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# Two-Dimensional and Three-Dimensional Numerical Simulation of Petroleum Systems Approaching the Deep-Water Gulf of Mexico (Kayab Area, Campeche Sound, Mexico): Definition of Thermally Mature and Prospective Areas

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## ABSTRACT

By integrating geological, geochemical, and geophysical data and using Temispack software, a two-dimensional (2-D) and three-dimensional (3-D) geological-numerical model is being developed for the sedimentary basins and petroleum systems in the Kayab offshore area.

The elements and processes of this petroleum system are intimately tied to its geodynamic history. The Oxfordian, Kimmeridgian, and Tithonian series contain source rocks buried to depths of between 4000 and 7500 m (13,123 and 24,606 ft). These sedimentary units are confined between autochthonous salt horizons, and allochthonous walls and intrusive bodies of salt. Salt is therefore a critical factor in the maturation of organic material (kerogen) in these strata. Salt-bounded subbasins are identified in which hydrocarbons were generated. The proximity to basement and the high thermal conductivity of the salt have generated liquid hydrocarbons from these source rocks. The numerical simulation of the

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shallower subbasins indicates that thermally immature conditions prevail, as in the case of the large Tunich structure.

Emphasis is placed on the importance of compression and halokinesis in focusing hydrocarbon migration toward Cretaceous breccia and limestone reservoirs within compressional stage anticlines and against salt wall structures.

The 2-D and 3-D numerical simulation permits the definition of drainage areas and petroleum accumulations in the Kayab area. In a preliminary manner, it has been possible to define the prospective areas and initially quantify the amount of trapped hydrocarbons. A hierarchy of economically viable prospects has been derived from the numerical simulation in this frontier region. These studies are fundamental in understanding this part of the marine region, presently characterized by heavy oil (Cantarell and Ku-Maloob-Zaap), and in predicting the existence of an important new heavy oil province in the deep-water Gulf of Mexico.

## INTRODUCTION

Recent exploration strategies in the Gulf of Mexico have directed studies and activities toward the continental slope and deeper water areas in the eastern part of Campeche Sound. These exploratory activities require regional studies, including basin modeling and petroleum systems, to evaluate exploration risk and identify exploration opportunities in this area. As the first step, exploration activities have begun in the Kayab area and adjacent deeper waters (200–1000 m, 656–3281 ft).

A basic geological model has been developed for the Kayab area, followed by numerical modeling of the evolution of the basin and its petroleum systems, including its thermal history, subsidence history, and kerogen maturation. The goal of this process is to understand the active petroleum systems and define the economic opportunities and petroleum prospects of the Kayab area. Numerical models employed the Temispack two-dimensional (2-D) and three-dimensional (3-D) modeling and simulation program (Ungerer et al., 1990; Rudkiewicz et al., 2000; Schneider et al., 2000), developed by the French Petroleum Institute and distributed by Beicip.

The basis for constructing the numerical models was the 3-D seismic data and wells drilled in the Kayab area. Information from seismic lines and wells adjacent to the Kayab area was also used, along with regional magnetometry, reports, and publications covering Campeche Sound. Among the most important studies conducted in this region is that of Ángeles (1982, 1988, 1993, 1996a, b), as well as numerous unpublished internal reports that have established the basic stratigraphic nomenclature for Campeche Sound. We also refer to studies by Ángeles et al. (1992) and Ángeles and Ortuño (1994) covering the stratigraphy and petroleum geology of this region, and the work of Araujo et al. (1986), Bello (1991), Ornelas et al. (1991), and Ornelas et al. (1994). Important work on the structural geology and tectonics of the area is that of Meneses (1980), Ramírez et al. (1996), and Salomón (1999). More recently, the structural aspect of Campeche Sound has been addressed by Mitra et al. (2005, 2006) on Cantarell-Sihil and Ku-Maloob-Zaap, respectively. Finally, in relation to petroleum geology and geochemistry of petroleum systems in Campeche Sound, we mention the fundamental work by Holguín and Romero (1982), Bañuelos (1993), García (1993), Hernández (1993), Medrano and Romero (1993), Ortega et al. (1995), Medrano et al. (1996), Romero et al. (1996, 2001, 2004), Guzmán and Mello (1999), Santamaría (2000), Santamaría and Horsfield (2000), and Guzmán et al. (2001) and the internal compilations conducted by the Instituto Mexicano del Petróleo (IMP) (2000), ''Atlas de las cuencas sedimentarias terciarias y mesozoicas de México,'' and by the Región Marina Noreste (RMNE) (2002), ''Sistemas petroleros en el área Tunich-Chilam.'' Most recently, Holguín et al. (2005) have presented a review of hydrocarbon seeps in the southern Gulf of Mexico.

## GENERAL GEOLOGIC CONTEXT

From the geological perspective, the Campeche marine region, as part of the Maya terrane, originated during the rifting and spreading phase of the Gulf of Mexico. Its basement consists of thinned transitional crust consisting of schists and granitoids intruded by hypabyssal calcalkaline igneous bodies as determined from potential field and geochemical and petrogenetic studies by the Mexican Petroleum Institute (2000). This was an area of internal and external shelf deposition during the Cretaceous and finally became the locus of Cenozoic siliciclastic deposition. This regional framework controlled the Mesozoic and Cenozoic geodynamic evolution of the Campeche Marine area, including its structural and tectonosedimentary characteristics.

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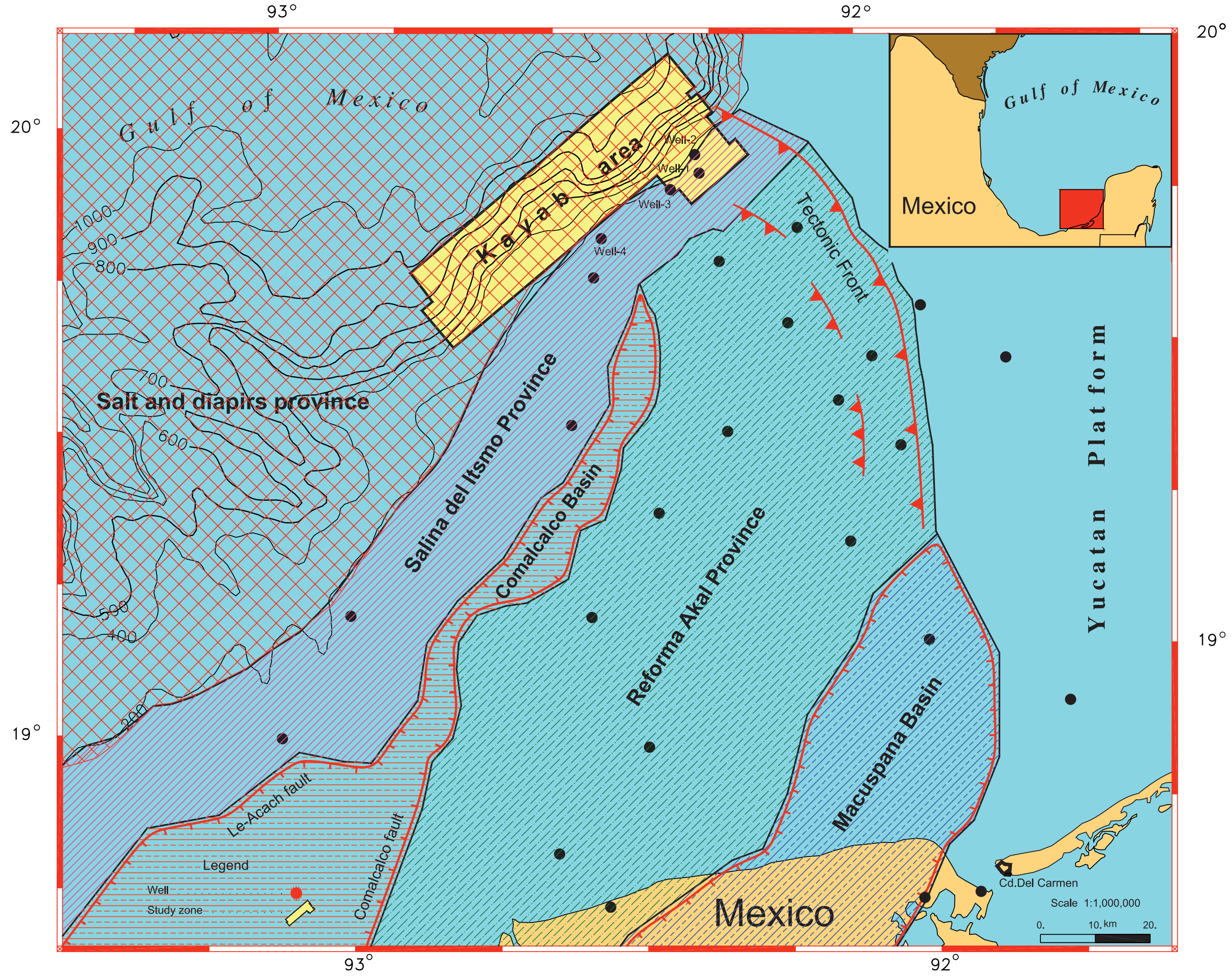

**FIGURE 1.** Location of the Kayab area in the Campeche Sound.

Figure 1 shows the location of the study area within the context of the geological provinces and tectonic entities of the Gulf of Mexico.

