by Bond et al. (2007) (Figure 6). Such bias can best be overcome by a good understanding of the relevant regional geological context.

While there are many potential iterations, the frontier exploration process (Figure 1) is straightforward in that information on the stratigraphy of the basin is gathered from a variety of data types, integrated (typically using sequence stratigraphy), and then converted into petroleum geology understanding as expressed in the form of CRS maps for various play elements. This then leads into prospect definition and risked estimates of volumes of hydrocarbons in place (Figure 7). Stratigraphy is thus at the heart of play-based exploration.

Exploration geologists are concerned with building up an understanding of the geological history of a basin and require a means to integrate many different types of data and knowledge. The most obvious commonality is geological age. For example, rock units, seismic horizons, and phases of tectonic history all have a geological age. This does not mean the absolute (or numerical) age, but the relevant geological period (as precise as possible). To achieve this, data can be attributed with sequence stratigraphic surfaces from a local or global model that acts as a proxy for age. These data can then be integrated into derived products that provide insight for the exploration workflow.

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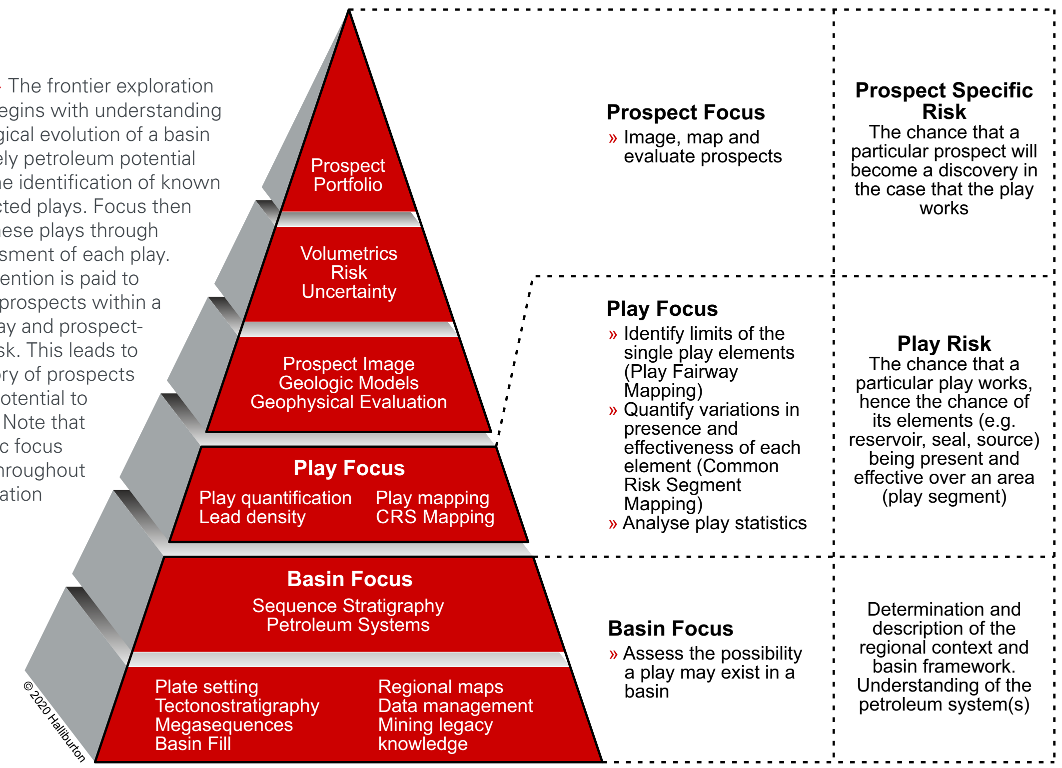
Figure 7 > The frontier exploration process begins with understanding the geological evolution of a basin and its likely petroleum potential through the identification of known and predicted plays. Focus then turns to these plays through risk assessment of each play. Finally, attention is paid to individual prospects within a play fairway and prospect-specific risk. This leads to an inventory of prospects with the potential to be drilled. Note that geographic focus tightens throughout the exploration process.



Gross Depositional Environment Maps

One approach to integrating seismic and well/outcrop data, and regional geology, is through the use of gross depositional environment (GDE) maps (Figure 8). These depict the sedimentary facies that are known or predicted to have been deposited at a given time.

The location of sedimentary facies varies greatly through time, so it is useful to depict GDE maps with a fair degree of temporal precision. Here, sequence stratigraphy can play a major role, with maps drawn on maximum flooding surfaces (MFS) (relative highs of sea-level) and maximum regression surfaces (MRS) (relative lows of sea-level), capturing the depositional limits of maximum progradation and retrogradation. Other systems tracts can be depicted as required.

To construct GDE maps based on sequence stratigraphy, any data used in constructing the maps must be attributed with the sequence stratigraphic model being used. Temporally-constrained sequence stratigraphic surfaces can be identified (picked) in well, outcrop and seismic data, with reference to lithology and depositional environment. These can provide the basic framework for GDE mapping, which integrates data and interpolates between data (Figure 8).

