THE BIGGEST RISKS IN HYDROCARBON EXPLORATION THAT ARE OFTEN OVERLOOKED: CASES OF EXPLORATION FAILURES IN INDONESIA AND THE SOLUTIONS

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ABSTRACT

Petroleum system analysis is a method commonly used by geoscientists to assess the possibility of an area containing petroleum. But the levels of analysis of the elements and processes of a petroleum system are often unbalanced. Some aspects are analysed in detail while others are overlooked. These overlooked aspects often turn out to carry the highest risks for exploration.

The author reviewed multiple cases of exploration failures in Indonesia post-2000 and found that these failures are generally related to an overlook of some elements and processes of the petroleum system. This includes the tendency to think of seismic low as a kitchen, being too optimistic in doing basin modelling, assuming that it is sufficient if kitchens have generated hydrocarbons whereas expulsion threshold is more critical, not mapping migration pathways in detail, and not evaluating carrier beds and regional sealing.

Revisiting the petroleum system analysis method, carrying out a more balanced analysis for all elements and processes of the petroleum system, and reconstructing it with the tectono-sedimentary evolution of the basin where the exploration area is located from its formation to the present day (dynamic interpretation) are the solutions offered. Hopefully these solutions can reduce exploration failures and increase success in Indonesia and other areas.

INTRODUCTION

Petroleum exploration is supported by a method called petroleum system analysis, which examines, characterizes and integrates the elements and processes in nature that are at the origin of petroleum accumulations (Magoon and Dow, 1994).

In addition, there is also the risk analysis method for petroleum accumulation to form in nature, which has been developed based on petroleum system analysis (e.g. Otis and Schneiderman, 1997). This method examines the risk or opportunity of each element and processes in the petroleum system to form, carry, or accumulate petroleum. The end result is a probability of success for a prospect to contain a predefined volume of petroleum.

With the two methods, namely petroleum system analysis and risk analysis, geoscientists seeking for petroleum are equipped with sufficient and scientifically tested methods to search for petroleum.

Nevertheless, petroleum exploration failures still occur frequently. This of course has many reasons. This is what this paper will focus on: (1) reviewing the methods of petroleum system analysis and risk analysis, (2) examining how geoscientists apply those methods in petroleum exploration, (3) examining other factors at the origin of exploration failures. Several cases in Indonesia will be presented to demonstrate this. In the discussion section, several issues related to petroleum system analysis are addressed which hopefully will help reducing the risk of exploration failure and increase exploration success.

METHOD

This paper is written based on case studies of exploration failures in Indonesia which have occurred since 2000. The author of this paper has reviewed and published papers on regional evaluations of major exploration successes and failures - in areas that are geologically, in an exploration point of view, important and interesting (Satyana, 2016). This publication was updated in 2020 (Satyana, 2020a) for the purposes of the Jakarta Scout Check meeting. In 2020 the author also gave a webinar with a limited exposure about the biggest risks in petroleum exploration (Satyana, 2020b). The three publications, both in the form of paper and webinar materials, are the main references for this paper.

In addition of the standard method of petroleum system analysis and risk analysis, the author refers to the publications of Magoon and Dow (1994) and Otis and Schneiderman (1997) respectively. A review is conducted to these methods considering the reasons for dry wells.

To summarize, this paper draws on case studies, with reviews of existing methods of petroleum system analysis and risk analysis based on input from these cases, and then addresses the issues identified with a range of solutions to improve the process.

RESULTS

Petroleum System Analysis

The world's petroleum industry has grown from the mid-1800s. Oil fields were initially discovered around the world based on the natural occurrences of surface seeps, then drilled to extract more oil than simply collecting it from surface seeps. The business in Indonesia began to be carried out in the 1870s and 1880s located in West Java and North Sumatra. However, oil as fuel was only felt to be important at the turn of the 20^{th} century when the combustion engine was invented and the oil was its prime mover. Thus, the application of geology to petroleum, particularly petroleum exploration, began to develop in early 20^{th} century.

The geological concepts for petroleum occurrence in consideration until the mid of 20th century are reported in the classic book Geology of Petroleum (Levorsen, 1958). Until that time, it had been understood that if an oil/gas field is found in subsurface, it means: (1) there has been a supply of petroleum to the field originating from somewhere, (2) the supply is concentrated in that field, (3) there is a mechanism to keep the accumulated petroleum from being lost and damaged. In this book, it is mentioned that there are four processes related to the occurrence of petroleum in subsurface: its origin, migration, accumulation, and preservation. The book discusses the elements of rocks that play a role in the occurrence of petroleum, namely reservoir rocks, sealing rocks, traps, and rocks containing organic substances to form petroleum (later named source rocks). So the geoscientists at that time were already likely looking for a petroleum accumulation by analysing a number of those geological elements and processes.

The elements and processes at the origin of petroleum occurrence in nature were subsequently progressively standardized from the 1970s to early 1990s with the introduction of the concept of petroleum system. The methods of petroleum system analysis are discussed in a landmark memoir of the American Association of Petroleum Geologists (AAPG): The Petroleum System - From Source to Trap (Memoir 60) - Magoon and Dow (editors, 1994).

The petroleum system is a naturally occurring hydrocarbon-fluid system in the geosphere. It encompasses a pod of active source rock (provenance) and all related oil and gas, and includes all the essential elements and processes needed for oil and gas accumulations to exist (Magoon and Dow, 1994). Elements in petroleum system are all rocks involved in the occurrence of petroleum, namely: source rock, reservoir rock, seal rock, and overburden rock. Processes in the petroleum system mean geological and geochemical processes involved in the occurrence of petroleum, namely: trap formation, generation/migration/accumulation of petroleum, and preservation of accumulation. The geological time relationships between all elements and processes of the petroleum system are shown in the petroleum system events chart, while the spatial relationships are shown in geological sections (Figure 1).

Geoscientists exploring for petroleum always use this petroleum system analysis method, examining every element and process of petroleum system to evaluate the possibility of petroleum occurrences in the subsurface.

Risk Analysis

The main objective of the risk analysis is to examine the risk associated with each element and process of the petroleum system. A petroleum prospect certainly contains risks for failure (ie. the prospect does not contain petroleum), as well as geological chance for success (ie. the prospect contains petroleum). To determine the probability of success or failure of a prospect to contain hydrocarbons, it is necessary to assess the risk factors.

Otis and Schneidermann (1997) published one method for risk- or chance-opportunity assessment based on the petroleum system analysis. This method was then widely applied and became the basis for the risk/opportunity assessments carried out by many companies. This risk/opportunity assessment is only the initial method of a series of processes to assess a prospect in detail, which includes: geological risk assessment, volumetric estimation, engineering support, and economic evaluation.

Those related risk/opportunity assessments based on the petroleum system are called geological risk assessments. Otis and Schneidermann (1997) classified the assessment of the elements and processes of the petroleum system into four factors: source, reservoir, trap (including seal), and dynamics (timing/migration). Risk assessment assigns a probability of success to each of these four elements and multiplication of these probabilities yields the probability of geological success.

For each factor, a checklist is given that contains aspects that need to be assessed from that factor (Figure 2). For source rock, this includes: capacity for petroleum charge and source rock maturity. For reservoir, this includes: presence of reservoir and quality of reservoir (capacity for stabilized flow). For trap, this includes: trap definition (confidence in data), trap characteristics, and seal. For timing and migration, this includes: timing, migration pathways, preservation/segregation.

The authors provide a number as a guideline for assessing each aspect of the petroleum system based on favourability (Figure 2). The value is < 0.30 if the risk factor contains unfavourable element(s); the value is 0.30-0.50 if one or more elements are questionable; the value is 0.50 if the elements are unknown or no definitive data (neutral); the value is 0.50-0.70 if all elements are at least encouraging to favourable; and the value is > 0.70 if all elements are well documented and encouraging to favourable.

Finally, the authors also distinguish risks based on the status of the investigation area from frontier areas with minimal data and where the exploration concept has not been proven, until mature areas which has many petroleum fields. The frontier area will of course be very high risk (averaged probability of geological success Pg 0.05) while the mature area will have very low risk (averaged probability of geological success Pg 0.75).

Because the probability of geological success is the product of the four probabilities of source rock, reservoir, trap, timing-migration, the weakest probability (or the greatest risk) has a strong impact on the probability of geological success. For example, if the probability value for source rock, reservoir and trap are 0.75 (very low risk) respectively, while the probability of timing-migration is only 0.20, then the overall probability of geological success will be only 0.08 (ie. 0.75x0.75x0.75x0.20 = 0.08, a very low probability of success).

DISCUSSION

Unbalanced Petroleum Systems and Risk Analyses

The petroleum system analysis and risk analysis methods, as described previously, rely on a balance analysis of each of the elements and processes. However and in reality, the analysis cannot be carried out in a balanced manner. There are elements and processes that are analysed in detail, but there are also several elements and processes that are only estimated without analysis. This is mainly due to data availability.

