

Influence of different probability based models on oil prospect exploration decision making: a case from southern Mexico

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ABSTRACT

Petroleum exploration is a high risk business. In this paper, we apply several fundamental concepts of petroleum prospect probability evaluation, illustrating the topic with a case study from southern Mexico. Prospect is a small geographic area where geotechnical evidence predicts the probable economic existence of oil and/or gas. Risk assessment helps to estimate discovery probabilities before drilling. Several geologic chance factors, i.e., reservoir facies, pore volume, geologic structure, seal, source rock, migration and retention were rated to obtain prospect probabilities for the potential accumulation for zones A to D. Zone A is composed of Upper Jurassic rocks, and includes a real reservoir(s). Zones B to D are hypothetical but based on geological facts of the same geologic province. They are respectively composed of Cretaceous, Miocene and Pliocene rocks and located in the same geographic area of Zone A. Based on the prospect geological framework and its associated geologic chance factors, we defined and calculated the corresponding common factor as well as the individual probabilities, thereby allowing us to build a clear picture of discovery probabilities. Three models, representing contrasting source rock concepts generated a range of discovery probabilities for each zone (A to D). Our results show that the discovery ranking begins with Model 2, followed by Model 1, and lastly by Model 3. Using those probabilities results we defined the best geological scenario and point out what we believe are the most appropriate next steps for an improved, less risky exploratory effort.

Key words: risk, probability, probability tree, oil exploration, southern Mexico.

RESUMEN

La exploración petrolera es un negocio de alto riesgo. En este artículo aplicamos algunos conceptos fundamentales de la evaluación de probabilidades de prospectos petroleros, ilustrando el tema con un caso de estudio del sureste de México. Un prospecto es un área geográfica pequeña donde la evidencia geotécnica predice la probable existencia económica de aceite y/o gas. La evaluación del riesgo ayuda a estimar las probabilidades de descubrimiento antes de perforar. Para obtener las probabilidades del prospecto valoramos varios factores geológicos de oportunidad—es decir, facies almacenadoras, volumen de poro, estructura geológica, sello, carga, migración y retención post-acumulación—para las zonas potenciales A a D. La Zona A está compuesta por rocas del Jurásico Superior e incluye un yacimiento real. Las Zonas B a D son hipotéticas, pero están basadas en hechos de la misma provincia geológica.

Estas zonas se componen de rocas del Cretácico, Mioceno y Plioceno, y se localizan en la misma área geográfica de la Zona A. Con base en el marco geológico y los factores geológicos de oportunidad asociados, definimos y calculamos el factor común respectivo así como las probabilidades individuales, lo que nos permitió construir una clara imagen de las probabilidades de descubrimiento. Tres modelos representando conceptos divergentes en cuanto al papel de la(s) roca(s) generadora(s), dieron lugar a un rango de probabilidades de descubrimiento para cada zona (A a D). Nuestros resultados muestran que las mejores probabilidades de descubrimiento están representadas por el Modelo 2, seguido por el Modelo 1, y finalmente por el Modelo 3. Usando esas probabilidades definimos el mejor escenario geológico, y señalamos los pasos apropiados siguientes para mejorar el esfuerzo exploratorio y hacerlo menos riesgoso.

Palabras clave: riesgo, probabilidad, árboles de probabilidad, exploración petrolera, sur de México.

INTRODUCTION

From concepts in North (1985), Harbaugh *et al.* (1995) and Hyne (1995) we may define “prospect” as a location or small area where the existence of oil and/or gas has not been proved, but that shows evidence of possible economically recoverable hydrocarbons. An important purpose of risk assessment in petroleum exploration is estimating the probability of discovery prior to drilling a prospect. The probability of discovery is an important parameter for a strategic exploration decision, especially during profitability studies of mapped prospects, their economic potential, and also as a vital indicator in assessing prospect ranking and portfolio management. For this work, we have constructed a hypothetical prospect in order to model the exploration of real accumulation zones on the principles of prospect probability, and extract conclusions that may improve exploration strategies in southern Mexico.

Currently, the most common method of calculating the probability of discovery for many petroleum companies is to use historical success ratios, which assumes the subsequent chance of discovery is a series of independent events. Unfortunately, while the concept is definitely useful for initial approximate guidelines, it is not realistic in the “real” world of petroleum exploration. Consequently, some explorationists prefer to adopt an alternative method of geological risk evaluation that is more rational and practical by incorporating the geological factors and geophysical evidence in the probability evaluation process (Newendorp and Schuyler, 2000).

PROBABILITY CONCEPTS IN PETROLEUM EXPLORATION

Petroleum exploration is a high-risk business. Its complex nature involves large elements of risk and uncertainty. One of the required skills to effectively perform risk analysis is the ability to think in probabilistic and statistical terms (Harbaugh *et al.*, 1977). There are four fundamental

probability theorems to be considered when dealing with prospect risk assessment:

1) Multiplication theorem

$$P(A \cap B) = P(A) \times P(B|A) \quad (1)$$

$$P(A \cap B \cap C \cap D) = P(A) \times P(B) \times P(C) \times P(D) \quad (2)$$

The probability that two outcomes occur successively, or the probability of various independent events occurring simultaneously, is equal to the product of their individual probabilities. This theorem is applied later in this article to illustrate the product of several geological independent factors all of which must be present concurrently in order to estimate discovery probability.

2) Addition theorem

$$P = P(A) + P(B) \quad (3)$$

$$P = P(A) + P(B) - P(A \cap B) \quad (4)$$

Given an occurrence of various mutually exclusive events, the probability of occurrence of at least one event is given by the sum of probabilities of each individual event, or the probability that outcome *A* and/or outcome *B* occur is equal to the probability of *A* plus the probability of *B* minus the probability of both *A* and *B*.

3) Combination theorem

$$(1-P) = [1-P(A)] \times [1-P(B)] \quad (5)$$

The probability of one or several independent events can be estimated by calculating the risk that neither of the events will occur. This third theorem is applied when dealing with interdependency between events or zones.