Sedimentary units overlying this basement were deposited throughout the entire Mesozoic and Cenozoic history of the Gulf of Mexico, as seen in the stratigraphic column in Figure 2. The oldest unit, which has not been penetrated by wells in the Marine Region, is inferred to be a siliciclastic sequence of continental origin (red beds) deposited during the initial stages of rifting. This continental sedimentary sequence overlies the basement and is probably of Middle Jurassic age with an average thickness of about 1000 m. This unit is overlain by an evaporite sequence (principally salt) of Callovian age whose thickness ranges from 500 to 4000 m (1640 to 13,123 ft) because of tectonic deformation. The Oxfordian series also varies greatly in thickness, generally between 500 and more than 1500 m (1640 and more than 4921 ft). Some wells have only reached the upper part of this sequence, a facies with source rock characteristics. In contrast, the Kimmeridgian and Tithonian series are thinner, each with average thicknesses of 200–300 m (656–984 ft). Of these, the Tithonian comprises the area's most important hydrocarbon-generating unit. The Cretaceous strata consist essentially of carbonates with thicknesses ranging from 600 to 1000 m (1968 to 3281 ft). Finally, siliciclastic Paleogene and Neogene units vary in thickness depending on their tectonosedimentary evolution during compression and salt tectonics. The average thickness of the Paleogene is about 700 m (2296 ft), and about 4500 m (14,764 ft) for the Neogene (Ángeles, 1996a; Ortuño et al., 2004). A representative Mesozoic–Cenozoic sedimentary column for the study area and Campeche Sound is shown in Figure 2.

Respecting structural styles and tectonic evolution, it is possible to distinguish between the deformation because of compression and that related to halokinesis, the latter consisting of enormous salt intrusions cutting across the Mesozoic and Cenozoic sedimentary sequences.

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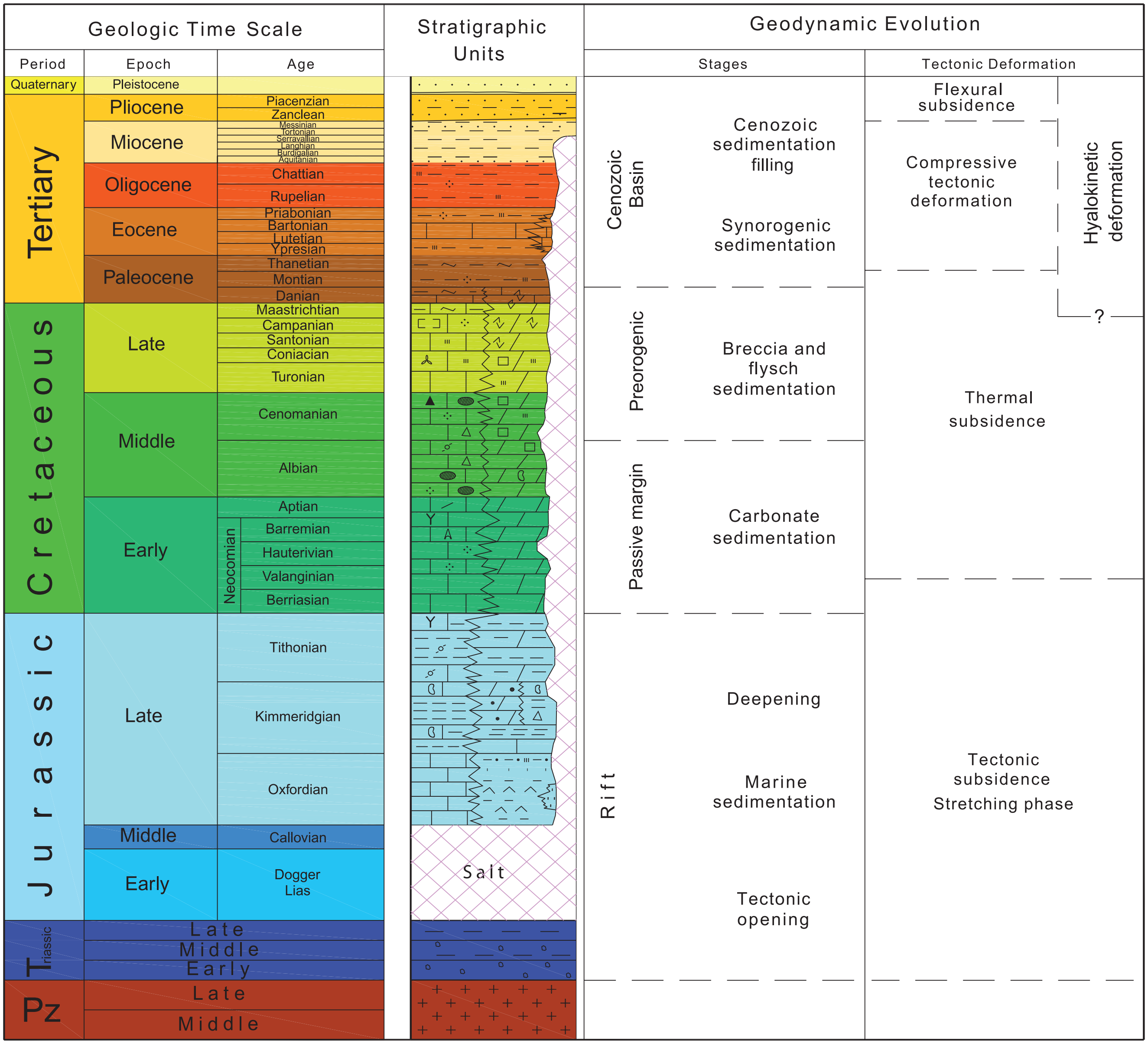

**FIGURE 2.** Generalized stratigraphic column for the Campeche marine region as it relates to the geodynamic evolution of the Kayab area.

The estimated age of the compressional tectonics is end Paleogene–lower Neogene comprising fault-propagation folds and reverse faults verging toward the northeast. Tectonic shortening is in the order of 10–14% depending on the location within the study area. The compressional tectonic style in the Kayab study area is very similar to that found within the tectonic front of Cantarell, Sihil, and Ku-Maloob-Zaap by Mexican specialists and later described by Mitra et al. (2005, 2006). It is evident that the geometries of the basement and the thick overlying Mesozoic–Cenozoic sedimentary series controlled both the dynamics and final geometry of the halokinesis. Moreover, depositional subbasins that formed during the Neogene (mainly in the Miocene) were a response to halokinetic inversion dynamics (Ortuño et al., 2004). Figure 3 is a schematic representation of the prevailing structural style in the study area along a southwest-northeast–oriented geological section based on seismic data.

The main objective of this study was to build a numerical model of hydrocarbon generation and migration in the Kayab area, as well as identifying the elements and processes of the existing petroleum systems employing the Temispack 2-D and 3-D program.

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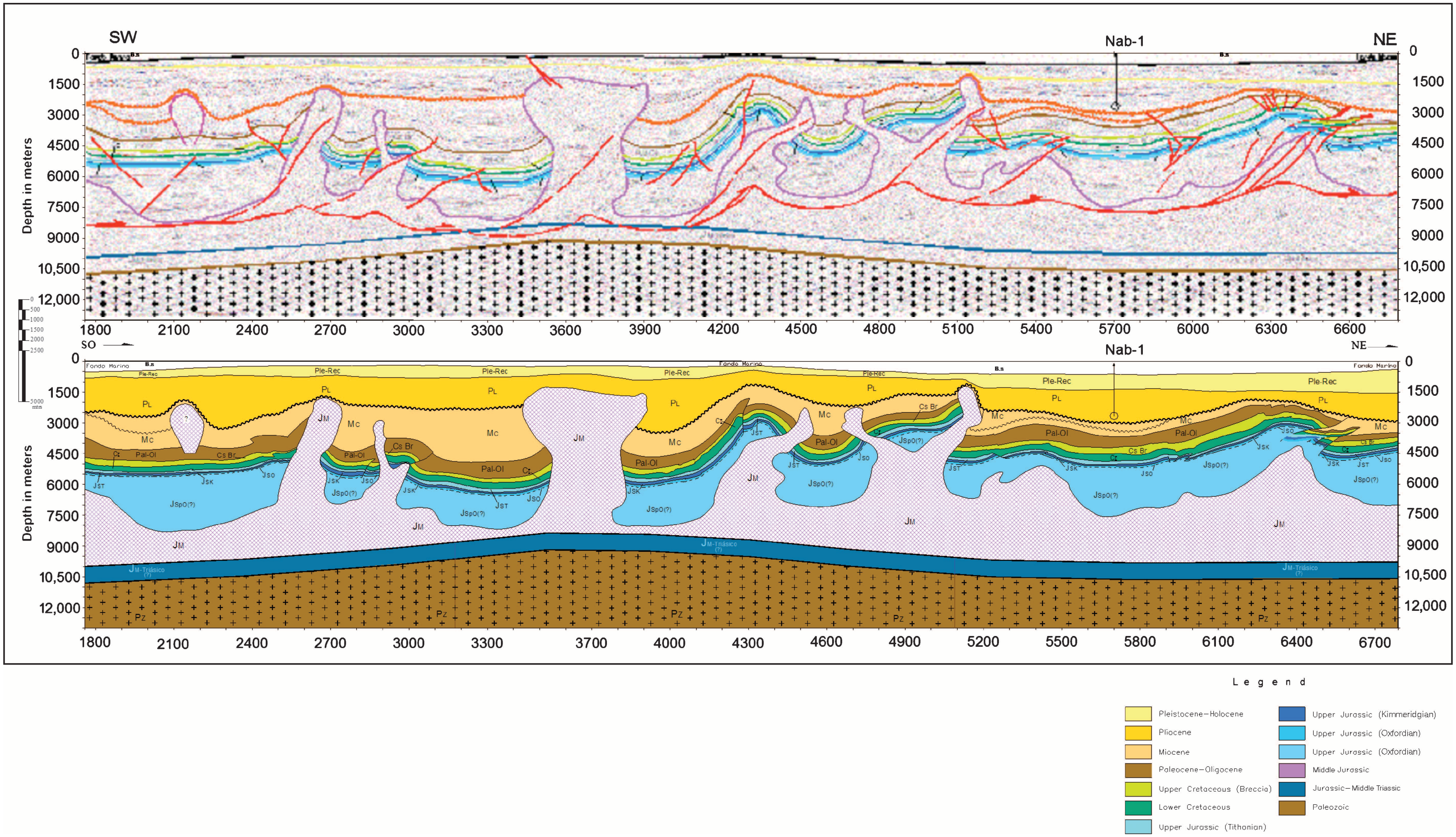