Magara (1981) wrote that there are seven important factors that must be evaluated in petroleum exploration, namely: (1) reservoir and effective pore spaces, (2) traps, (3) seal or cap rock, (4) secondary hydrocarbon migration, (5) primary hydrocarbon migration, (6) hydrocarbon generation and maturation, and (7) source rock. Although it would be ideal to have sufficient information/data for all of these factors, Magara (1981) observed that usually, the amount of available data decreased from factor 1 to factor 7 (Figure 3). This remains true forty years later as this paper is written.

From observations made by the author following his 20 years of employment with BPMIGAS and SKK Migas, many E&P companies mature their prospects with detailed analyses for only two factors, namely reservoirs and traps. It is easy to understand this because the most available data companies have only cover traps and reservoirs. For the sealing rock however, although it is part of the trap and there are seismic data/wells that penetrate it, it is rarely characterized in detail. The source rock factor - kitchen, dynamic factor (timing and migration) - are usually discussed simply, are oversimplified, and are often misleading. It is not uncommon that areas of mature source rocks (kitchen) and their migration areas (fetch areas) are outside the working areas of the companies, so the analysis only relies on regional data or just speculation.

The absence of sufficient data for several factors (elements and processes) of the petroleum system has two main consequences: (1) immature evaluation, and (2) oversimplification of the problem. This has become the biggest risk in petroleum exploration. Unfortunately, this problem is classic and has yet to find a sufficient solution. Source rock is a very important, if not the most important, element in the petroleum system because that is the source rock which contains petroleum. If reservoir is of poor quality, or the trap is not definitive, you can move to a prospect with a better trap and reservoir quality (based on study and where sufficient data are available). But if there is no mature source, and there is not enough expulsion of generated petroleum, then there is no migration of petroleum to the traps, even if the prospect is a large trap with estimated excellent reservoirs. In fact, the analysis of source rock, its maturation, and generation-expulsion-migration of petroleum from mature source rock to trap have been minimally evaluated if not oversimplified and is frequently speculative.

Revisiting Petroleum System Analysis

As noted above, petroleum systems are described spatially in the geological section or temporally using events chart, which only lists elements of: source rock, reservoir rock, seal rock, overburden rock; and processes of: trap formation, generation/migration/accumulation, and preservation.

Actually, there are two additional elements of petroleum system which are the extensions of reservoir rock and seal rock on the route toward the trap, and which describe the connectivity of the kitchen and the trap: rock for media of migration (carrier bed) and rock for roof or sealing of migration (sealing of carrier bed).

In order for a large amount of expulsed petroleum from mature source rock in the kitchen to enter the reservoir rock in the trap, there must be a good flow/migration of petroleum through a carrier bed of good quality (porous and permeable). This is critical so that the flow of petroleum does not decrease or there is a lot of loss due to leakage. There must be also a rock sealing the migration media or sealing rock of the carrier bed. The more homogeneous, porous, and permeable the carrier bed, the more volume of petroleum migration. The more homogeneous the sealing carrier bed, the smaller the potential loss volume of migrated petroleum. Seismic data can be used to check the homogeneity and degree of deformation of the carrier bed and sealing rock of the carrier bed. The more minimally the carrier bed and sealing of the carrier bed are deformed, the better the petroleum migration will occur from the kitchen to the trap, as long as there is a regional dip from kitchen to trap. However, the carrier bed deformation can also transfer volumes of migrated petroleum to younger carrier bed layers and eventually charge trap with younger reservoir rock. In this case, petroleum migration occurs through faults that deform between carrier beds.

This full version of the petroleum system (Figure 4) also connects spatially the six elements of the petroleum system (source rock, overburden rock, carrier bed, sealing of carrier bed, reservoir rock, and seal rock of trap) with the four processes of the petroleum system (formation of trap, maturation of source rock, generation of petroleum, expulsion and migration of petroleum out of source rock to trap, preservation of petroleum accumulation within trap). The temporal relationship is shown in the petroleum system events chart as presented by Magoon and Dow (1994) but with an additional elements of carrier bed and sealing of carrier bed, and process of maturation of source rock.

With this full version of the petroleum system, it is hoped that all the factors (elements and processes) involved in the occurrence of subsurface petroleum accumulation have been listed and included in the petroleum system analysis checklist. But as other analyses performed outside of the reservoir and trap are minimal, analyses for carrier bed and sealing of carrier bed are minimal to none too. This makes the factor of petroleum migration one of the biggest uncertainties in petroleum system analysis.

Seismic Low Area is Not Necessarily Kitchen Area

Many geoscientists regard the seismic lows in the horizons known as bearing source rocks as potential kitchens. In fact, seismic lows could be the product of a recent tectonic event, while at the time of deposition of the formation, the location was in fact a high area (Figure 5).

Good source rock is usually formed in original depressions. Those depressions are often anoxic environment which results in the preservation of organic matter in the absence of oxygen (Figure 5). On the other hand, original high areas are not optimal locations for preservation of organic matter because their oxic condition causes oxidation of organic matters. The low areas as time of formation of the source rock which do not become high areas in the next period before being covered by younger rocks (so that the preserved organic matter is not later oxidized) are good candidates to host active kitchen areas when those area reach maturity.

So in case readers identify a present day seismic low area, do not immediately think of it as a kitchen area because it might initially be a high area that did not preserve organic matter. When readers map the present seismic low area, before assuming it as a kitchen area, flatten the seismic horizon of the top of the formation that is thought to contain the source rock. Then see after flattening whether at approximately the source bed level it shows a depression. If a depression exists, the source bed can be presumed to contain good organic substances. Flatten one more time on the seismic horizon above it to see if the source bed remains in the depression area so that the organic matter is preserved. When the flattened source bed is in a high area, it is very likely that no organic matter will be deposited in it because oxidation in the high area will damage the organic matters.

Basin Modeling Should Be Rechecked in Geologic Context

Basin modeling must use logical parameters and assumptions. After the results are known, it must be checked whether the modeling is geologically reasonable. In many cases the results of modeling are geologically unreasonable, meaning that parameters and assumptions used are not appropriate.

This is exemplified by a petroleum system events chart for the Halmahera Basin (Ryan et al., 2012) (Figure 6). Source rocks are said to be Middle-Upper Miocene age with maturation interpreted to be syn-deposition. The author believes this is illogical. The timing of source maturation is based on basin modeling so the input parameters for the modeling should be re-examined.

Another case is from South Sumatra Basin. The source rock is the lower Talang Akar and is of Upper Oligocene age. Several basin modeling results show that there has been a generation of these rocks in the Middle Miocene age and some even earlier in the Lower Miocene. This is geologically unreasonable because the deposition of overburden rocks that will mature the lower Talang Akar source rock in the Lower Miocene or Middle Miocene is not thick enough to bury the Talang Akar source rock to reach the oil window. Even without doing any basin modeling, it is geologically more logical to expect the Talang Akar source rock to enter the maturity zone in the Upper Miocene after the deposition of the Gumai and Air Benakat formationsso that the main migration occurs in the Pliocene.

In general, geoscientists are less likely to re-examine their basin modeling results based on the geological and stratigraphic evolution of the basin and tend to model basin models with earlier maturation of the source rocks. Modeling needs to be put into a geological context for proper interpretation.

Dembicki Jr. (2009) also suggest using a vitrinite reflectance [VR, Ro (%)] cut off for maturation value that matches the dominant kerogen type in a basin for evaluation of maturity rather than using a general VR value (0.5-0.6% of Ro). Adjusting the onset of significant hydrocarbon generation based on VR value for kerogen type is as follows: kerogen Type I: 0.7 Ro (%), Type II: 0.6 Ro (%), Type IIS: 0.45-0.5 Ro (%), Type III: 0.8 Ro (%).

Petroleum Expulsion Is More Important Than Petroleum Generation

There is important issue regarding petroleum generation and expulsion from source rock that geoscientists generally do not realize. It is that the main phase of oil expulsion only happens until around 40% generation has occurred (Hunt, 1996). Oil generative source rock with average initial S2 > 5 kg/ton and average initial TOC > 1.5% are efficient in expelling 60-90% of their generated oil at temperature between 120-160 °C. Meanwhile, oil generative source rock with S2 < 5 kg/ton and TOC < 1.5% are less efficient in expelling only up to 40% of their generated oil. Un-expelled oil resides in the source rock, to be cracked and ultimately expelled as a high GOR (gas oil ratio) gaseous phase if it is exposed to much higher maturity (>160 °C). (S2 is source potential to generate hydrocarbon in catagenetic maturation window, TOC is total organic carbon – parameters of rock pyrolysis in geochemical laboratory).

Petroleum generation depends upon both the temperature to which kerogen has been heated and the duration of the heating. The conversion of kerogen to petroleum results in a significant volume increase. This causes a pore pressure build up which is sometimes large enough to result in micro-fracturing. This releases pressures and allows the migration of petroleum out of source rock into adjoining carrier beds, from which secondary migration processes take over. Cycles of petroleum generation, pressure build up, micro fracturing, pressure release, petroleum migration continue until the source rock is exhausted.