4) Bayes' theorem

$$P(B|A) = \frac{P(B, A)}{P(A)} = \frac{P(A|B)P(B)}{P(A)} \quad (6)$$

Bayes' theorem relates the conditional and marginal probabilities of events *A* and *B*. The conditional probability that event *B* will occur given the occurrence of event *A* is stated as the joint probability that both events *A* and *B* will occur, divided by the marginal probability that event *A* will

occur. Alternatively, Bayes's theorem can be restated as a partition of the event space A_i ,

$$P(B_i|A) = \frac{P(A|B_i)P(B_i)}{\sum_{j=1}^n P(A|B_j)P(B_j)} \quad (7)$$

where $i \neq j$; $S = B_1 \cup B_2 \cup \dots \cup B_n$; $B_i \cap B_j = \emptyset$, in which prior knowledge of conditions affects the value of a probability assigned to an event. The formula used to revise probabilities based on additional information if available.

PROSPECT PROBABILITY FACTORS

The evaluation of geologic risk requires knowledge of the geologic chance factors critical for the discovery of recoverable amounts of hydrocarbons in a prospect, and it is calculated through the decomposition of those chance factors. A probability scheme to rate every geologic factor is employed, e.g., CCOP (2000). The probability assigned can range from 0.0 to 1.0, which means 0% certainty and 100% certainty respectively. This probability depends on the geologic factor's physical characteristics, geologic history, and the reliability of available information. Following the scheme proposed by the CCOP (2000), the discovery probability is the product of the following major probability factors and each of these factors must be evaluated with respect to presence and effectiveness of its sub-factors: (1) probability of reservoir [*i.e.*, (1a) reservoir facies, (1b) effective pore volume]; (2) probability of trap [*i.e.*, (2a) mapped structure, (2b) effective seal mechanism]; (3) probability of petroleum charge [*i.e.*, (3a) effective source rock with respect to maturity and volume, (3b) effective migration and timing]; (4) probability of retention of petroleum after accumulation.

Reservoir facies are rocks having porosity and permeability sufficient to reservoir contain hydrocarbons. For example, rocks formed from sediment deposited in the marine environment, near the shoreline (or in higher energy settings), show a tendency to contain less clay, while sediment deposited in deeper areas (or in lower energy settings) of the ocean tends to have higher clay content. Because clay usually lowers permeability, higher probabilities of reservoir facies will tend to be assigned to rocks formed from sediment deposited in higher energy environments. As a rule, both porosity and permeability decrease with the depth of burial inside the earth's crust, because of the lithostatic pressure from the overlying rocks. Hence, the shallower the reservoir rocks in the earth crust, the higher their probability to contain hydrocarbons. Furthermore, effective pore volume is often dependent upon subsequent diagenesis of the reservoir facies, and carbonate rocks tend to show several superimposed diagenetic stages each of which may either open or occlude their porosity.

The hydrocarbon trap is composed of two elements, structure and seal. The structure is typically formed by the

mechanical deformation of rock layers causing folds and fractures. Lower structural complexity increases the probability of encountering a potentially hydrocarbon-bearing structure. A seal can be a structural element (e.g., a fault) or an impermeable rock (e.g., salt rock, a thick shale, basalt). Seal quality ranges from very good to poor.

Petroleum charge is the sufficient volume of mature source rock combined with the effective migration of oil and/or gas from the source rock to the reservoir rock. A sedimentary rock rich in *in situ* organic components which can be or have been transformed into oil and/or gas is a petroleum source rock. The source rock probability is basically determined by its volume, potential to generate and expel petroleum, maturity of the *in situ* organic components, and data reliability. Higher volume and petroleum potential, maturity degree within the oil/gas window range, and higher data reliability, imply higher source rock probability. To rate migration it is necessary to define if it may have been local or long distance, presence or absence of barriers, position of the trap relative to the migration pathway(s), if the trap was formed before, during, or after the source rock entered the oil/gas window, etc. Higher probabilities can be assigned to local migration, absence of barriers, and traps formed before the onset of petroleum generation and expulsion from the source rock.

Petroleum reservoirs can be either partially or totally destroyed by geologic phenomena. Therefore, the probability of retention after accumulation is evaluated on the basis of the geological events that may have occurred since the time the hydrocarbons were reservoir until the present day. Basically, higher probabilities of retention are assigned when no further significant deformation of the trap, reservoir and seal have occurred after accumulation, although there may be exceptions.

PROBABILITY OF COMMON FACTOR(S)

Different geologic factors can be independent, partially dependent or totally dependent. Dependency and correlation do matter when risking prospects. One or more geologic factors can be shared among two or more prospects; CCOP (2000) and Rose (2001) refer to these as "common factors". For instance, if the oil and/or gas of two or more different zones was sourced from the same source rock and migrated through the same pathways, that rock and migration pathways are the common factors to those potential zones.

Furthermore, if we are interested in estimating the probability of an effective source rock and migration pathway in a prospect, this can be done by using the Addition and Combination theorems mentioned earlier. For example, consider source rocks 1 and 2 as common factors. Therefore, the probability of an effective source rock for Zone A is the combination of probability for source rock 1 (SR1) and source rock 2 (SR2) minus the probability of both source

rocks existing, and is represented by:

$$\begin{aligned}
 P(\text{effective source rock in Zone A}) &= \\
 &P(\text{presence of SR1 in Zone A}) + P(\text{presence} \\
 &\text{of SR2 in Zone A}) \\
 &= P_A(\text{SR1}) + P_A(\text{SR2}) - P_A(\text{SR1} \cap \text{SR2}) \\
 &= P_A(\text{SR1}) + P_A(\text{SR2}) - (P_A(\text{SR1}) \cap P_A(\text{SR2})) \\
 &= P_A(\text{SR1}) + P_A(\text{SR2}) - (P_A(\text{SR1}) \times P_A(\text{SR2})) \quad (8)
 \end{aligned}$$

The common migration pathways from SR1, SR2 and source rock 3 (SR3) can be calculated by using the Combination Theorem and probability complementary rule (*i.e.*, the probability of not having any effective migration pathways to Zone A is the product of not having migration pathways from any source rocks in Zone A), which can be written as:

$$\begin{aligned}
 [1 - P(\text{effective migration to Zone A})] &= \\
 &[1 - P(\text{migration from SR1 to Zone A})] \\
 &\cap [1 - P(\text{migration from SR2 to Zone A})] \\
 &\cap [1 - P(\text{migration from SR3 to Zone A})] \quad (9)
 \end{aligned}$$

Therefore,

$$\begin{aligned}
 P(\text{effective migration to Zone A}) &= \\
 &= 1 - \left[\begin{array}{l} [1 - P(\text{migration from SR1 to Zone A})] \\ \times [1 - P(\text{migration from SR2 to Zone A})] \times \\ [1 - P(\text{migration from SR3 to Zone A})] \end{array} \right] \\
 &= 1 - [(1 - P_A(\text{migration SR1})) \times (1 - P_A(\text{migration SR2})) \times \\
 &\quad (1 - P_A(\text{migration SR3}))].
 \end{aligned}$$

Calculating the probability of the common factor can become even more complex when it consists of several sub-common factors, and all of which can also be interdependent or independent.