**FIGURE 3.** Representative geological section for the Kayab area. The geological section shows the complexity of the structure and the general structural style in the study area. Ple-Rec = Pleistocene-Recent; PL = Pliocene; Mc = Miocene; Pal-Ol = Paleocene-Oligocene; Cs Br = Upper Cretaceous (Breccia); Cs = Upper Cretaceous; Ci = Lower Cretaceous; Jst = Upper Jurassic Tithonian; Jsk = Upper Jurassic Kimmeridgian; Jso = Upper Jurassic Oxfordian; JspO (?) = Upper Jurassic (probably Oxfordian); JM = Middle Jurassic; Pz = Paleozoic.

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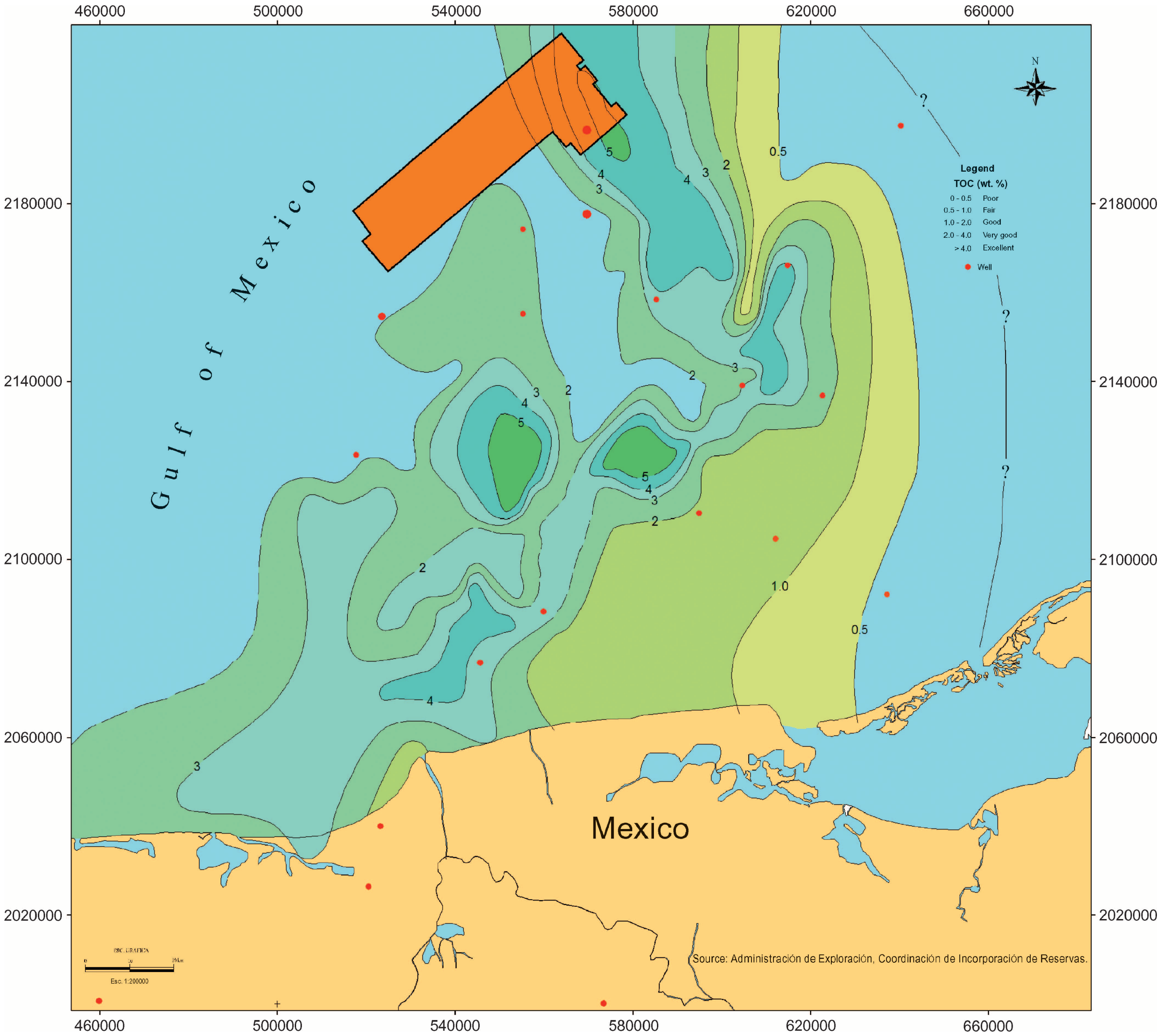

Source: Administración de Exploración, Coordinación de Incorporación de Reservas.

**FIGURE 4.** Map of Tithonian total organic carbon (TOC) distribution in the Campeche marine region and the study area. Source of data: Activo región Marina, PEMEX.

## GENERALIZED ECONOMIC GEOLOGY OF PETROLEUM IN CAMPECHE SOUND

The following discussion is a general panorama of the petroleum factors and processes affecting Campeche Sound and describes the source and reservoir rocks. These updated data integrations were provided by the Reserve Incorporation Coordinating Office of the Northeast Marine Region and served as the basis for numerical modeling in Temispack.

### Source Rocks (Tithonian, Kimmeridgian, and Oxfordian)

The predominant lithologies in the Tithonian series are argillaceous limestones and calcareous shales deposited in a deep-water anoxic environment. The Tithonian facies is widely and continuously distributed in the Campeche marine region. This is the principal component of the petroleum system and generated nearly all the hydrocarbons produced from several stratigraphic levels in the Campeche Sound. The Kimmeridgian series, with source rock characteristics in its shaly sections, covers a smaller area than the

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Tithonian. Finally, some intervals in the Oxfordian series also have source potential. Tithonian, Kimmeridgian, and Oxfordian source rocks are shown in the stratigraphic chart in Figure 2.

The Oxfordian and Kimmeridgian units in the classic Campeche Sound sections each have an average thickness of about 600 m (1968 ft), whereas the Tithonian may average 200 m (656 ft). It is probable that the Tithonian, Kimmeridgian, and Oxfordian are thinner (~200 m [~656 ft] each) condensed sections in the Kayab area deeper water environment, although their total organic carbon (TOC) values may be higher because of better preservation of their organic content.

The TOC of the Tithonian series across Campeche Sound is quite variable with values ranging from 0.5 to 5.0%. The kerogen is type 1–2 (oil prone) to 2 (oil and gas prone), and occasionally type 2–3. The TOC values in the Kayab area generally range between 4 and 6% (Romero et al., 2001). Organic material within the Kimmeridgian is of good quality derived from algae (kerogen type 2) with TOC values from 0.5 to 3.0% (Ángeles, 1996b). The Oxfordian series in the marine region has TOC contents ranging from very low to very high within a relatively small area; e.g., they are quite variable and spatially discontinuous (Romero et al., 2001). Figure 4 shows the general TOC distribution of the Tithonian series in the study area.

The maturity of the kerogen, or its degree of transformation into hydrocarbon, is defined on the basis of maximum pyrolysis temperature ($T_{\max}$) and vitrinite reflectance ($R_o$). The $T_{\max}$ values in the Tithonian of the marine region are mainly between 435 and 460°C, corresponding to the oil generation window. Over most of the marine region, the Tithonian source rocks are in the oil and gas generation window, becoming overmature only in the central and shoreward parts of the area. The Tithonian is thermally immature in the northeastern part of Campeche Sound.

The $R_o$ values for the Tithonian and Oxfordian series exceed 0.4%, having reached thermal maturity for the generation of liquid hydrocarbons. These rocks have not reached the $R_o$ threshold value of 1.2% required for thermal gas generation. Only the Tithonian has measured values approaching 1.1% $R_o$ (Ángeles, 1996a, b; Romero et al., 2001). Figure 5 shows the $R_o$ value distribution for Campeche Sound, including the study area. The areas of greater thermal maturity (0.5–1.3% $R_o$) lie in the southern part of the Gulf of Mexico (Figure 5).

With the application of these geochemical parameters to the model, generation-expulsion in Campeche Sound occurred during the Miocene–Pliocene.

### Reservoir Rocks (Kimmeridgian, Lower and Upper Cretaceous, and some Cenozoic Intervals)

Several reservoir units for hydrocarbons generated from the Tithonian system are observed, including the Kimmeridgian facies, Lower Cretaceous limestones, Upper Cretaceous breccias, and sandstones at different stratigraphic levels in the Cenozoic (Ortuño et al., 2004). Of these rocks, the most prolific producers are the Upper Cretaceous breccias. These rocks are shown in the stratigraphic column of Figure 2.