The implication of this theory is that mature source rock will always expel petroleum as long as they are rich enough. But a lean oil prone source rock may not generate sufficient hydrocarbon to cause micro fracturing. As a result, no expulsion will occur. If raised to higher maturity however, the oil that has remained in the source rock will be cracked to gas.

If there is no expulsion of petroleum due to the lack of generation in the source rock, there will be no migration of petroleum, so there will be no accumulation of petroleum into the trap. Therefore, the parameter of petroleum generation that is very important besides temperature level is the duration of the maturation process itself, how long the source rock is exposed to a certain temperature, whether the duration of maturation is sufficient to produce at least 40% of the volume of petroleum generation for expulsion and petroleum migration to take place.

Often for a proposed exploration well, a geological section (present time) is shown which shows the configuration of the basin with the location of the prospect to be drilled and an approximate depth of the kitchen completed with a line drawn at one depth of top of oil window and then another line as depth of top of gas window (Figure 7). Depths of top of oil and gas windows are usually based on vitrinite reflectance data from previous exploration wells. Usually, a geological section like this is considered quite satisfactory, but actually it is still not related to the things described above.

The first is that the geological section is constructed at the present time. Present time is not significant for the petroleum system because almost all elements and processes of the petroleum system occur in the geological past. Second, it is more important to know how long the source bed has been in the oil-gas window to estimate whether there is sufficient volume of petroleum generation from the source bed so that there has been expulsion and migration of petroleum going into the trap/prospect proposed to be drilled. The above cannot be captured using a geological section of the present time. We would rather advise the construct a section showing the kitchen setting at the time of optimum expulsion and migration (Figure 7).

Carrier Beds and Their Sealing Should Be Evaluated

As described in the section of Revisiting Petroleum System Analysis, the carrier bed and its sealing are the critical elements for an optimal petroleum migration to occur. The carrier bed and its sealing are the link between the pod of active source bed (kitchen) and the trap. So, if they are not present or their function as a petroleum migration medium is not working properly, then there will be no accumulation of petroleum in the available traps or accumulations may be present but insignificant.

Unfortunately, those elements of the petroleum system are never or rarely evaluated. The absence or lack of data to characterize them is the main reason they are not evaluated. A working area is sometime at up dip position outside of carrier bed area (Figure 8). Wells usually do not exist to penetrate them because the wells are not placed to test the migration media. However seismic data are usually available. This seismic data can be used to characterize them based on their internal seismic characters. The seismic data can show the homogeneity or heterogeneity of the carrier bed and its sealing, the quality of the carrier bed (porosity and permeability) and its sealing bed impermeability, if necessary, advanced seismic processing is carried out to know this. The deformation intensity of the migration media layer can also be revealed from the seismic data. The intensity of deformation such as the presence and pattern of faults can affect migration pathways.

That is the least that can be done to examine the elements of the carrier bed and its sealing in the petroleum system analysis. This can increase the confidence in the petroleum system analysis and risk analysis. If this is not done, it will usually be oversimplified that the migration path, carrier bed and its sealing, does not bear any concerns.

Migration Pathways Should Be Mapped

Migration concentrates hydrocarbons into specific subsurface sites where they may be commercially produced. There are two main driving forces for migration: (1) buoyancy caused by the density difference between oil (or gas) and the formation waters within the pores of the carrier beds, (2) pore pressure gradients which attempt to move all pore fluids (both water and petroleum) to areas of lower pressure (generally the high areas of the subsurface). The main resistive forces for migration are capillary pressures which increase as pore size become smaller. When capillary pressure exceeds the driving forces, entrapment occurs. The factors which control the migration pathways are not yet completely clear, although migration may be simplified as a type of percolation of petroleum through a water wet carrier bed. The natural buoyancy of migrating petroleum provides a force that drives oil and gas on average, up dip. Capillary forces however will encourage petroleum to utilise the coarser regions of the carrier bed with the lowest pore entry pressures.

Migration pathways from identified kitchen to available traps should be mapped and not in the form of straight arrows in contour map (Figure 9). Petroleum will tend to move perpendicular to structural contours (ortho-contour) since this direction is the low pressure in subsurface therefore petroleum flow along regional highs (regional noses) and may be split to avoid a low area in subsurface (migration shadow area). Ortho-contours should actually be constructed for the actual/optimum time of migration which is usually in the geologic past. Flattening with a datum of horizon at optimum time of migration, and isopaching between this horizon and the horizon of the carrier bed can be used to model paleo-migration. Most of modelling of migration pathways today are conducted on time structure map of reservoir horizon (present time map) which is, in most cases, not the time of occurrence of the optimum migration. Present day structure map may be used to model present day migration, which remains barely significant. Significant migration usually took place between 15 to 5 Ma in most Tertiary basins of western Indonesia, therefore ortho-contour maps should be reconstructed for this period.

Faults also affect migration pathways. Lateral migration will tend to be inhibited by the presence of faults, since they interrupt the lateral continuity of the carrier bed. Sealing faults may deflect petroleum flow laterally. Non-sealing faults allow petroleum to flow across the fault plane into juxtaposed permeable units at a different stratigraphic level. Fractures formed in either the footwall or hanging wall, if they remain open, may form effective vertical migration pathways. This may occur in the uplifted hanging walls of compressive faults on release of compressive stresses. Tensional fractures in the crestal zones of anticlinal structures may also allow migration of petroleum.

Reconstructing Petroleum System with a Dynamic Interpretation

Most of the events of petroleum system elements and processes from source deposition to preservation of accumulation took place in geologic history. One should think of the geology, geophysics, geochemistry for all elements and processes of petroleum system historically (in geologic time). Reconstruction of the petroleum system is the key to do this (Figure 10).

Magara (1981) introduced the way to reconstruct the factors that now more generally refer as elements and processes of the petroleum system, referring as dynamic interpretation. The presence of all factors necessary for petroleum exploration (reservoir and effective pore spaces, trap, seal or cap rock, secondary hydrocarbon migration, primary hydrocarbon migration/expulsion, hydrocarbon generation and maturation, source rock) in a certain area currently does not necessarily indicate a petroleum accumulation. Most people discuss these factors in terms of their current presence or absence, as well as their extent and their effectiveness. If the timing of their occurrences was not appropriate, petroleum either could not accumulate properly or was later lost. The importance of the geologic timing of development or destruction of these factors should be discussed. Proper interpretation of the relative timing of these geologic factors may help the readers to discover more petroleum accumulations.

Two basic methods express the historical nature of a rock. The first method analyses the geologic age of the rock at the present time. For a given rock formation, only one geologic age can be inferred. Such a method of historical analysis presents a static view of the geology. The second type of historical analysis is based on the concept of successive historical changes. It is one that can be important in petroleum geology. The latter may be called a dynamic analysis of the rock because, for a given sample of rock, a series of historical interpretations, with regard to change in rock properties, can be made.

Processes of sedimentation of source, seal, reservoir and overburden rock, maturation of source rock, generation and expulsion of petroleum from source rock, migration of petroleum, formation of trap, charging of trap by migrated petroleum, and preservation of accumulation are historical processes, therefore one should evaluate these historically using a dynamic interpretation. What is needed for historical analysis of each element and process of petroleum systems is dynamic information but what is mostly available is merely the static information that applies to the present time. It is therefore recommended that petroleum geologists use these static data to reconstruct the evolution through time in order to obtain a picture of the geologic past.

Dynamic interpretation can be conducted through reconstruction of elements and processes of petroleum system successively through the geologic ages since the time of deposition/formation until present time. It is a complex endeavour, but that is how it should be done. Due to mostly lack of data, not all reconstructions can be conducted in detail. However, if the elements and processes of the petroleum system can be reconstructed, then it should be done.
Ideally, the following reconstructions should be done in dynamic interpretation (Figure 10).

- Reconstruct tectonics of the area (basin evolution, tectonic evolution).

- Reconstruct paleogeography and geologic evolution of the area dynamically at successive geologic ages.

- Reconstruct source facies at the time of source deposition.

- Examine the possibility of source deposited in anoxic/suboxic/oxic environments.

- Reconstruct the deposition of reservoir, carrier and sealing beds.

- Reconstruct the subsidence history of source pod (burial history plot with right and reasonable inputs).

- Reconstruct formation of traps.

- Reconstruct generation of petroleum from source pod, determining time of optimum migration.

- Reconstruct paleo migration at the time of optimum migration and examine its successive pathways through geologic ages.

- Reconstruct critical timing between time of charging and formation of trap.

- Reconstruct successive geologic occurrence of accumulation, determining its preservation or destruction through geologic ages until present time.

Even minimal level reconstruction provides great insights because the factors that caused the accumulation of hydrocarbons did not occur at present time but in the geological past. Therefore, the reconstruction of the petroleum system needs to be carried out.

CONCLUSIONS

Petroleum exploration is based on two methods, namely petroleum system analysis and risk analysis, which in an integrated manner can help assess exploration potential, opportunities and risks. However, due to various reasons, there is great disparity in the level of detail those analysis are performed on the elements and processes of a petroleum system. Reservoir and trap are the most matured factors, while other factors are often oversimplified or neglected and are usually considered positive. This is what the author believes is at the origin of most failures in exploration.