GDE mapping can be further supported by Earth systems science approaches that consider palaeoclimate, and source-to-sink depositional processes (Figure 5). Amplitude extractions from 3D seismic volumes can also be a powerful tool. In the future, we may expect to see process-based sedimentological understanding contributing more substantially to GDE mapping. Forward stratigraphic modeling provides a means of determining a 3D sedimentary model of the subsurface by integrating data with the controls on depositional processes such as sediment flux, subsidence and relative

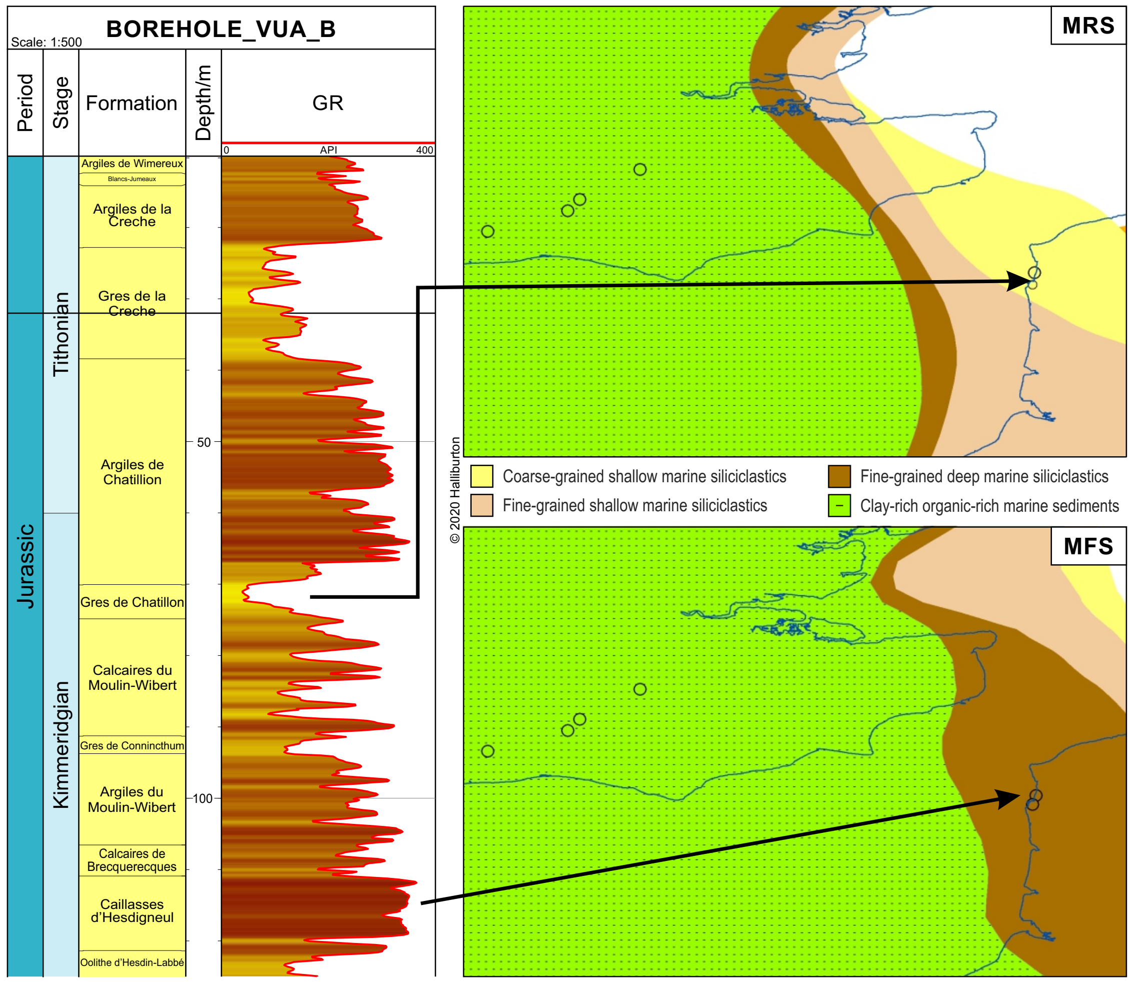


Figure 8 > A pair of gross depositional environment (GDE) maps for a sea-level high (MFS) and sea-level low (MRS) in the Late Jurassic of north-western Europe. Identification of sequence stratigraphic surfaces in a well provided constraint for the maps, which were constructed from a large number of well and outcrop data points, along with (as available) seismic facies, tectonic elements and models of drainage and currents.

sea-level change. From such 3D models, 2D GDE maps can be extracted.

GDE maps represent what was deposited, but to be fully effective, they need to be integrated with a depiction of preservation limits. For example, this includes taking into account subcrop preservation limits beneath unconformities. Gross thicknesses, but ideally net thicknesses, of depositional facies are also a key consideration to be integrated with GDE maps, as potential source rocks, reservoirs and seals have minimum absolute viable thickness limits. This information can be determined from the data used in GDE map construction (e.g. well thickness), but ideally needs combining into an isopach map.