CONSTRUCTION OF A HYPOTHETICAL PROSPECT

The geology of our hypothetical prospect is based on published literature of the Área Chiapas-Tabasco (*e.g.*, Sánchez-Montes de Oca, 1980; Santiago *et al.*, 1984; Aguayo *et al.*, 1985; Roadifer, 1987; Holguín-Quiñones, 1985 published in 1988; González-García and Holguín-Quiñones, 1992; Rosales *et al.*, 1992; PEMEX, 1999a; Guzmán-Vega and Mello, 1999; Guzmán-Vega *et al.*, 2001; Magoon *et al.*, 2001; Sosa-Patrón and Clara-Valdés, 2001; Williams-Rojas and Hurley, 2001), coupled with published information from a real field, *i.e.*, Jujo-Tecominoacán (García Hernández *et al.*, 1989; Santiago and Baro, 1992; Porres *et al.*, 1996; PEMEX, 1999b; Aranda-García, 1999; Rosales *et al.*, 1999; Rosillo *et al.*, 2004). The location of the Área Chiapas-Tabasco and Jujo-Tecominoacán field are

shown in Figure 1.

We defined four pay zones for our hypothetical prospect (*i.e.*, A, B, C and D), Therefore, it is a multi-zone prospect. Figure 2 graphically summarizes some geologic elements forming the prospect. Pay zones A and B are thought to reservoir oil with associated gas, pay Zone C probably reservoirs a gas/oil mixture, and pay Zone D only gas.

In a very large area of Southern Mexico, the Tithonian is the main petroleum source rock, and our hypothetical prospect is not an exception. This source rock (SR1a and SR1b respectively) is repeated by a thrust fault zone below the deepest reservoir (RR1). SR2 in Figure 2 represents a Cretaceous source rock (of Cenomanian-Turonian age). SR3, SR4 and SR5 are identified as Cenozoic source rocks that are either immature or marginally mature in Southeast Mexico (González-García and Holguín-Quiñones, 1992). Gas reservoirs in Pliocene sandstones (RR4) and gas/oil reservoirs in Miocene rocks (RR3) have been drilled above the cited Cenozoic source rocks in the Área Chiapas-Tabasco. However, the origin of the fluids reservoid in those siliciclastic rocks (*i.e.*, the Miocene and the Pliocene) remains speculative.

THREE POSSIBLE MODELS

The source-reservoir relations in the Área Chiapas-Tabasco are still under discussion regarding the role of the Tithonian as a source rock for any Cenozoic reservoirs as well as for some Mesozoic reservoirs, other than the

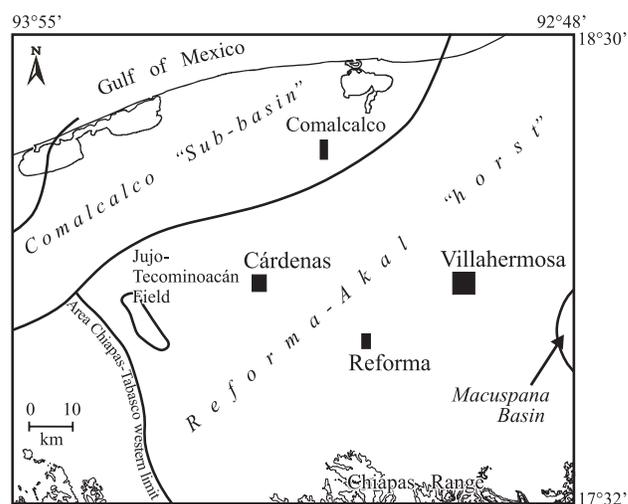


Figure 1. Location map of the Área Chiapas-Tabasco and Jujo-Tecominoacán field. The northern and southern limits of the Área Chiapas-Tabasco are identifiable by physiographic features, *i.e.*, the coastline and the Chiapas Range, respectively. The eastern and western limits of the Área Chiapas-Tabasco are buried geologic features. The east limit is the Macuspana Basin, whose western limit is located just outside the right edge of the map. The west limit of the Área Chiapas-Tabasco is the border of the hydrocarbons producing zone, indicated with dashed line. The Jujo-Tecominoacán field is one of several petroleum fields located close to the West border of the Área Chiapas-Tabasco.