Several analytical suggestions are brought forward in this paper for those factors that are often oversimplified or neglected. Some misleading concepts are discussed so that the readers increase their level of awareness and get more careful and accurate in their assessment. Reconstruction of the petroleum system in the past (also called dynamic interpretation) is recommended because the processes of petroleum accumulation occurred in the geological past so historical evaluation through successive reconstruction is a must have.

The author is aware that its suggestions may not always be practically possible to implement due to data limitations, however, our words of wisdom to conclude this paper is that the “little that can be done is still better than not doing things at all”.

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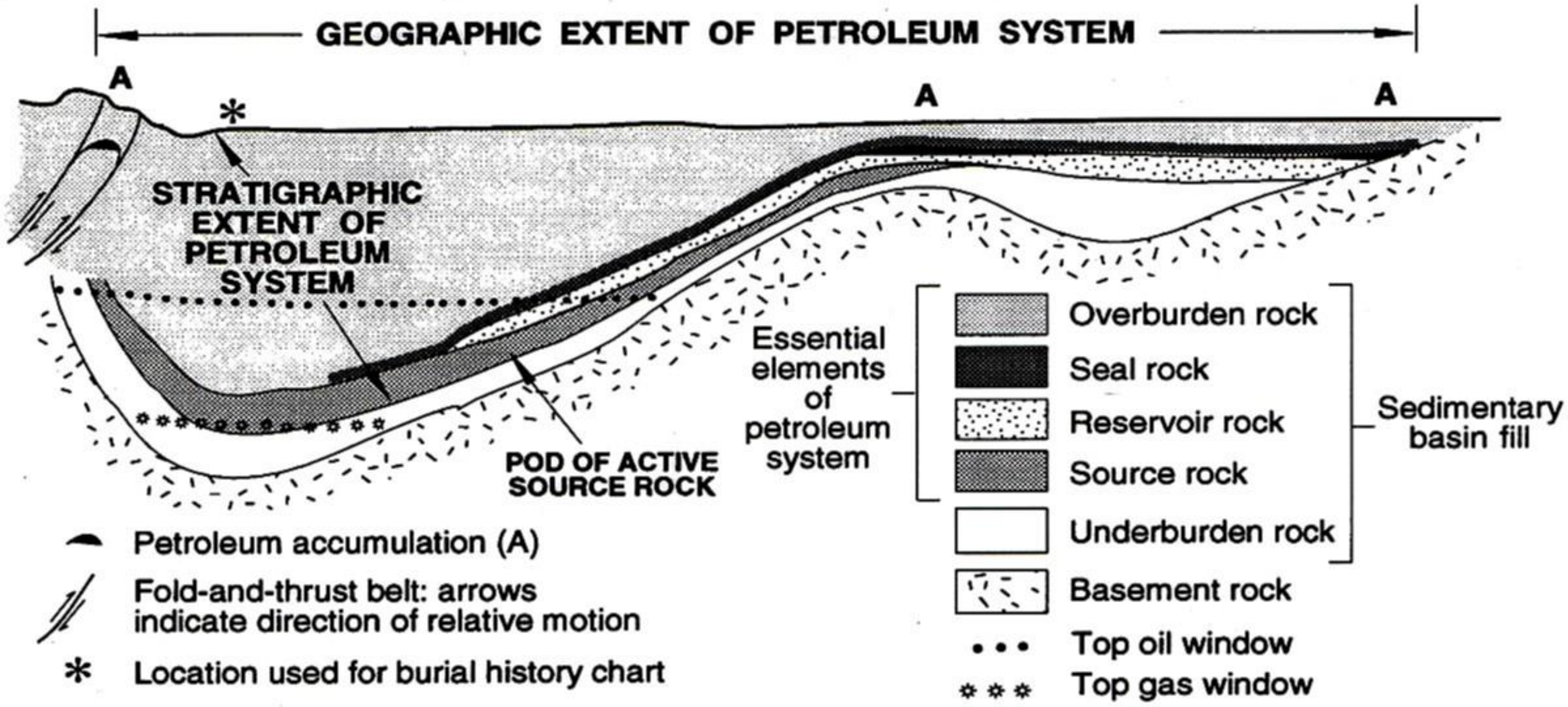
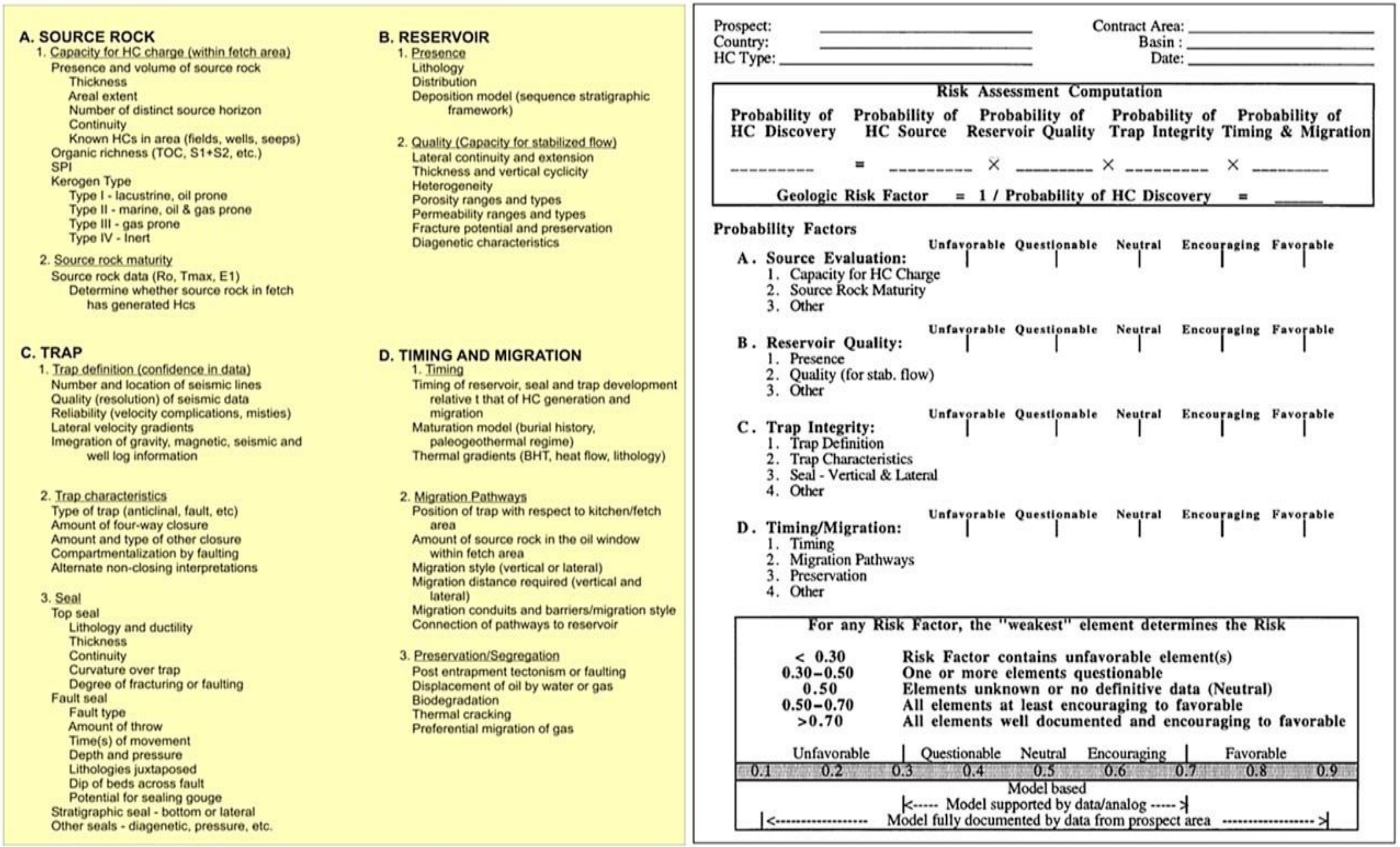


Figure 1 – Petroleum system at its geographic and stratigraphic extents (Magoon and Dow, 1994). Geographic extent is determined by similarity in oil characteristics across the area. Stratigraphic extent involves essential elements (rock units) of petroleum system (source, reservoir, seal, overburden rocks). Petroleum formation and trapping in sedimentary basin is illustrated by this schematic section.