Sealing units correspond to shales, and trapping structures are folds related to the compressional and halokinetic episodes. The sealing beds occur at several stratigraphic levels within the Upper Jurassic, Paleogene, and Neogene.

## THE MODEL AND NUMERICAL SIMULATION IN TEMISPACK 2-D AND 3-D

The integrated numerical simulation of petroleum systems in the Kayab area consists of two parts: a 2-D simulation evaluated on two-dimensional geological sections and a 3-D simulation wherein several maturity parameters are calculated and visualized in three dimensions.

The particular methodology used in the modeling and numerical simulation consists of the following fundamental steps: (1) construction of the 3-D geological model; (2) the integration of thermal and geochemical parameters; (3) 1-D modeling; (4) 3-D modeling; (5) an estimation of generation processes; and (6) the definition of drainage areas, volumetric calculations, and prioritization of prospects.

For the 2-D simulation, interpreted geological sections were interpreted from seismic data (Figure 6). The specific 3-D Temispack model was constructed from stratigraphic horizons identified in the Kayab 3-D seismic volume. Thirteen stratigraphic horizons were identified and used to construct the 3-D volume in Temispack.

As for the construction of the numerical model, it was assumed that the tectonic deformation only created small folds and a tectonic ramp in the Tunich anticlinal structure, which was slightly displaced. Thus, it is also assumed that the tectonic horizontal displacement did not influence the thermal maturity of the source rocks. Considering this factor, and being aware that horizontal displacements are not handled by Temispack, the geologic model only included the thicknesses of the sedimentary columns, their position at depth, the degree of subsidence, compaction, and the vertical displacements of salt intrusions. Vertical movements related to subsidence and a high rate of Cenozoic sedimentation are the main factors that have placed the source rocks in the oil window.

### Construction and Calibration of the Numerical Model

The 3-D model was constructed from depth-converted seismic horizons. After this step, the lithologic and petrophysical properties for each stratigraphic horizon were

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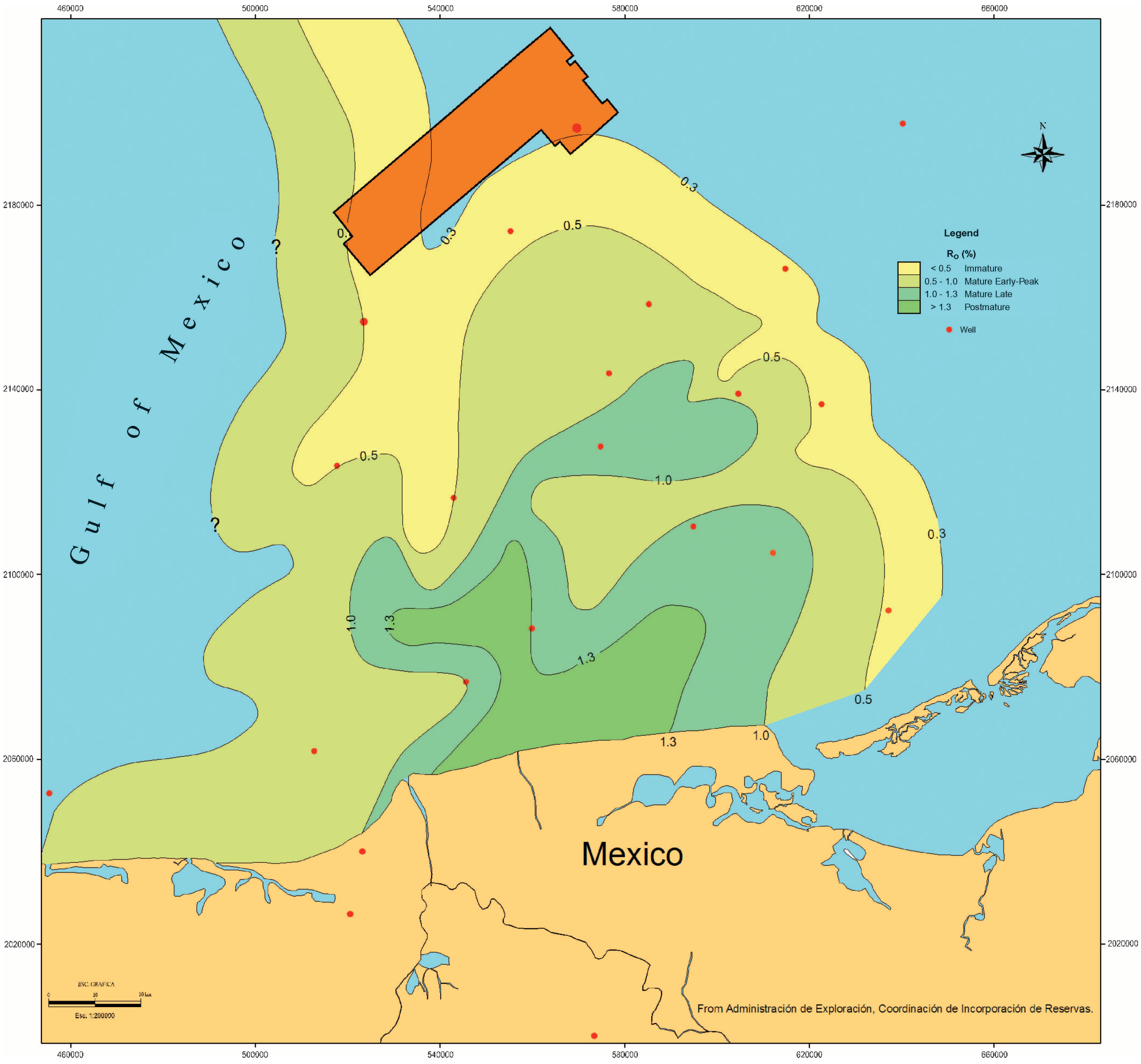

From Administración de Exploración, Coordinación de Incorporación de Reservas.

**FIGURE 5.** Map of Tithonian vitrinite reflectance ($R_o$) distribution in Campeche Sound and the study area. Source of data: Activo Región Marina, PEMEX.

defined and attributed by integrating all existing data. The 1-D numerical model was derived by simulating the thermal maturity of kerogen in the lithologic column while characterizing the lithofacies and geochemical attributes of all generating levels with their temperature distribution, and other important parameters.

The top and geometry of the basement proceed from the magnetometric and gravimetric model, as well as the petroleum genesis studies conducted by the Mexican Petroleum Institute (2000).

At this stage, calibrations were made of the wells and pseudowells in the study, consisting principally of their temperatures, geothermal gradients, heat flows, $R_o$ values, $T_{max}$ values, etc. The principal calibrations concerned temperature determined from bottom-hole measurements. These calibrations were done for the different models that were constructed. In all cases, the analytical data were adjusted to the modeled results. Generally, the most sensitive and variable of the parameters in the modeling was the temperature. Disparities were noted between the analytical and modeled curves, but these intervals were, in reality, minor. The simulations were run under two scenarios by placing the crust-mantle interface at 1300°C as the heat source with pre-established heat flows. The heat flow range that most closely matched the analytical data was between