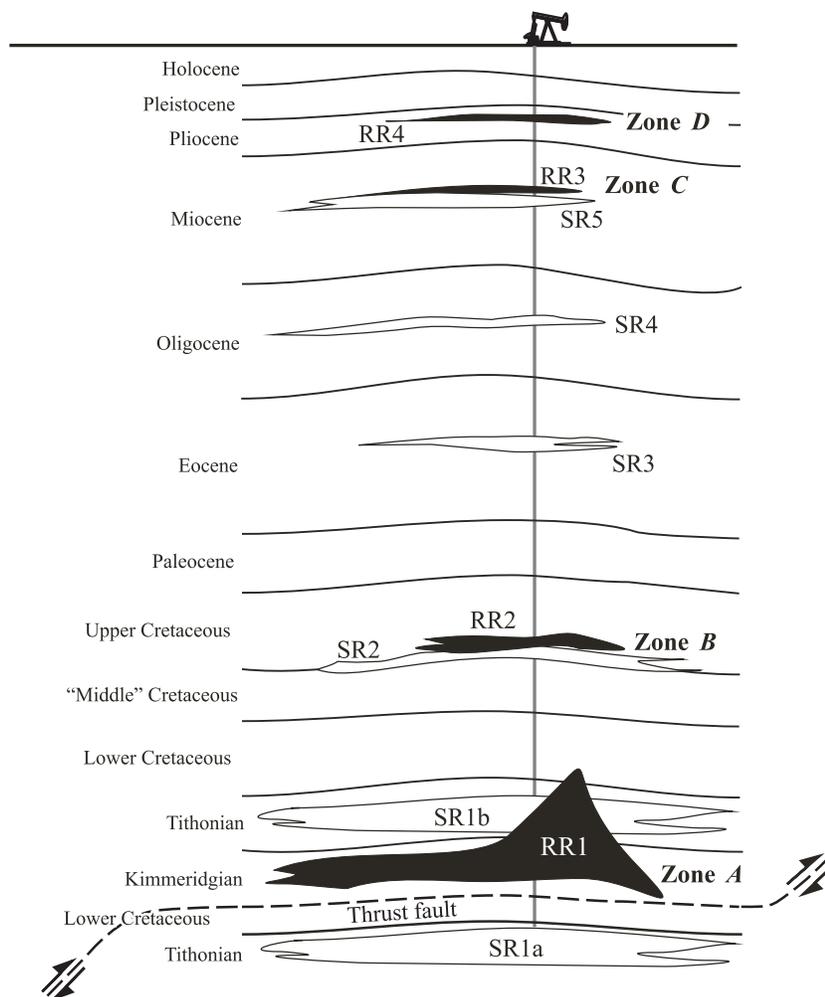


Figure 2. Schematic representation of some elements of the hypothetical prospect. SR: source rocks; RR: reservoir rocks. The reservoir rock 1 (RR1) is located at more than 5,000 m below the surface. The pay Zone A is associated with RR1, mainly of Kimmeridgian age; pay Zone B corresponds to a hypothetical reservoir rock 2 (RR2), of Upper Cretaceous age; pay Zone C is associated with the hypothetical Miocene age reservoir rock (RR3); and pay Zone D is associated with RR4, hypothetical reservoir rock of Pliocene age.

Kimmeridgian or the Tithonian itself (Julio Cerrillo Cruz, 2004, personal communication). Three main possible models can be proposed to explain the role of the Tithonian as a source rock: 1) the Tithonian generated petroleum reservoir only in Mesozoic rocks, but not in Cenozoic reservoir rocks; 2) petroleum was mainly sourced by the Tithonian, but source rocks of other ages also played a role in forming commercial accumulations; (3) the Tithonian is the only source rock. Table 1 summarizes the mentioned models relating them to their respective geologic systems.

HYPOTHETICAL PROSPECT GEOLOGIC CHANCE OF SUCCESS (P_g)

We now evaluated the geologic chance factors for Zones A, B, C and D. This evaluation was carried out for the presence of reservoir facies (P1a), effective pore volume

(P1b), mapped structure (P2a), effective seal mechanism (P2b), effective source rock (P3a), effective migration (P3b) and retention after accumulation (P4). The probabilities for the hypothetical prospect were calculated based on the information provided in the cited geological literature of the Jujo-Tecominoacán field and the Área Chiapas-Tabasco, and using the risk assessment guidelines by the CCOP (2000) as well as considering key non-quantitative aspects of decision-making to reduce biases (Bratvold *et al.*, 2002).

The calculated conditional probabilities are shown in Table 2. The conditional probabilities given a discovery in A are important in estimating the total resource potential of the prospect while the conditional probabilities given that A is dry is a must for the economic potential estimation of the prospect. Generally, the probability of discovery of Zone " X_i " ($i = B, C$ or D) given that A is dry can be calculated by the following conditional probability formula derived from Bayes's theorem: The probability of discovery in any given

Zone " X_i " $i = B, C, D$ can be expressed as

$$P(X_i) = P(S) \times P(X_i|S)$$

where $P(S)$ is the probability factors which are common to all zones; and $P(X_i|S)$ are those factors which are independent. $P(X_i|A)$ is the probability of discovery in any Zone given discovery in A :

$$P(X_i|A) = \frac{P(X_i, A)}{P(A)} = \frac{P(A|S)P(X_i)}{P(A)} \quad (10).$$

Therefore, $[1-P(A)] = P(\bar{A})$ is the probability of A being dry; $[1-P(A|S)] = P(\bar{A}|S)$ is the probability of A being dry, even though common factors work; and $P(X_i|\bar{A})$ is the probability of making a discovery in the other zones given Zone A is dry:

$$P(X_i|\bar{A}) = \frac{P(X_i|A)P(S)P(\bar{A}|S)}{P(\bar{A})}.$$

For Model 1, the individual probabilities are higher for the Mesozoic zones and lower for the Cenozoic zones. Since the probability of discovery in B given A is first a discovery, $P(B|A) = (0.5 \times 0.47)/0.49 = 0.53$ (rounded) and the probability of discovery of B given A is dry, $P(B|\bar{A}) = (0.53 \times 0.9 \times 0.45)/0.51 = 0.42$ rounded; it implies the discovery in Zone B is almost independent of Zone A and *vice versa*. The probability tree in Figure 3a illustrates this scenario given a discovery in Zone A and a dry hole in Zone A . We interpret these probabilities as being related to the presence of Tithonian source rock specifically associated with Zone A , and also the presence of Cenomanian-Turonian source rock associated with Zone B . Regarding the Cenozoic reservoirs, Zone C (*i.e.*, associated with the Miocene reservoir rock) is indicated to have a higher individual probability than Zone D (*i.e.*, as-

sociated with the Pliocene reservoir rock). This is mainly because, unlike the reservoir rock of Zone D , the reservoir rock of Zone C has an adjacent source rock.

The conditional probabilities of finding oil are shown in Figure 3b; $P(D|C) = (0.49 \times 0.14)/0.29 = 0.24$ (rounded) while $P(D|\bar{C}) = (0.24 \times 0.58 \times 0.51)/0.71 = 0.10$ (rounded) implying that exploration in the Cenozoic should be initiated by Zone C and if a discovery is established, exploration should continue to Zone D , but not the other way around.