A. SOURCE ROCK

1. Capacity for HC charge (within fetch area)
   - Presence and volume of source rock
     - Thickness
     - Areal extent
     - Number of distinct source horizon
     - Continuity
     - Known HCs in area (fields, wells, seeps)
   - Organic richness (TOC, S1+S2, etc.)
   - SPI
   - Kerogen Type
     - Type I - lacustrine, oil prone
     - Type II - marine, oil & gas prone
     - Type III - gas prone
     - Type IV - Inert
2. Source rock maturity
   - Source rock data (Ro, Tmax, E1)
     - Determine whether source rock in fetch has generated Hcs

B. RESERVOIR

1. Presence
   - Lithology
   - Distribution
   - Deposition model (sequence stratigraphic framework)
2. Quality (Capacity for stabilized flow)
   - Lateral continuity and extension
   - Thickness and vertical cyclicity
   - Heterogeneity
   - Porosity ranges and types
   - Permeability ranges and types
   - Fracture potential and preservation
   - Diagenetic characteristics

C. TRAP

1. Trap definition (confidence in data)
   - Number and location of seismic lines
   - Quality (resolution) of seismic data
   - Reliability (velocity complications, misties)
   - Lateral velocity gradients
   - Imegration of gravity, magnetic, seismic and well log information
2. Trap characteristics
   - Type of trap (anticlinal, fault, etc)
   - Amount of four-way closure
   - Amount and type of other closure
   - Compartmentalization by faulting
   - Alternate non-closing interpretations
3. Seal
   - Top seal
     - Lithology and ductility
     - Thickness
     - Continuity
     - Curvature over trap
     - Degree of fracturing or faulting
   - Fault seal
     - Fault type
     - Amount of throw
     - Time(s) of movement
     - Depth and pressure
     - Lithologies juxtaposed
     - Dip of beds across fault
     - Potential for sealing gouge
   - Stratigraphic seal - bottom or lateral
   - Other seals - diagenetic, pressure, etc.

D. TIMING AND MIGRATION

1. Timing
   - Timing of reservoir, seal and trap development relative t that of HC generation and migration
   - Maturation model (burial history, paleogeothermal regime)
   - Thermal gradients (BHT, heat flow, lithology)
2. Migration Pathways
   - Position of trap with respect to kitchen/fetch area
   - Amount of source rock in the oil window within fetch area
   - Migration style (vertical or lateral)
   - Migration distance required (vertical and lateral)
   - Migration conduits and barriers/migration style
   - Connection of pathways to reservoir
3. Preservation/Segregation
   - Post entrapment tectonism or faulting
   - Displacement of oil by water or gas
   - Biodegradation
   - Thermal cracking
   - Preferential migration of gas

Prospect: ____________ Contract Area: ____________
Country: ____________ Basin : ____________
HC Type: ____________ Date: ____________

Risk Assessment Computation

Probability of HC Discovery		Probability of HC Source		Probability of Reservoir Quality		Probability of Trap Integrity		Probability of Timing & Migration
________	=	________	×	________	×	________	×	________

Geologic Risk Factor = 1 / Probability of HC Discovery = _____

Probability Factors (Unfavorable | Questionable | Neutral | Encouraging | Favorable)

A. Source Evaluation:
1. Capacity for HC Charge
2. Source Rock Maturity
3. Other

B. Reservoir Quality:
1. Presence
2. Quality (for stab. flow)
3. Other

C. Trap Integrity:
1. Trap Definition
2. Trap Characteristics
3. Seal - Vertical & Lateral
4. Other

D. Timing/Migration:
1. Timing
2. Migration Pathways
3. Preservation
4. Other

For any Risk Factor, the "weakest" element determines the Risk

< 0.30	Risk Factor contains unfavorable element(s)
0.30–0.50	One or more elements questionable
0.50	Elements unknown or no definitive data (Neutral)
0.50–0.70	All elements at least encouraging to favorable
>0.70	All elements well documented and encouraging to favorable

Unfavorable | Questionable Neutral Encouraging | Favorable
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Model based
|<----- Model supported by data/analog ----->|
|<------------------ Model fully documented by data from prospect area ------------------>|

Figure 2 – Risk assessment (Otis and Schneidermann, 1997). Left - checklist lists the critical aspects of geologic risk assessment to help ensure all aspects have been considered. Right - worksheet providing a method for transferring qualitative judgments on geologic risk to quantitative probability of geologic success.

- What data cover (in lesser amount): reservoir, trap, seal, migration, kitchen.
- What people know (in lesser detail): reservoir, trap, seal, migration, kitchen.
- The least known element/process of petroleum system may give the biggest risk in petroleum exploration and the weakest part of petroleum system.
- Too much evaluation on reservoir and trap. Too less evaluation on hydrocarbon charging (evaluation on kitchen and migration are over-simplified).

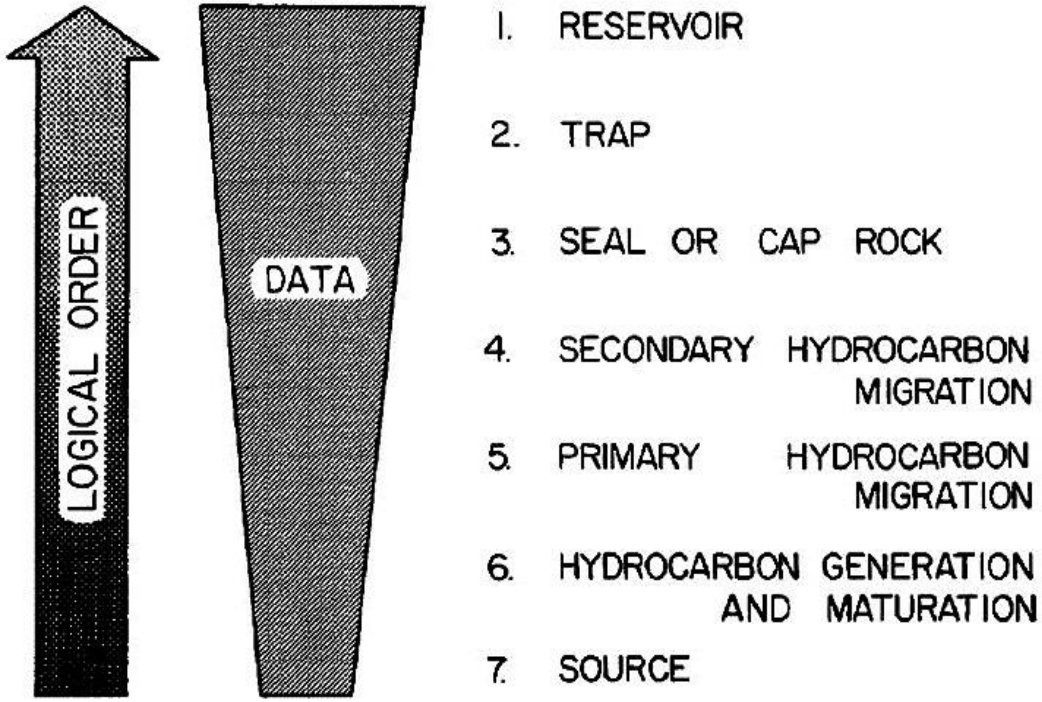


Figure 3 - Diagram showing seven important factors for petroleum accumulation (Magara, 1981). The trend is still similar today. Most of the data available relate to factors that usually exist in the working area and their data in computer (reservoir and trap). Source is usually beyond the working area therefore no data available, and migration process is something cannot be seen accordingly easy to forget or assumed that it exists. These actually cause the biggest risks in petroleum exploration.