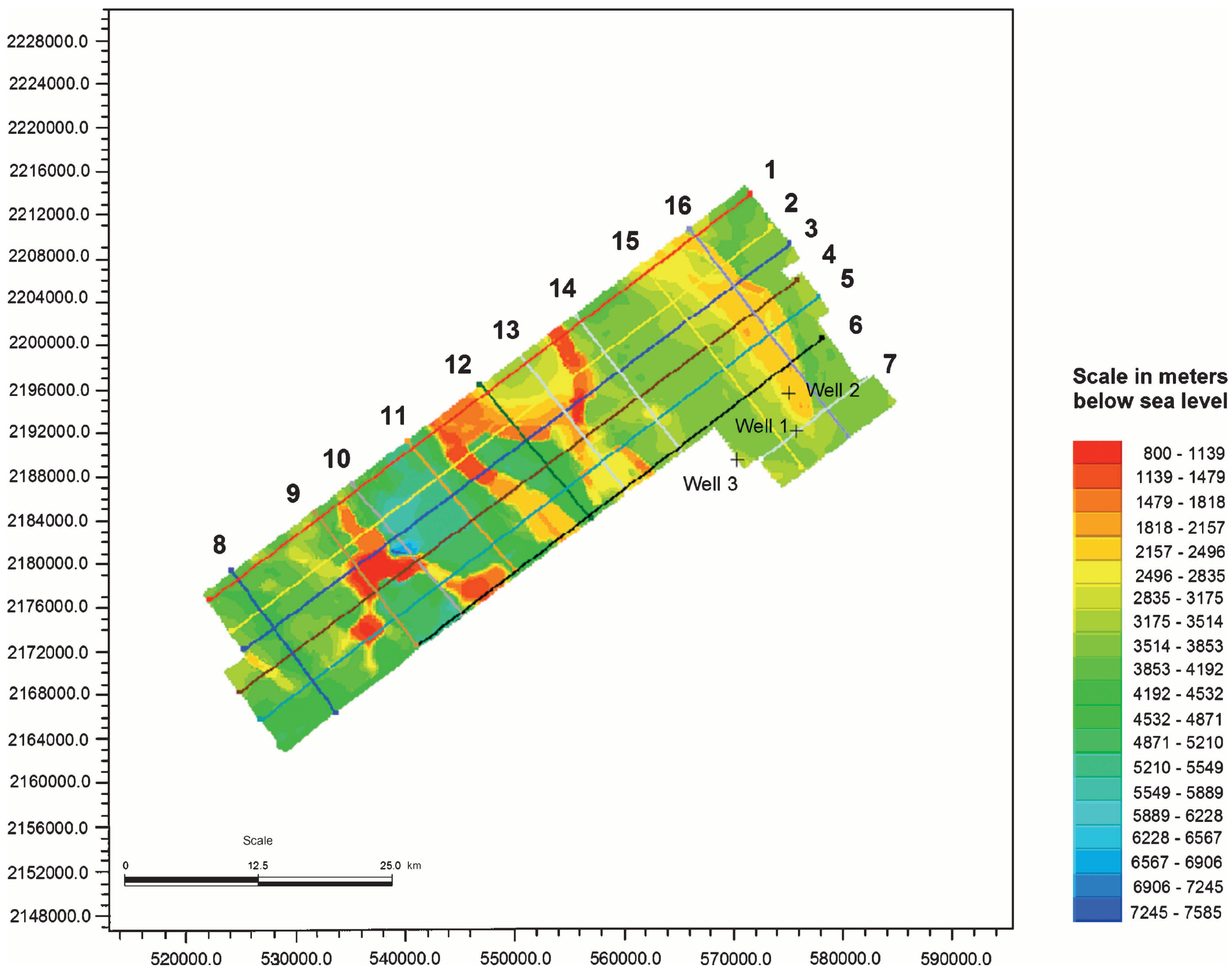

**FIGURE 6.** Location map for geological sections modeled in Temispack 2-D. The background is the Breccia stratigraphic horizon. The numbers correspond to the modeled geological sections, only a few of which are included in this chapter (the numbers of the 2-D sections are very difficult to see).

20 mW/m$^2$ and 30 MW/m$^2$ and, in some cases, by modifying the magnitude of heat flow through the geological history of the basin. The Kayab area is situated on the continental crust in the vicinity of the Yucatan Platform, a region of low to medium heat flow.

Figure 7 shows two of the applied adjustments, i.e., temperature and $T_{\text{max}}$, for the different runs that were conducted. The heat flows obtained through the model were congruent with the limited data available in the study area. Besides the mentioned wells, other nearby wells were used for a more precise calibration. These calibrations were adequate compared to the known bottom-hole temperature, gradient, and heat flow data in the area of Campeche Sound.

The presence of intrusive salt bodies within the Mesozoic and Cenozoic section required a detailed kinematic-structural analysis of the deformation and diapiric emplacement into the sedimentary column using the seismic data and geological cross sections instead of the modeling software. Once the kinematic and tectonic evolution of the intrusive bodies was defined, adjustments were made and thermal history scenarios constructed to adequately model the influence (anomalous conductivities) of the salt bodies on the thermal evolution of kerogen in the source rocks. Comparison of the model results with actual data in the study area was a fundamental aspect in calibrating the simulation.

## Two-Dimensional Numerical Simulation on Geological Sections (Generation and Expulsion)

Among the most important parameters generated by the simulation and plotted on the geological sections whose locations are shown in Figure 6, are $T_{\text{max}}$, transformation ratio (TR), fluid saturations in the source rocks, $R_o$, and temperature distribution in the sedimentary column. Some of these parameters are discussed below and are referred to on the geological sections shown in the figures.

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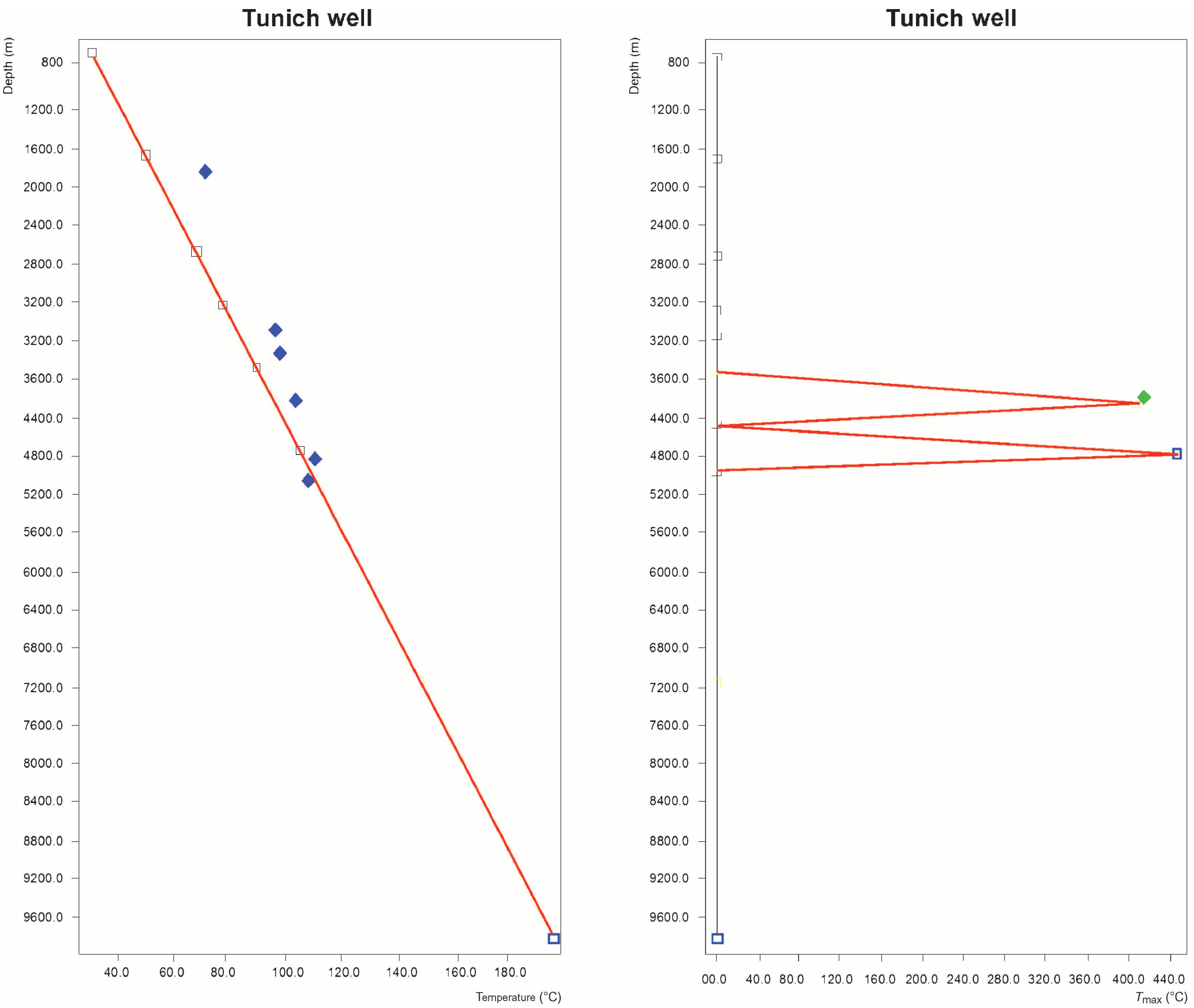

**FIGURE 7.** Calibrations between temperature and $T_{max}$ data and results of modeling of the Tunich well.

### *Distribution of Maximum Pyrolysis Temperature*

The values of this parameter range from less than 410 to about 490°C for Tithonian to Oxfordian source rocks. The highest values correspond to the deepest subbasins and the lowest in the shallowest subbasins, as in the case of the Tunich structural subbasin.

### *Transformation Ratio*

The evolution of this parameter is shown on geological sections 3 and 11 (Figures 8, 9). The TR values in the subbasins of the southwestern Kayab volume, located between salt intrusions, range from 0.3 to 0.7, reaching perhaps 0.8 or 0.9. Therefore the Tithonian and Oxfordian rocks, as well as the Kimmeridgian, are considered to be in the hydrocarbon-generating window. The TR values in the Tunich well are very low and do not indicate sufficient maturity to have expelled hydrocarbons.

### *Vitrinite Reflectance*

The $R_o$ values range, in general, from 0.5 to 1.0% in Tithonian and Oxfordian source rocks across the study area. According to these results, the deeper subbasins are in the initial stages of maturity (in the case of Tunich area), whereas only the deepest subbasins (areas of the greatest subsidence) would be in the very mature generation stage (block 3-D in Figure 10).