In Model 2 (Table 2), where the Tithonian is the main source rock and there are migration pathways connecting it to Cenozoic reservoirs, the individual probabilities show one significant difference compared to Model 1. The chance of finding oil in Zone C is similar to the chance of finding oil in Mesozoic zones, A and B , implying that the risk of Zone C in Model 2 is lower than in Model 1. The geologic success of Zone D is also higher in Model 2 than in Model 1. However, the risk of exploring the Cenozoic in Model 2 is similar to Model 1 in terms of the higher chance of discovery in C rather than in D . Therefore, exploration in the Cenozoic sequence should start with Zone C . The probability trees in Figures 4a and 4b illustrate the chance of finding oil for Model 2.

When the Tithonian is the only source rock as indicated in Model 3, there is a clear difference in the zones geologic chance of success for each zone. Zone A has the same probability as in Models 1 and 2, but the other three zones have significantly lower probabilities (Table 2). Their chance of being productive is conditioned by the success or failure of Zone A , as is shown in the probability trees in Figures 5a and 5b. The only similarity of Model 3 to Models 1 and 2 is that exploring the Cenozoic is less risky for Zone C . Figure 6 compares the corresponding zones conditional probabilities. The ranking begins with Model 2, followed by Model 1, and lastly by Model 3.

Table 1. Summary of models and geologic systems. SR: source rocks; RR: reservoir rocks.

Zones ^a		Model 1 ^b	Model 2 ^c	Model 3 ^d
Geologic systems	D Source Reservoir	SR3, SR4, SR5	SR1a, SR1b, SR3, SR4, SR5 RR4	SR1a, SR1b
	C Source Reservoir	SR3, SR4, SR5	SR1a, SR1b, SR3, SR4, SR5 RR3	SR1a, SR1b
	B Source Reservoir	SR1b, SR2	SR1a, SR1b, SR2 RR2	SR1a, SR1b
	A Source Reservoir		SR1a, SR1b RR1	

^aPay zones A to D are located within the area of our hypothetical prospect. ^bModel 1: the Tithonian sourced oil fills Mesozoic, but not Cenozoic reservoir rocks; *e.g.*, for pay Zone A , both SR1a and SR1b expelled oil to fill RR1; SR3 (Eocene), SR4 (Oligocene) and SR5 (Miocene) are common factors for pay zones C and D . ^cModel 2: the Tithonian is the major source rock of the entire geologic column; SR1a and SR1b are common factors for pay zones A to D , while source rocks SR3, SR4 and SR5 are common factors for pay zones C and D . ^dModel 3: the Tithonian is the only source rock of the oil reservoir in the entire column, therefore SR1a and SR1b are the only common factors for pay zones A to D , since there are no other source rocks.

Table 2. Probabilities for pay zones A to D according to the three models.

Geologic Factors	Model 1 ^a				Model 2 ^b				Model 3 ^c				
	Zones				Zones				Zones				
	A	B	C	D	A	B	C	D	A	B	C	D	
<i>P1 Prob. of reservoir</i>													
P1a	Reservoir facies	0.90	0.90	0.95	0.95	0.90	0.90	0.95	0.95	0.90	0.90	0.95	0.95
P1b	Porosity	0.80	0.80	0.80	0.95	0.80	0.80	0.80	0.95	0.80	0.80	0.80	0.95
<i>P2 Prob. of trap</i>													
P2a	Mapped structure	0.85	0.90	0.95	0.95	0.85	0.90	0.95	0.95	0.85	0.90	0.95	0.95
P2b	Effective seal	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
<i>P3 Prob. of petroleum charge</i>													
P3a	Effective source rock	0.90	0.90	0.58	0.58	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
P3b	Effective migration	0.99	0.95	0.95	0.62	0.99	0.95	0.97	0.78	0.99	0.62	0.44	0.44
<i>P4 Prob. of retention</i>													
P(X)	Individual probability	1.00	0.95	0.80	0.50	1.00	0.95	0.80	0.50	1.00	0.95	0.80	0.50
P(S)	Common factor	0.49	0.47	0.29	0.14	0.49	0.47	0.46	0.27	0.49	0.31	0.21	0.15
P(X S)	Other independent factors	0.90	0.90	0.58	0.58	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
		0.55	0.53	0.49	0.24	0.55	0.52	0.51	0.30	0.55	0.35	0.23	0.17

^aModel 1: the Tithonian source rock does not fill Cenozoic reservoirs and it is not the only source rock; the probability of geologic success P_g of individual zones, its common factor and the conditional probabilities for B, C and D (rounded to 2 decimal points); we defined our common factor as the effective source rock; Zone A shares the common factor with Zone B, and Zone C shares its common factor with Zone D. ^bModel 2: the Tithonian source rock provides hydrocarbons to Cenozoic reservoirs and it is not the only source rock; the P_g of individual zones and the discovery probabilities for zones B, C and D is conditioned by the common factor (rounded to 2 decimal points). ^cModel 3: the Tithonian is the only source rock; the P_g of individual zones and the calculated conditional probabilities for B, C and D (rounded to 2 decimal points).

RETROSPECTIVE TESTING

Next, we test on how well our models and procedures described in the previous sections match reality. We compared the results from the models to pertinent geotechnical information, including actual production data.

Evidently, the risk is lower when reservoir rocks are of Mesozoic age and there is more than one effective source rock. On the contrary, the risk tends to be higher when the reservoir rock age is Cenozoic and the Tithonian is the only effective source rock. Our prediction was compared to eleven main new discoveries as were reported for the onshore area of the Sureste Basin during the 1978-1988 decade (Table 3).

The production data shown in Table 3 do not imply total absence of Cenozoic reservoir hydrocarbons onshore the Sureste Basin. Well known fields located in the Comalcalco sub-basin (e.g., Santuario, Castarrical, Tupilco, El Golpe, Mecocacán, Chipilín, Puerto Ceiba) have been producing almost exclusively from Cenozoic rocks, although lower hydrocarbon quantities compared with the production from Mesozoic rocks. Aquino-López (2004) has cited that the Saramako field, producing from Early Pliocene reservoir rocks, is an important discovery for the Cenozoic plays of the onshore Sureste Basin, with proven reserves of 8.44 million barrels of oil equivalent. Other than that, production data in the region still show that accumulation clearly favors Mesozoic over Cenozoic reservoir rocks which support our prediction, *i.e.*, a clear tendency to

higher probabilities for Mesozoic reservoir rocks and lower probabilities for Cenozoic rocks.