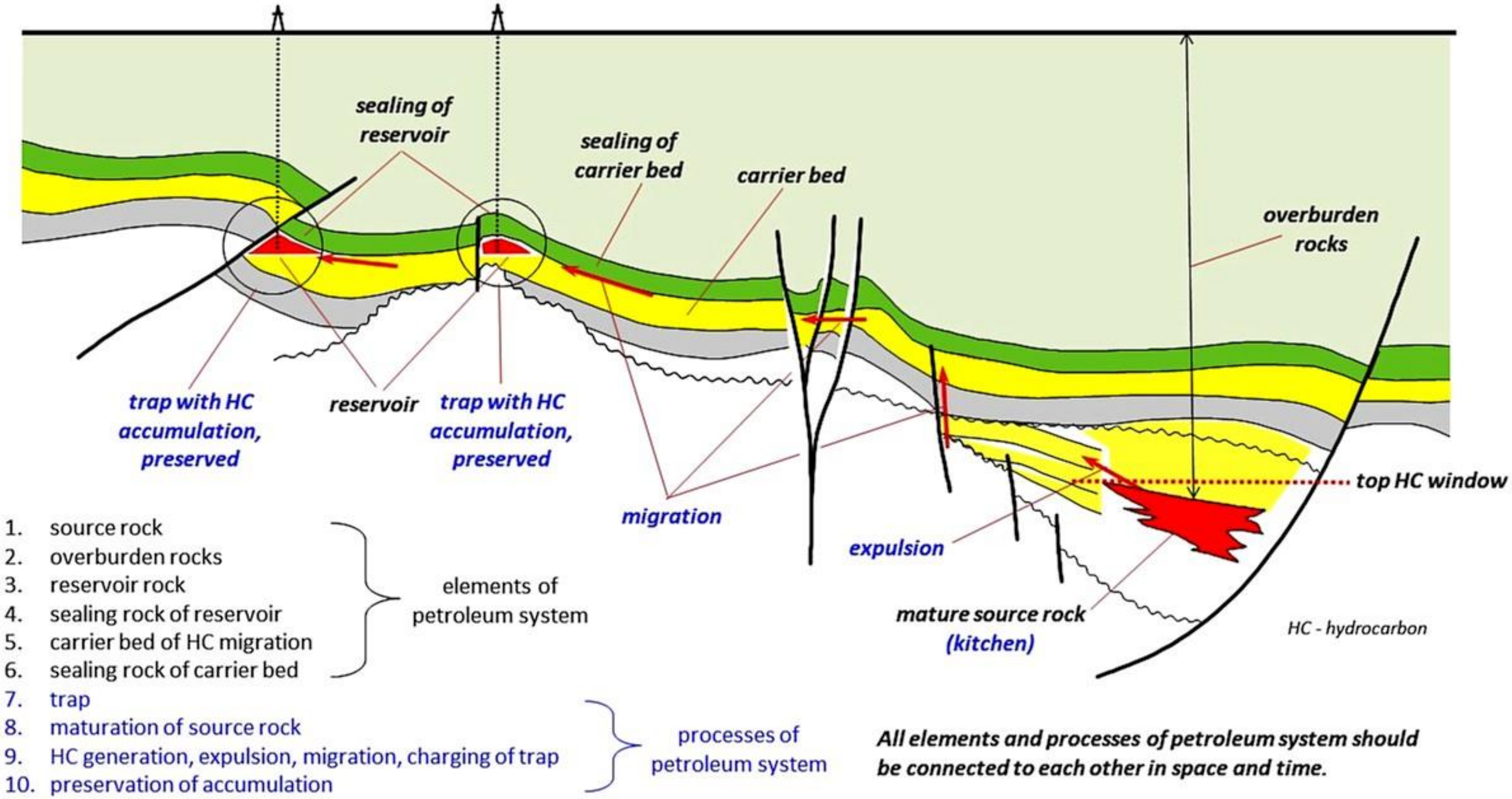


Figure 4 – Revisited petroleum system listing all elements and processes of petroleum system. Petroleum accumulation in trap actually involve complicated processes on many elements illustrated above that cannot be evaluated in balance. Evaluation of trap and reservoir is the most done, while others are little done, or not done, and are assumed to exist. When an exploration well discovers petroleum in a prospect, it is partly luck as well because not all the factors that influence the formation of oil/gas and its trapping can be identified and evaluated with confidence. But an ideal petroleum system analysis should evaluate the ten factors illustrated above that influence the formation and trapping of petroleum.

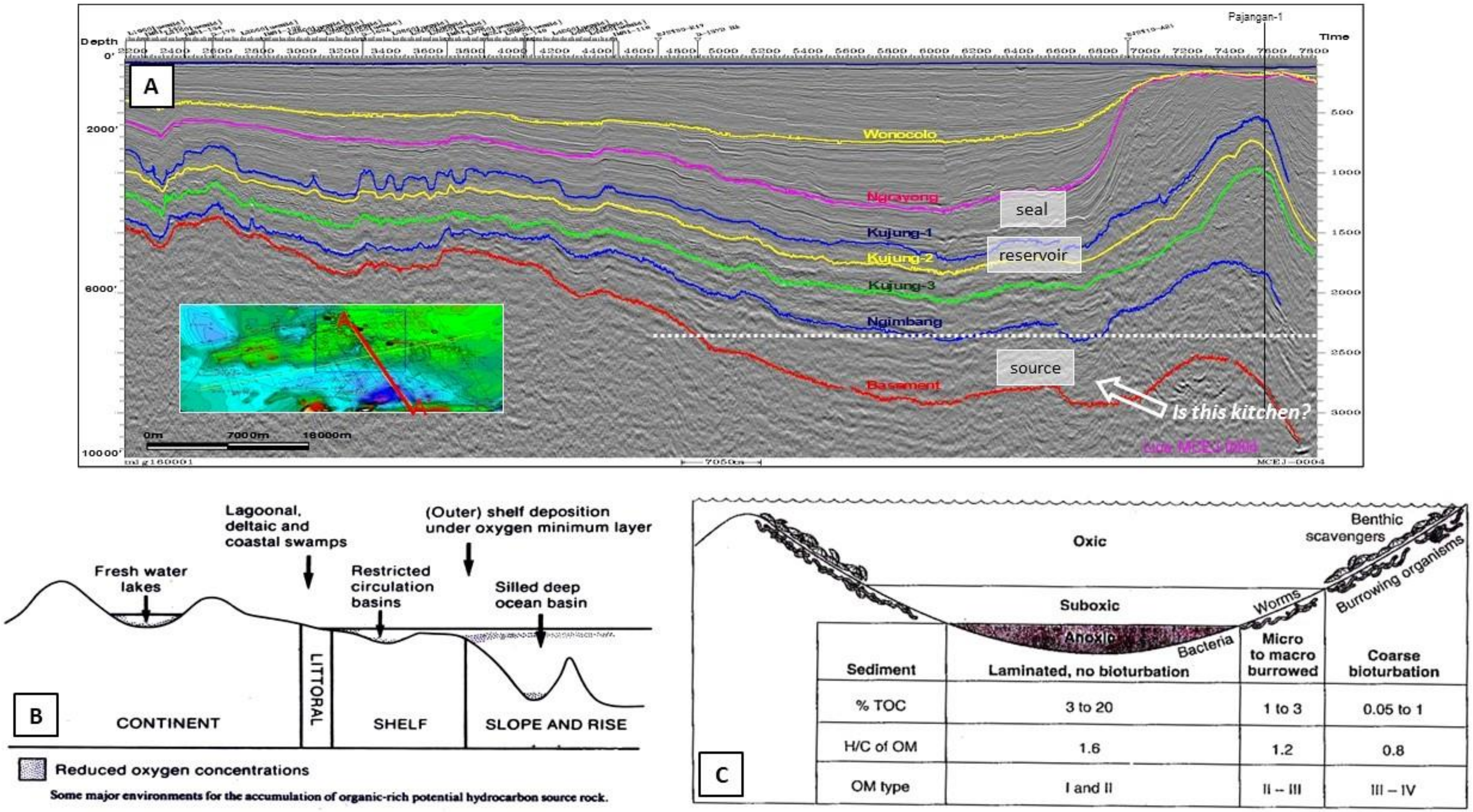


Figure 5 – Seismic low area is not necessarily kitchen area. A - A seismic section with a low area which is often mistakenly considered as kitchen. This is present time - low area, not necessarily a low area in time of source rock deposition. Low area in time of source deposition is good area for organic preservation due to anoxic condition as shown by sections at B (Brooks et al, 1987) and C (Hunt, 1996). The top of formation containing assumed source rock should be reconstructed/flattened to know whether it was past low or high. Past high would not be kitchen although it is low area.