### *Fluid Migration and Generated Hydrocarbons*

From the 2-D numerical simulation of the Kayab sections, it is possible to visualize a nominal scheme

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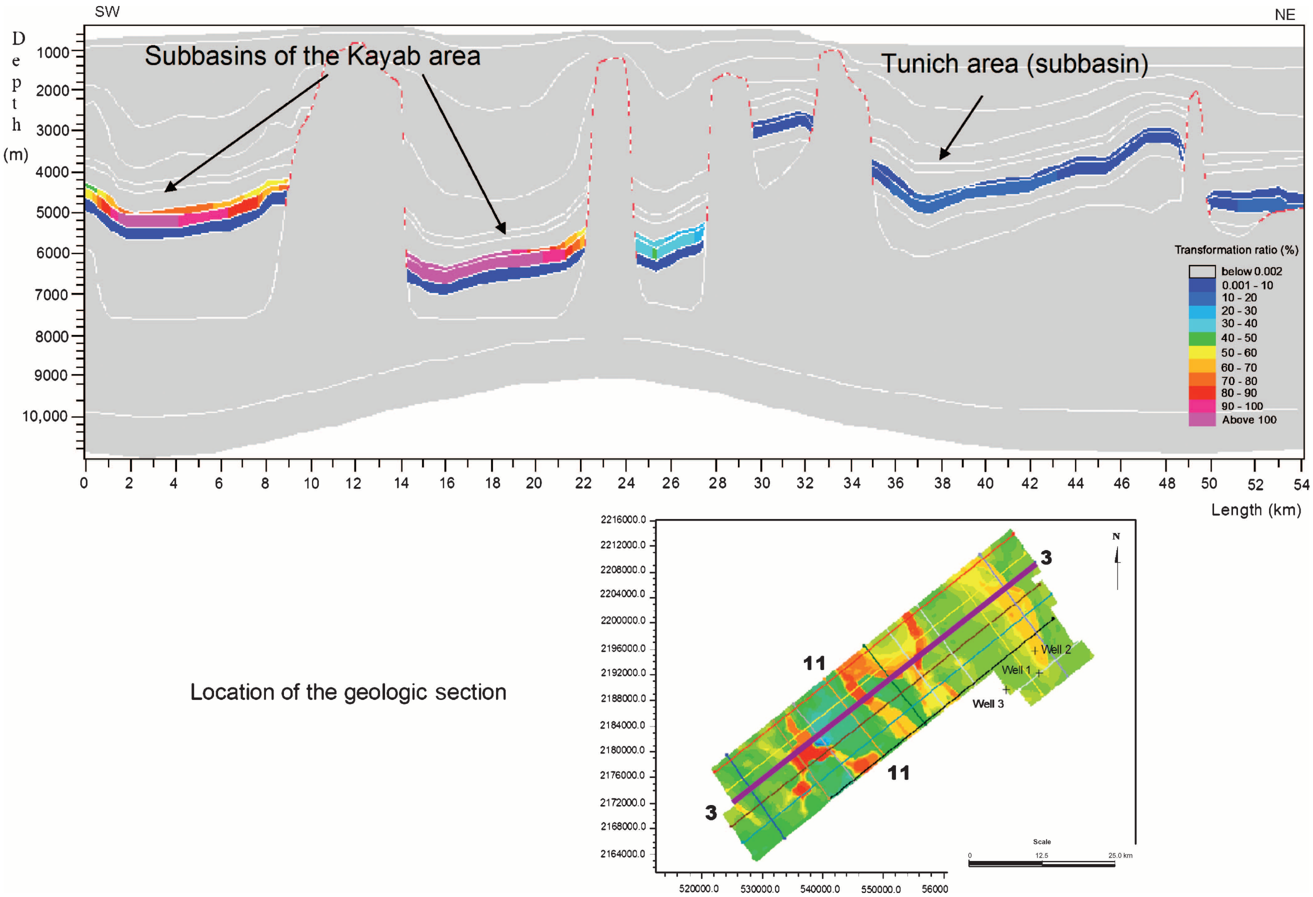

**FIGURE 8.** Distribution of transformation ratio (TR) magnitudes for the Tithonian, Kimmeridgian, and Oxfordian series along geological section 3. The TR values for these series in the zones of maximum subsidence are 10%, whereas for the Tunich area, the respective values are very low.

for fluid migration pathways through the several different lithofacies that are involved. Among fluids migrating through the rocks is water from the compaction of diverse lithologies, as well as fluids produced during different phases of hydrocarbon generation. Some of these fluid (hydrocarbon) migration pathways are depicted on section 11 (Figure 11). Among these, the most important are vertical migration routes that ascend into Cretaceous strata or toward anticlinal structures that close toward salt intrusions. These migration pathways tend to ascend through the Cretaceous and Cenozoic series in anticlinal structures and along the salt walls.

### *Thermal History*

The numerical simulation provided estimates of some of the thermal parameters that controlled the maturation of the organic matter, including heat flow, temperatures, and geothermal gradients.

Heat flow values of 25 mW/m$^2$ to more than 40 mW/m$^2$ were obtained for the Upper Jurassic units in the different subbasins. The higher values correspond to the subbasin in section 11. Temperature values for the source rocks are estimated to range from 100 to more than 160°C, and temperature gradients were critical for generation from the source rocks.

The salt acts as a catalyst for maturation of the kerogen; however, it may also retard maturation (Stover et al., 2001). This is dependent on the existing geometry of the salt and the rocks around it. From the analysis of these thermal parameters, it may be deduced that the subbasins southwest of Kayab are at different stages of hydrocarbon generation. Consistent with the preceding parameters, the Tunich structure is shown to have the lowest heat flow, temperature, and gradient values. In general, the temperature at Tunich structure did not exceed 120°C (Jurassic and Cretaceous at depths of 3500–4500 m [11,483–14,764 ft]), which corresponds to a zone with hypothermal (prematuration) characteristics.

## Three-Dimensional Numerical Simulation

This simulation mode incorporates the complete 3-D volume constructed in Temispack, and its visualization

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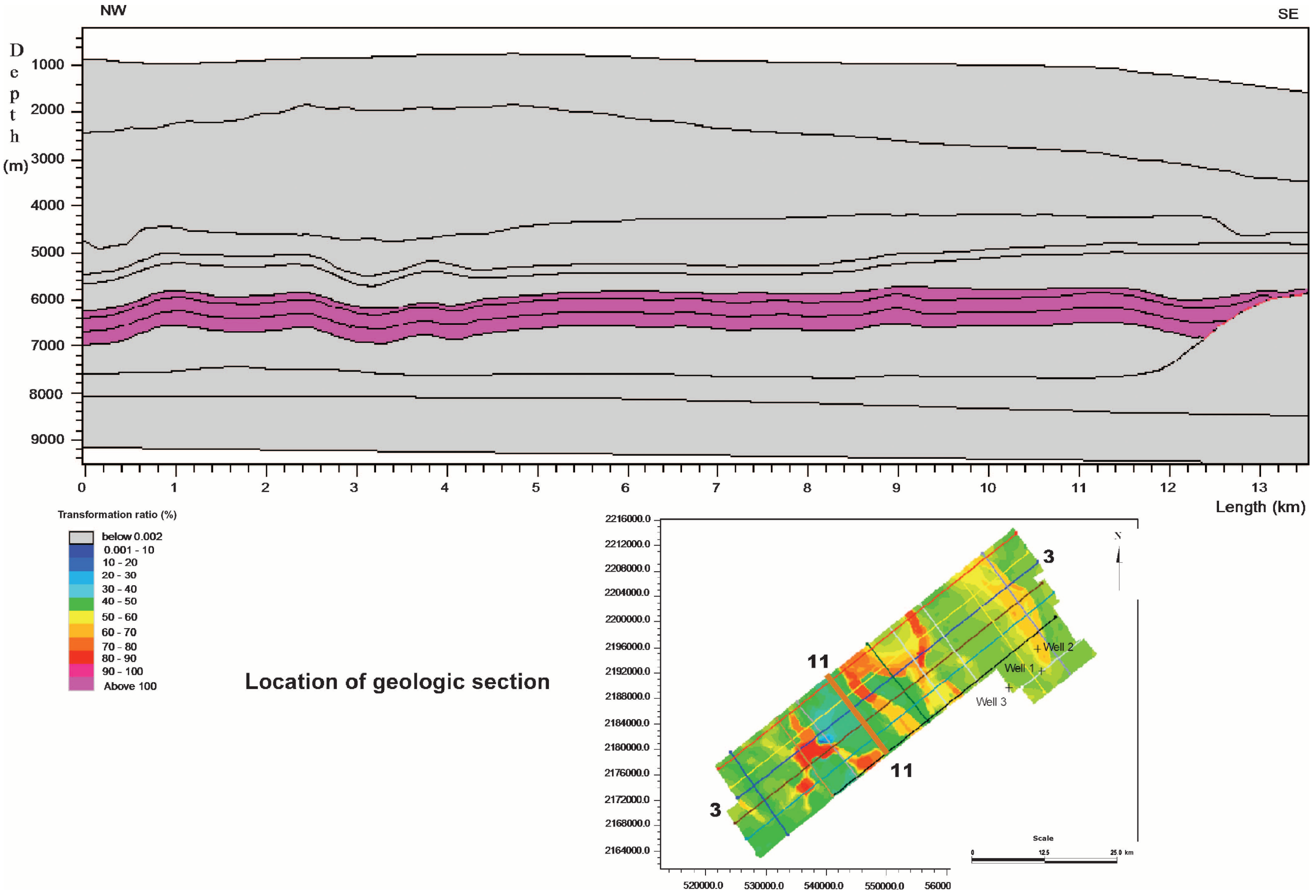

**Figure 9.** Estimate of the transformation ratio (TR) magnitudes for the Tithonian, Kimmeridgian, and Oxfordian series (red-pink) along geological section 11. The corresponding values exceed 60%.

permits the observation of the actual values and evolution of variables that indicate the thermal maturity of the kerogen. Figures 10 and 12 illustrate the results of 3-D modeling for two parameters within the stratigraphic section of the basin, i.e., $R_o$ and temperatures.