Regarding the number of effective source rocks involved, the currently dominant view is that reservoir hydrocarbons were generated by a single source rock, the Tithonian (e.g., Guzmán-Vega and Mello, 1999; Magoon and Henry, 2000; Sosa-Patrón and Clara-Valdés, 2001). Nevertheless, the existence of Cretaceous organic rich facies in Southern Mexico was postulated by Bello Montoya *et al.* (1986), and later demonstrated by Rosales *et al.* (1992, 2005). Therefore, Models 1 and 2 match the combined evidence from production data and source rock geochemistry, making them reliable tools to help evaluating exploration opportunities.

POTENTIAL APPLICATIONS

It may be reasonable to attempt the application of the above procedures to study other prospective areas of Southern Mexico and beyond. Zone A may become an analog if in the future, while exploring within the Área Chiapas-Tabasco, where our hypothetical prospect is located, a rock sequence tentatively composed of the same geologic factors as Zone A is discovered. We can call it "Prospect X", and Zone A would be its analog model. In our case, analog models are real prospects so well documented and understood that they can be employed to anticipate the geological phenomena of newly encountered prospects. The

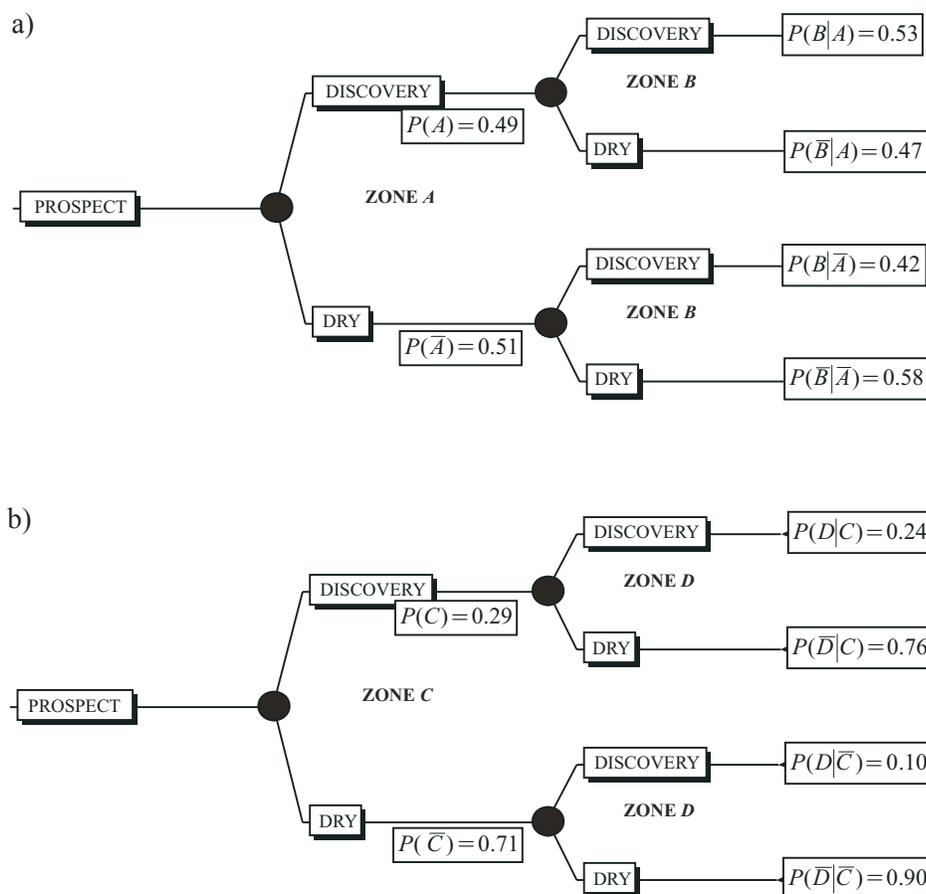


Figure 3. (a) Model 1. The conditional probabilities of discovery in zones *A* and *B*, is illustrated in this probability tree. $P(A) = 0.49$ is read as the probability *A* is discovery, $P(\bar{A}) = 0.51$ is the probability of *A* is dry, and $P(B|\bar{A}) = 0.42$ is read as the probability of a discovery in Zone *B* discovery given the probability of Zone *A* is dry. If Zone *A* is dry there is still chance to have discovery in Zone *B*, since there is a source rock adjacent to Zone *B*. (b) Model 1. The same rules applied for Zone *C* and a potential discovery in Zone *D*. $P(\bar{D}|C) = 0.76$ is read as the probability of dry Zone *D*, given a discovery in Zone *C*; and $P(\bar{D}|\bar{C}) = 0.90$ as the probability of dry Zone *D* given by Zone *C* is also dry. This is because the Cenozoic source rocks are closer to Zone *C*.

practical use of analog models and their economic impact cannot be overemphasized.

However, regarding the probability Models 1 and 2, they either may be or may not be applicable to other areas of southern Mexico and beyond. For instance, several offshore Sureste Basin fields with hydrocarbon accumulations in Cretaceous-Paleocene rocks have been reported (e.g., Santiago and Baro, 1992) in which porosity is at least partially controlled by the Chicxulub impact effects, while Zones *A* to *D* do not include Paleocene reservoir rocks. Hence, further refinement of the probability models should be carried out to include a set of factors detailed enough to achieve results with the required accuracy, and to attempt reflecting the entire geological nature of the area under scrutiny.

Because large uncertainties in probability estimates exist, which in the present work are expressed in terms of different models, alternative methods of risk analysis such as Monte Carlo simulation and other stochastic calculations are therefore very useful methods to support the methodology

we employed. Should it be the case, all of our geotechnical variables in the models will be random parameters which can be assigned as probability distributions and for some parameters which are normally and log-normally distributed, they must be tested for possible outliers by using statistical techniques such as those suggested by Verma and Quiroz-Ruiz (2006a, 2006b).