GDE maps and related preservation limit and isopach maps are often stacked to generate an interval map in which the maximum preserved depositional extent and thickness of a key reservoir, source rock or seal facies are captured. These later form the feedstock into the CRS mapping process.

Subsurface Maps

Structure depth maps depict the present-day depth of burial of a particular stratigraphic horizon. They can be used to depict the depth of a key source rock or reservoir, and to draw inferences about source rock maturity or reservoir effectiveness. This is especially so when integrated with an understanding of the geochemistry of a particular potential source rock and its burial history, or the likely changes in rock properties of a reservoir at depth. Not all rocks are currently at their maximum burial depth, and they may have experienced a varied tectonic history. Thus, integration with structural modeling is also important.

Chronostratigraphic Charts

A full stack of GDE maps captures the depositional history of a basin. Another way of depicting this is through use of chronostratigraphic charts that depict the geographic distribution of facies along a transect, through time. They typically show only the preserved rock record, and provide insight into play concepts, and the likely geology that a well might encounter at any given location. While chronostratigraphic charts are usually produced manually by interpolating between wells/outcrops using sequence stratigraphic principles, they can be also be generated from forward stratigraphic models.

Play Cross Sections

Alongside chronostratigraphic charts, play cross sections are useful, as they capture the depositional history of a basin in depth, as opposed to in geological time. They usually begin as geo-seismic sections, where a seismic line is overlain with the geology it represents. Once the seismic data are depth

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converted, the section can be regarded as a play cross section, and with knowledge of geothermal gradient, oil and gas generation windows can be added. Moreover, they are an excellent means of capturing play concepts and visualizing the link between various play elements, especially source, reservoir, seal and trap.

Common Risk Segment Mapping

Having established the geological history of a basin or region, and the likely pattern of sedimentary fill, work can now proceed on assessing the potential plays in the basin. These can be extensions of existing plays, analogue play concepts from other, similar basins, or completely novel ideas. In all circumstances, the same set of basic questions about play risk need to be answered:

- What is the extent of a potential viable source rock with hydrocarbon generation potential? Where is it likely to be mature (for oil and/or gas), and what are the likely migration limits for hydrocarbons from the kitchen?
- What is the extent of a possible reservoir and where will it be effective (i.e. not deep enough that porosity and permeability are occluded)?
- What is the extent of a possible seal and where will it retain its integrity?

Such questions can be answered by CRS mapping (Figure 2), and definition of the play fairway — the basic high-graded area in which all the key elements of a play are thought to work. This play fairway can then scrutinized in detail to identify specific drillable traps (i.e. prospects), that will carry their own prospect-specific risk (White, 1993).

Prospect Evaluation

For each viable prospect, a well prognosis is created, which predicts the likely stratigraphy that will be penetrated. This is built from the regional geological understanding and depositional history that was created as part of the screening process. The well prognosis can highlight drilling hazards and information regarding the reservoir.

The potential value of a prospect is calculated from the volume of the recoverable hydrocarbons present, risked against the likely play risk and prospect risk. Thus, a prospect may be said to have 500 million barrels of oil recoverable at a risk of 1:10. An oil company will keep a prospect inventory, ranked by risk versus reward, along with geopolitical considerations, and the overall reward and risk of a play.

If a prospect in a new play is successful it may open up the play to the drilling of more prospects and a greater prize overall. For example, the Zohr discovery of 2015 was a play opener in the Eastern Mediterranean. It led to other prospects in the same play fairway being successfully drilled in the basin, where isolated Cretaceous/Miocene carbonate reefs were charged with biogenic gas and sealed with Messinian evaporites.

SUMMARY AND LOOK AHEAD

Frontier exploration is founded upon a sound understanding of the geological history of a basin, which enables play concepts to be identified for exploration (Figure 7). Geological context and the identification of analogues inform this process. Play concepts are evaluated by assessing the risk on the various geological components that comprise the play — reservoir, charge and seal. This creates a high-graded play fairway in which the prospects for drilling can be sought. The size and number of prospects informs the likely yet-to-find volume of hydrocarbons within the basin and the play, allowing these to be ranked within a company's exploration portfolio.

Knowledge and integration of a variety of data types and geoscience specialisms is key to the success of this process. Explorationists predict the subsurface. Thanks to improvements in technology, data availability and quality, and, not least, geological understanding, arising from an integrated geoscience approach, predictions are becoming more accurate. The digital transformation of exploration that facilitates this process is already well underway (for example, our DecisionSpace® 365 FairwayFinder application). This will enable more subtle exploration objectives such as stratigraphic traps to be identified. These can be hard to recognize in seismic data. A digital subsurface model, informed by geological context and supported by machine learning, could incorporate tools to identify the subtle geometries in seismic volumes, estimate rock properties, and establish play concepts.

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