The $R_o$ distribution is shown in Figure 10, where values are between 0.5 and 1.0 in the deepest, most subsided subbasins. The values in the 3-D models agree with modeled estimates from the 2-D geological sections. The 2-D sections were extracted from the 3-D model, but an independent 2-D model was run for each of these sections using the same geochemical parameters.

Figure 13 shows the evolution of TR through the late Oligocene, late Miocene, Pliocene, and Pleistocene to Holocene for the Tithonian series. This evolution shows a gradual increase in maturity with the resulting generation-expulsion of hydrocarbons as the subsidence and temperature of the source rocks increased, mostly because of abundant Miocene to Pleistocene sedimentary overburden. The TR, therefore, would have been less than 0.1 during the Paleocene, whereas in the Miocene, TR values varied from 0.1 to 0.4 indicating potential incipient generation at that time. In the Pliocene, however, TR values reached levels of 0.4 to 0.8 in parts of the deepest subbasins, and hydrocarbons were clearly generated from the Tithonian strata. Finally, during the Holocene, TR values range from 0.4 to more than 0.8. Therefore, Tithonian source rocks have generated and expelled hydrocarbons since the Pliocene, and the petroleum system is currently still active. The temperature estimates would be about 140°C. In this way, maturity parameters for the Oxfordian rocks can be estimated. The evolution of this system through geological time is the basis for constructing timing diagrams that show the effects of critical elements and processes on the petroleum system.

Note that the Tithonian and Oxfordian source rocks are thermally immature in the area of the large fault-propagation fold in the northeastern part of the represented area penetrated by the Tunich 1 and 101 and Baksha wells.

A preliminary conclusion from the 3-D model of kerogen maturity is that two active petroleum systems currently generating and expelling hydrocarbons (Tithonian and Oxfordian) in the subbasins of the southwestern Kayab area exist. Of these, the most prolific would be the Tithonian. The proof of this will depend on new exploratory drilling.

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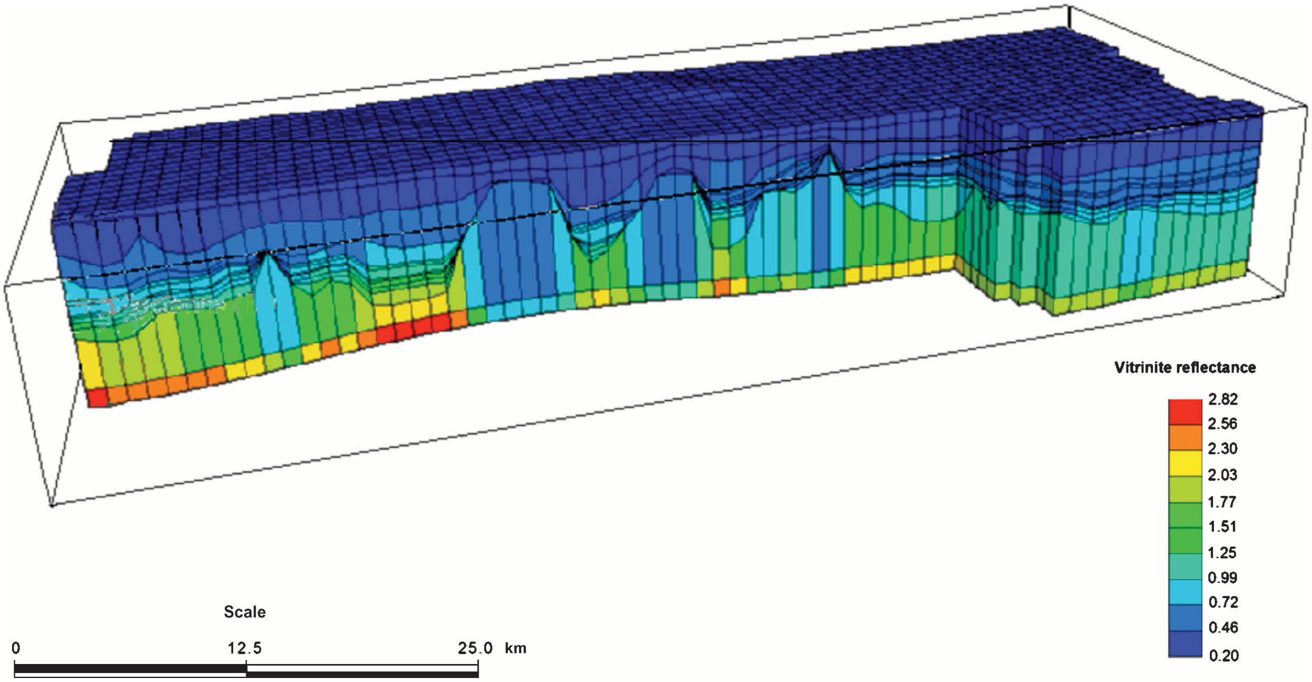

**FIGURE 10.** Distribution of nominal vitrinite reflectance ($R_O$) values for the sedimentary sequence across the 3-D area. The nominal $R_O$ values for Tithonian and Oxfordian source rocks range from 0.5 to more than 1.0 in the areas of greatest subsidence. These values are lower in the Tunich area, indicating the immaturity of the kerogens.

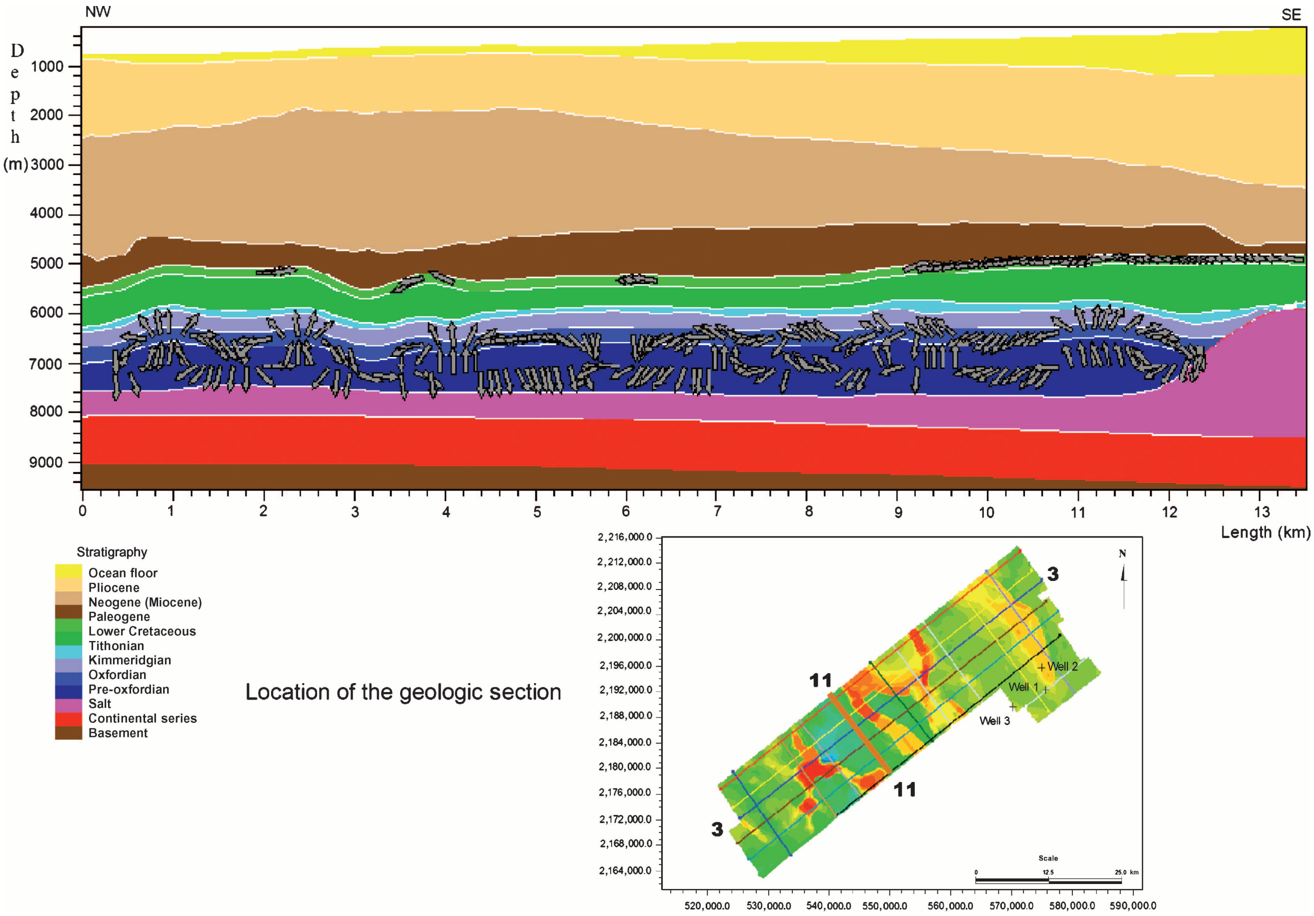

**FIGURE 11.** Estimate of hydrocarbon migration pathways from the Tithonian, Kimmeridgian, and Oxfordian source rocks along geological section 11.