The use of specialized software (e.g., BasinMod[®], Risk, GeoX[®], Multizone Master[®], PetroRisk[®], PetroVR[®], Prospect Risk Analysis[®], the Geological Survey of Canada's SuperSD[®], the US Geological Survey's Emc2 and EMCEE), greatly enhances the task of risking petroleum prospects, although outputs may differ.

CONCLUSIONS

Under the current geological knowledge of the study area, particularly the connection of the Tithonian source rock with reservoir rocks of other ages, there are

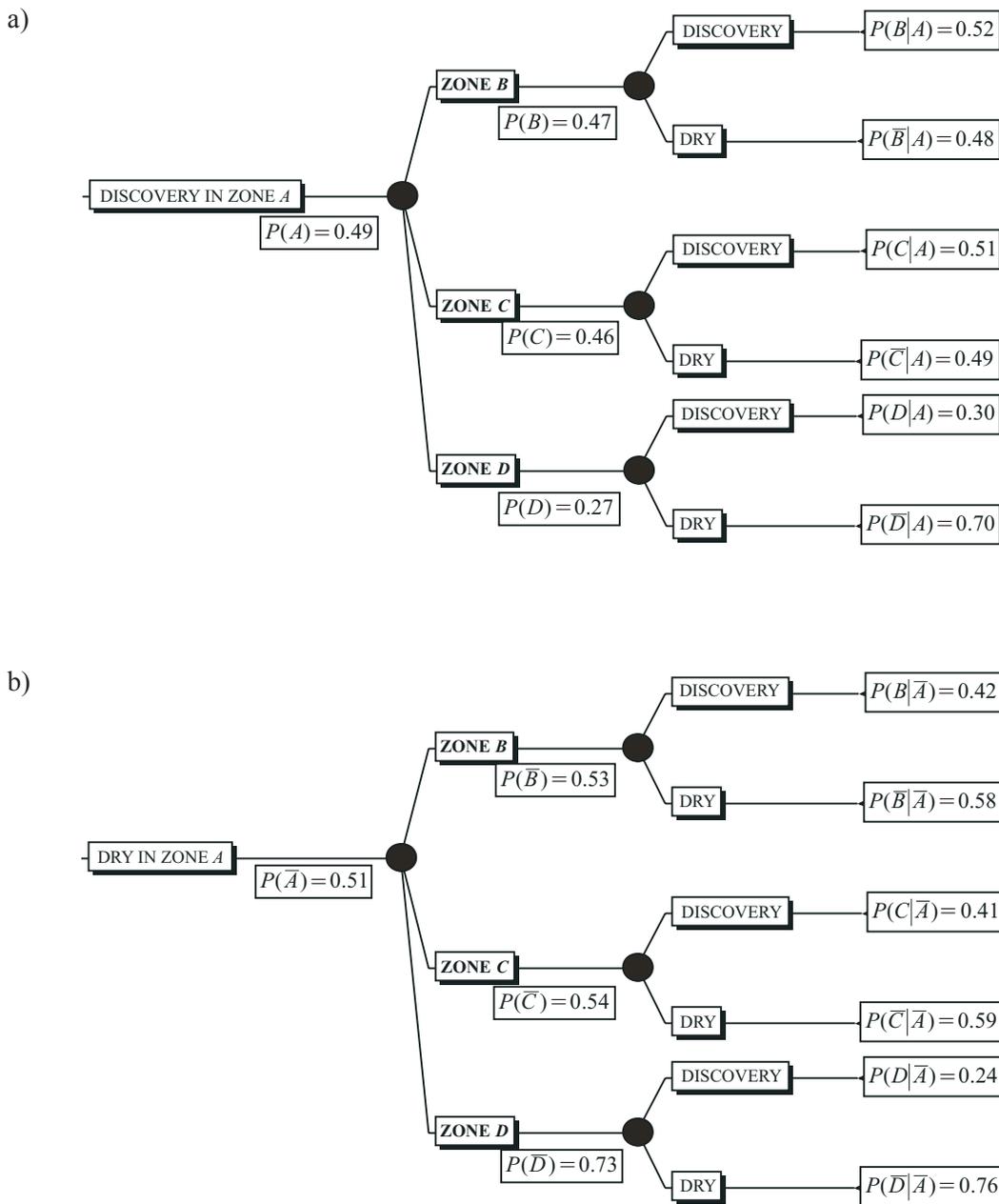


Figure 4. (a) Model 2 with discovery in Zone A. The geologic chance of success for the respective zones, $P_g = 0.49, 0.47, 0.46, 0.27$, and their corresponding conditional probabilities of discovery given success in Zone A. (b) Model 2 with dry Zone A. The conditional probabilities of finding oil in the other zones given the failure of Zone A. The success chance in Zone A and Zone B can be still considered positive despite the failure in Zone A. This is due to the presence of possible source rocks other than the Tithonian filling zones B and C.

large probability differences for Zones B, C and D under Models 2 and 3. Given such a situation, by risking petroleum prospects in the study area, we have pointed out the need for refined geotechnical models, especially in modeling migration pathways.

Zone A has the overall lowest risk of all, showing the same risk under the all three models. For future exploration, we conclude that drilling Prospect X is highly recommended as Zone A would be its analog and results from Model 3 can

be employed to evaluate its drilling success. We also noted that the best geologic probabilities of success for Zones B, C and D occur in Model 2, implying that the best exploration condition is where the Tithonian and also source rocks of other ages occur. The retrospective testing reconfirms and supports our models predictions which match the real scenario in the region.