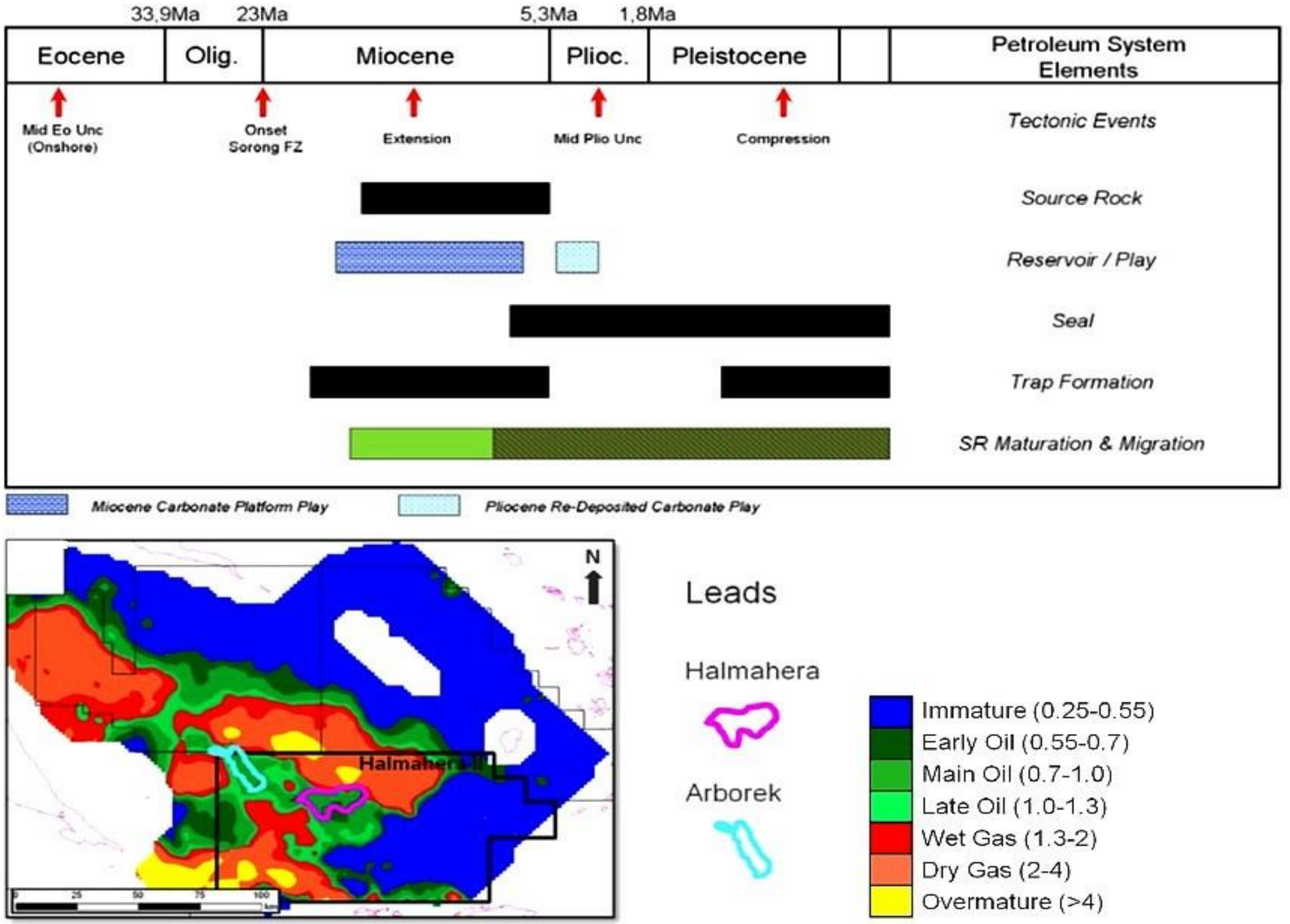


Figure 6 – Basin modeling should be rechecked in geologic context. Above, source rock maturation will not be in same period with source rock deposition as shown on the chart, input from basin modelling is erroneously here and resulted in mistaken areas of petroleum generation shown below (Ryan et al., 2012).

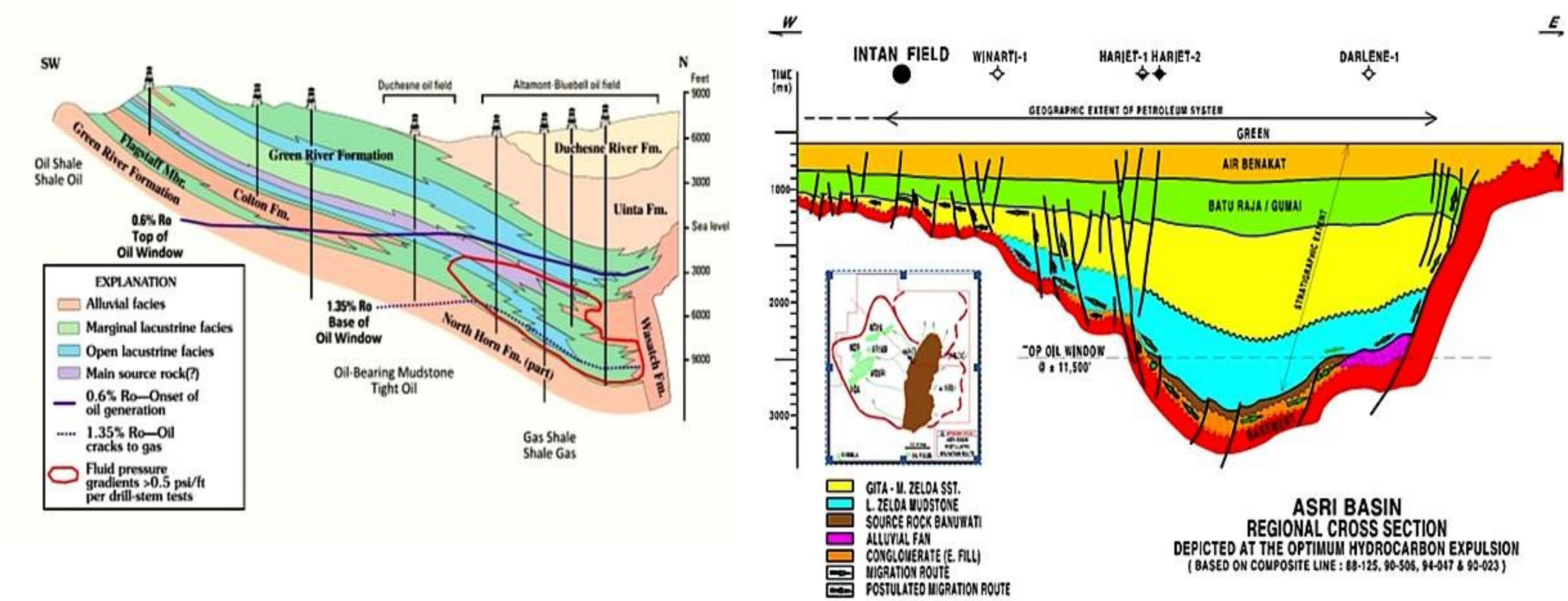


Figure 7 – Representing migration at time of optimum hydrocarbon expulsion. Left – schematic section showing present setting of a kitchen defined by present top of oil window (USGS Uinta-Piceance Assessment Team, 2003). Right - schematic section showing past setting of a kitchen reconstructed at the time of optimum hydrocarbon expulsion defined by past top oil window (Sukanto et al., 1998). Past setting of kitchen like on the right is much more useful than present setting of kitchen on the left because the generation, expulsion, and migration of petroleum occurred mostly in the past, not in the present time, always reconstruct the kitchen to the time of optimum expulsion and migration.

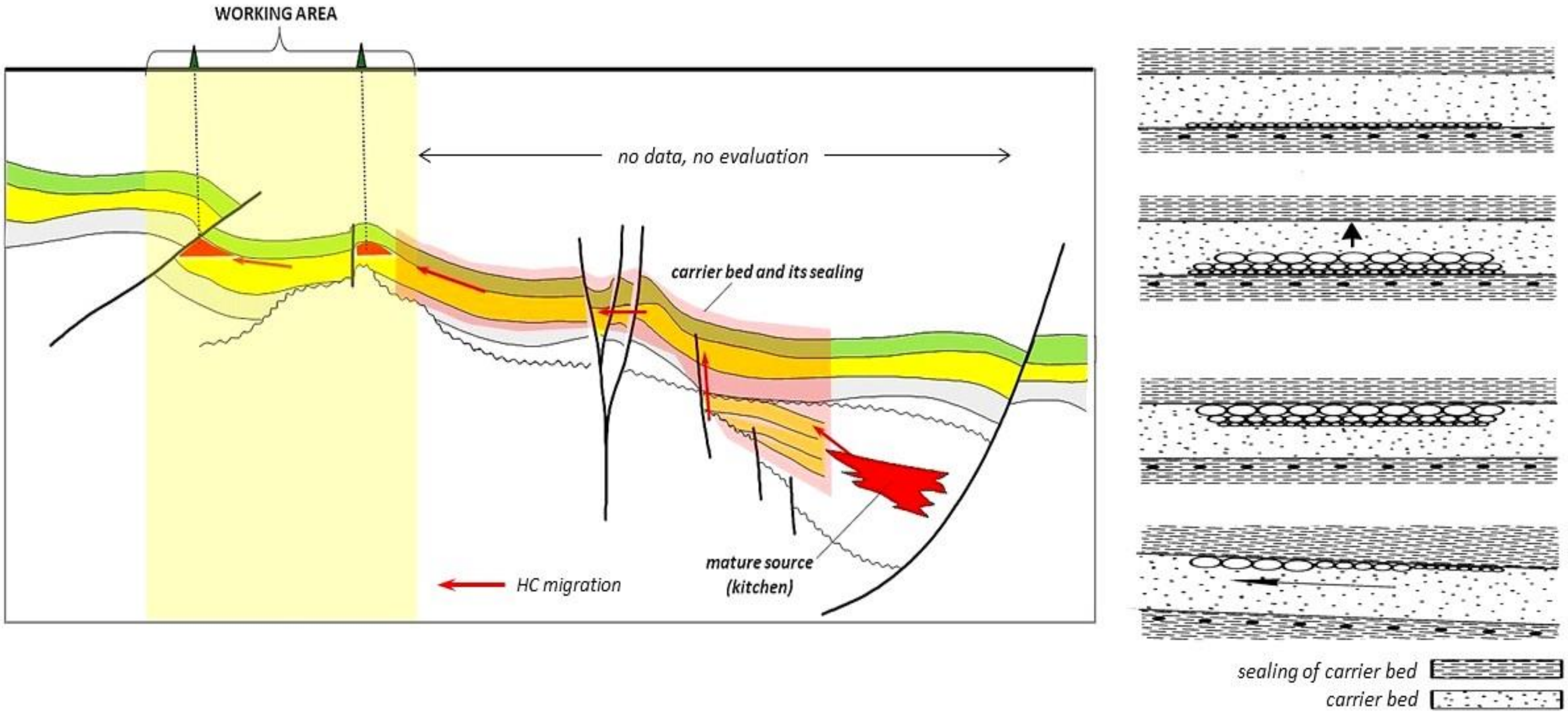


Figure 8 – Carrier beds and their sealing should be evaluated. Left - the carrier bed of petroleum migration and its sealing are the elements of the petroleum system that have been evaluated at least or never. This area is generally located outside the working area so that the data does not exist. In fact, this is the area that losses the most petroleum after migrating from the kitchen. Dry traps may be associated with loss of petroleum in carrier bed areas. Right - how petroleum migration occurs in the carrier bed, just below the sealing surface (Csato, 2002).