Regarding the specific case of exploring for Cenozoic reservoirs, Zone C (*i.e.*, associated with Miocene reservoir

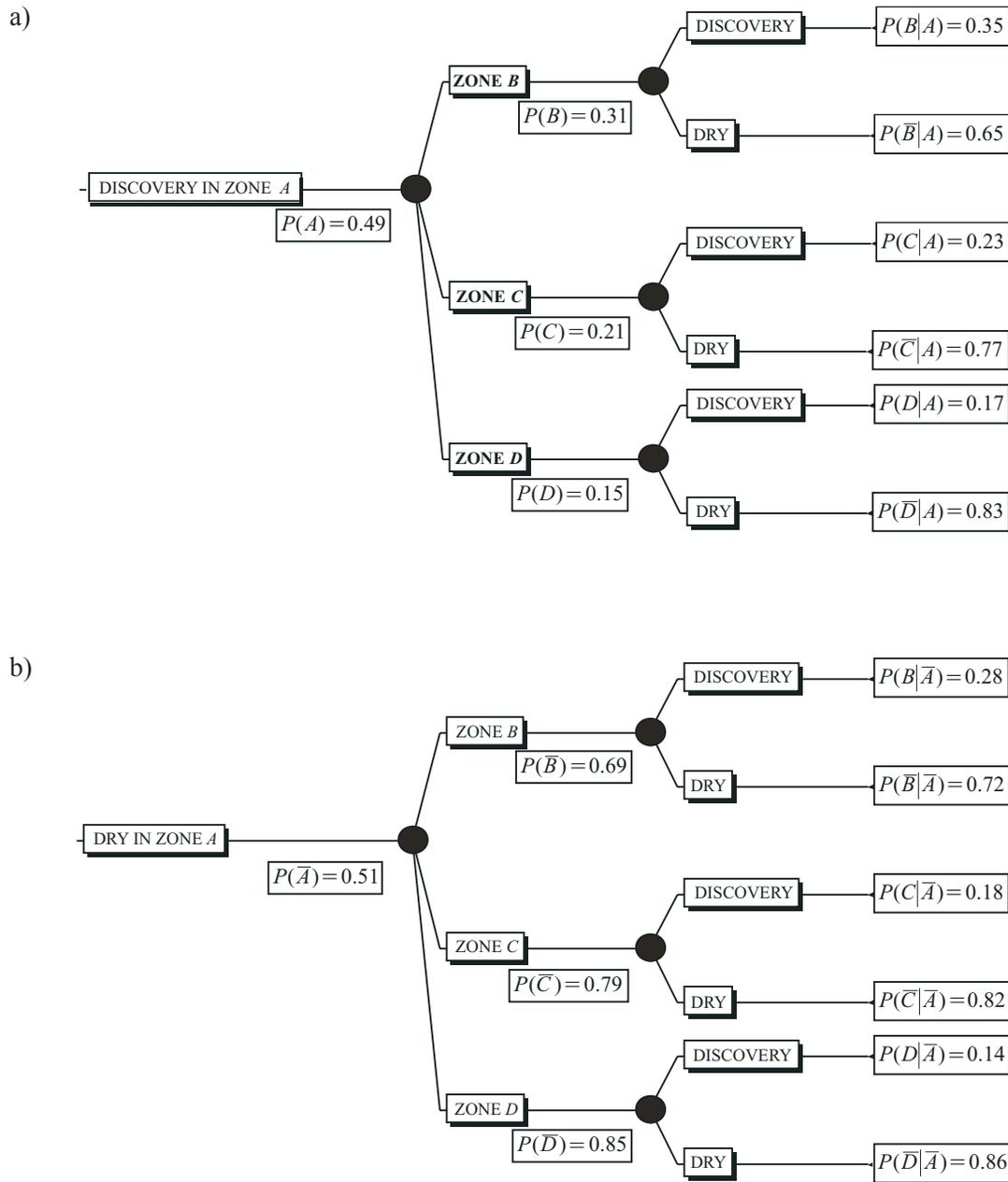


Figure 5. (a) Model 3 with discovery in Zone A. This probability tree shows partly possible outcomes in drilling a multi-zone prospect. The conditional probabilities calculated given a discovery in Zone A and ranking the probabilities of success for drilling activities in the other zones. (b) Model 3 with dry Zone A. The probability tree shows that even if Zone A is dry there is still chance to have a discovery in the other zones. The chances of discovery in the other zones are assumed partially dependent to Zone A, regardless if it is productive or not.

rocks) consistently shows lower risk than Zone D (*i.e.*, associated with Pliocene reservoir rocks). Consequently, exploring for Miocene reservoirs before Pliocene reservoirs should be a safer decision than first exploring for Pliocene reservoirs.

Considering the presence of only Tithonian source rocks in Model 3, it is recommended that more elaborate probability trees be built in the future, specifically for this case, in order to have a broader view regarding the depend-

ency of each zone and the possible drilling outcomes in the prospect. These trees will help to answer questions such as: (1) if we find a jackpot in Zone A, what is the probability of the other zones being productive?; (2) if Zones A, B and C are dry, what is the chance to find oil in Zone D?; (3) or what is the likelihood of at least one zone be productive?; (4) what will be the economic difference if we decide to start drilling from the shallowest Zone D to the deepest Zone A instead?; etc.

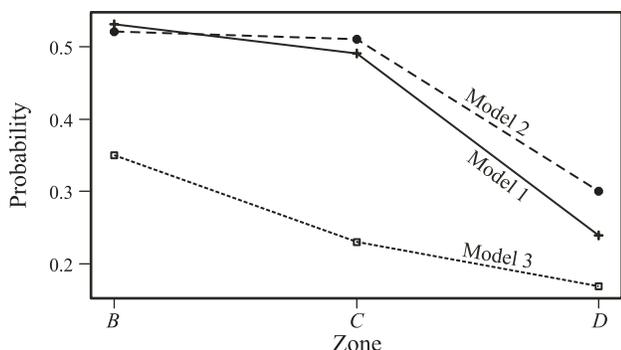


Figure 6. Comparison of the conditional probabilities $P(X|S)$ for zones B, C and D according to the three Models. Zone B, associated with an Upper Cretaceous reservoir rock; Zone C, associated with a Miocene reservoir rock; Zone D, associated with a Pliocene reservoir rock. In Model 1 the Tithonian source rock does not fill Cenozoic reservoirs and there are source rocks of other geologic ages. In Model 2 the Tithonian is connected to Cenozoic reservoirs and, again, it is not the only source rock. In Model 3 the Tithonian is the only source rock and is connected to reservoir rocks of Mesozoic and Cenozoic ages.

Table 3. Main discoveries made during the 1978–1988 decade inland the Sureste Basin. From data in Santiago and Baro (1992). BOPD: barrels of oil per day.

Reservoir rock age	Number of discoveries	BOPD
Jurassic	3	22,525
Jurassic and Cretaceous	3	8,227
Cretaceous	5	6,449
Cenozoic	0	0

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