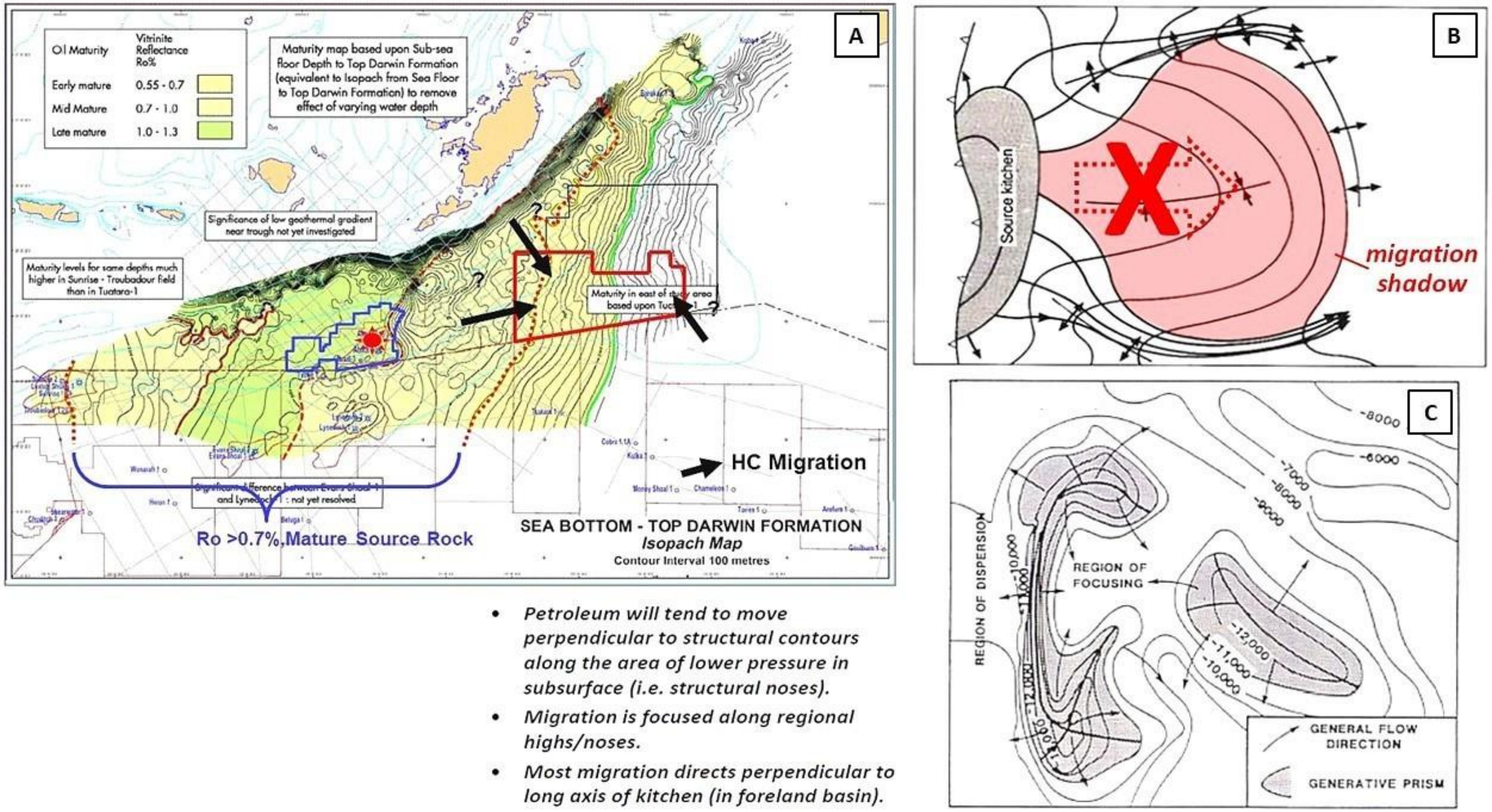
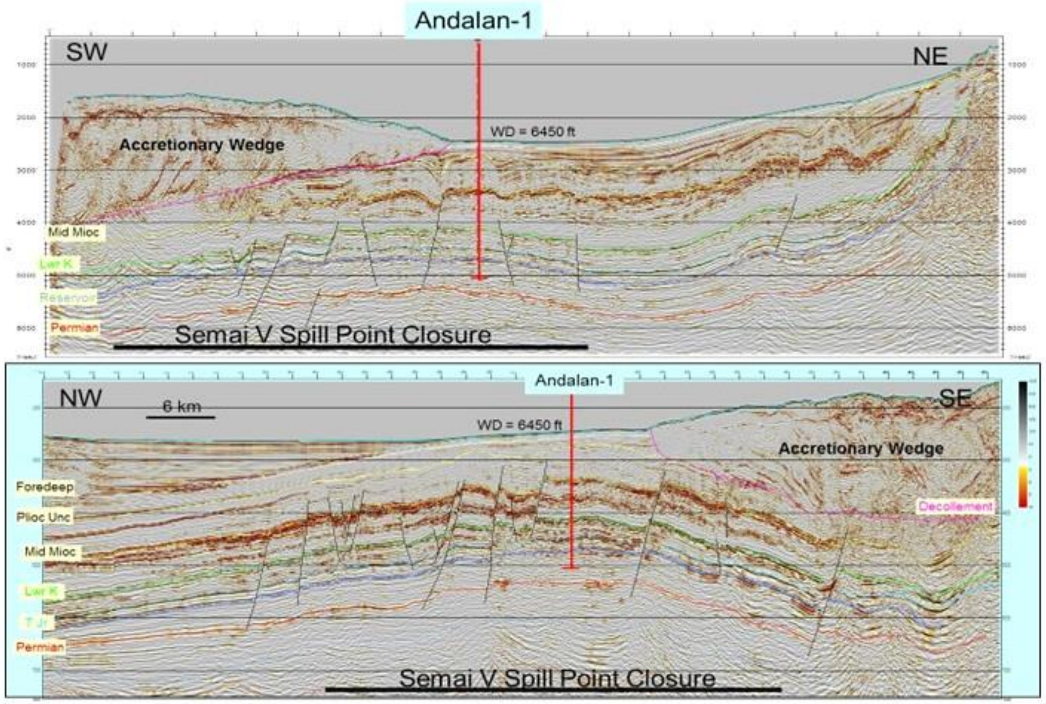


Figure 9 – A- oversimplification of migration pathways. Migration pathways are often oversimplified illustrated as arrows from the kitchen to the trap. B- a prospect even though is located directly in front of the kitchen it could be an area without migration (migration shadow area) due to it is located in regional low area (Allen and Allen, 2005). Migration pathways must be mapped based on the principles of fluid mechanics, that is, they occur in structural highs/noses on the subsurface. C- kitchen areas must also be divided based on the fetch area so that the supply of migration to prospect is clear (Pratsch, 1982).



Method: reconstruction of all elements and processes of petroleum system, successively through the geologic ages since the time of formation until present time.

1. Reconstruct tectonics of the area (basin evolution, tectonic evolution)
2. Reconstruct paleogeography and geologic evolution of the area dynamically at successive geologic ages
3. Reconstruct source facies to the time of deposition
4. Examine the possibility of source deposited in anoxic/suboxic/oxic environments
5. Reconstruct the deposition of reservoir, carrier , sealing beds
6. Reconstruct the subsidence history of source pod (burial history plot with right and reasonable inputs)
7. Reconstruct formation of traps
8. Reconstruct generation of petroleum from source pod, determining time of optimum migration
9. Reconstruct paleo-migration at the time of optimum migration and examine its successive pattern through geologic ages
10. Reconstruct critical timing between time of charging and formation of trap
11. Reconstruct successive geologic occurrence on accumulation, determining its preservation or destruction through geologic ages until present time.

Figure 10 – Dynamic interpretation is mainly to reconstruct all elements and processes of petroleum system from time of deposition to the present setting. Eleven reconstructions are suggested but quality depends on the data availability. Seismic sections show the location of Andalan-1 well drilled in Semai area, offshore west of the Bird's Head of Papua. The well is proposed to test a very large anticline which appears to be giant prospect. However, the well is dry and the Jurassic objective is tight. The objective ever subsided deeply degrading the porosities and was uplifted forming large anticline in later time. Histories of reservoir subsidence and late structure formation would have been captured prior drilling if a dynamic interpretation had been conducted.