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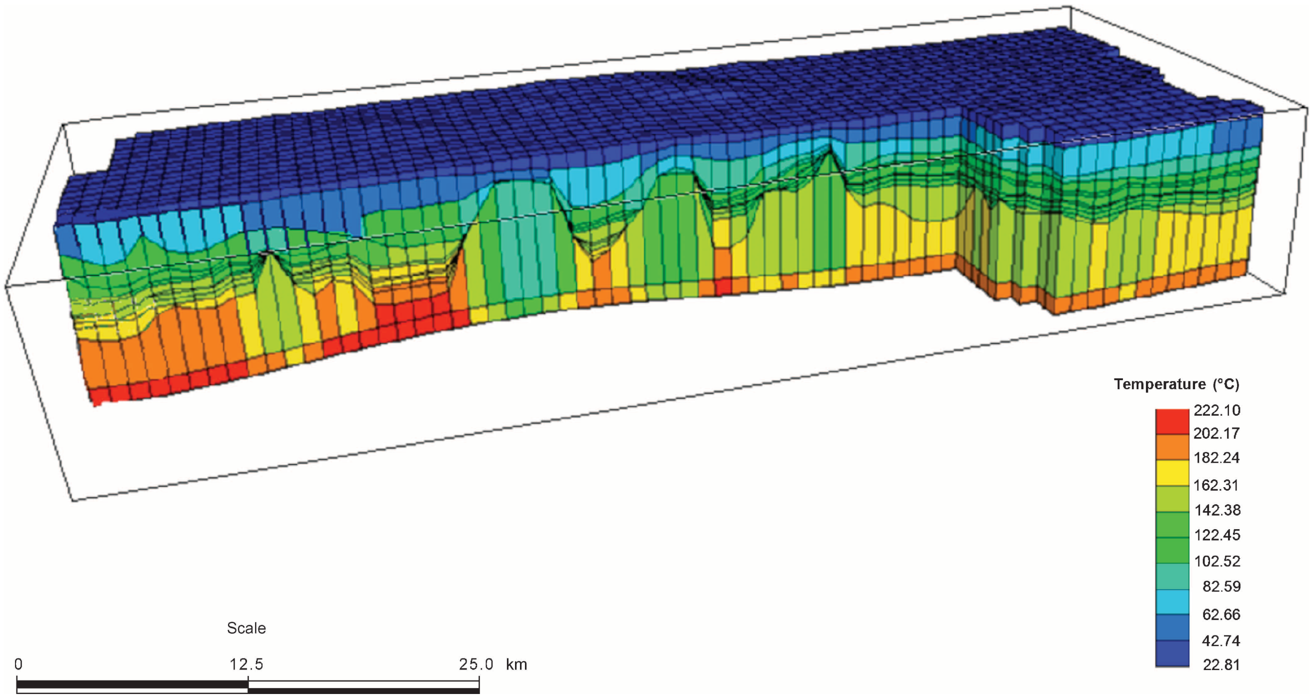

**Figure 12.** Distribution of temperature values across the Kayab 3-D area. The temperatures in the deepest subbasins (at the Upper Jurassic level) oscillate around 135°C (intervals range between 120 and 165°C), whereas the temperature in the Tunich structure is approximately 90 or 100°C.

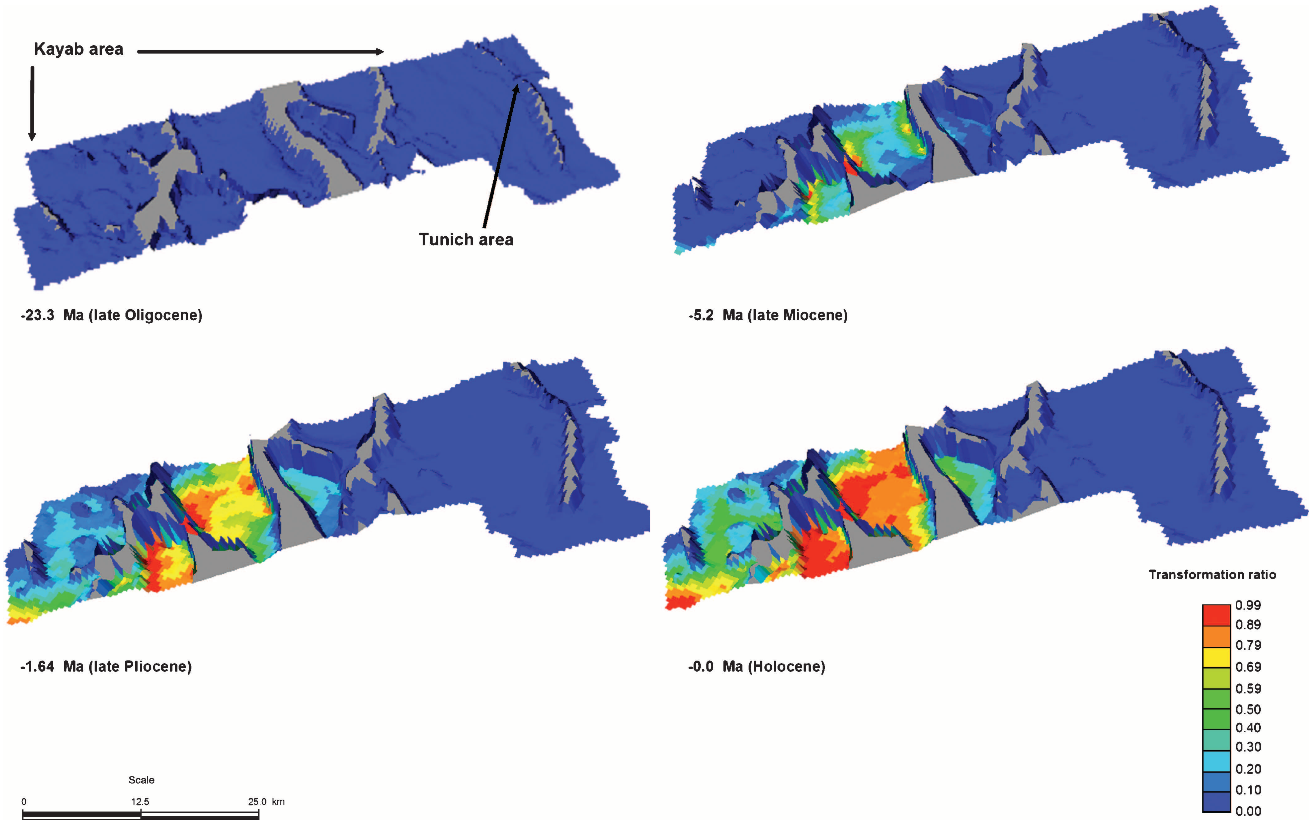

**Figure 13.** Evolution of transformation ratio (TR) magnitudes in the Tithonian rocks during (a) Paleocene, (b) Miocene, (c) Pliocene, and (d) Pleistocene–Holocene. These values continuously increase through time until achieving maxima of around 1.0, with a Pleistocene–Holocene low of 0.3 in the southwestern part of Kayab. The Tunich area shows consistently low TR values (0.1 or less), indicating an immature thermal state.

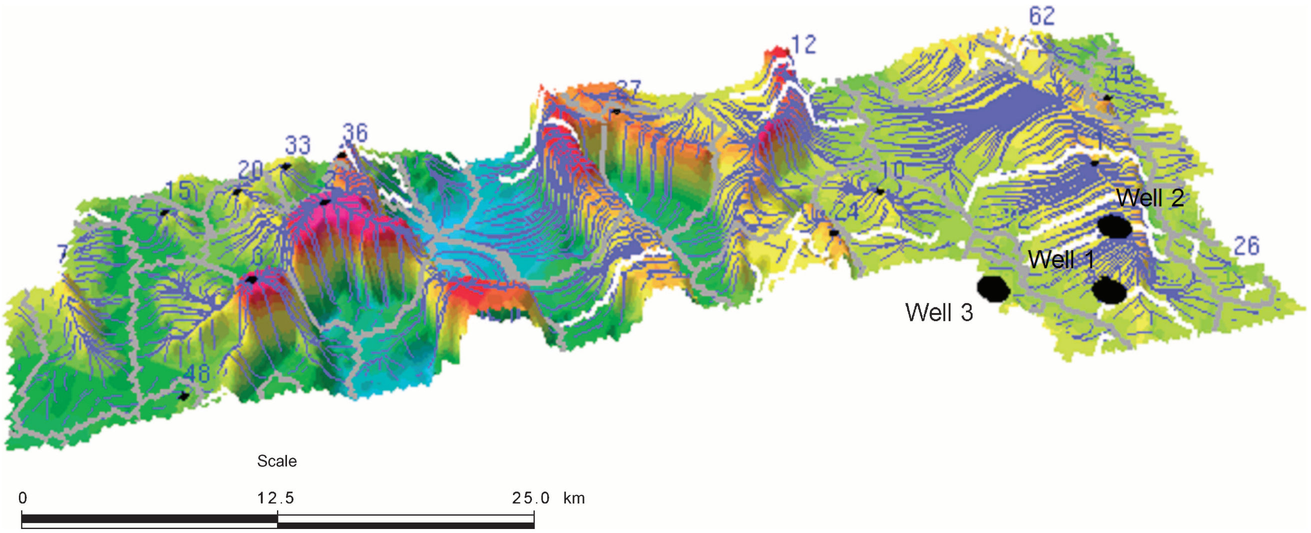

**FIGURE 14.** The 3-D configuration of drainage areas showing hydrocarbon flow susceptible to trapping at the Upper Cretaceous Breccia level. Blue lines show the most likely path of gravity migration in the reservoir rocks toward structural highs (or traps). The crests in this depiction are continuous, although in most cases, the Breccia level is interrupted by intrusions of Callovian salt. This estimate is based on the geothermal gradients. The Tunich area is very risky for the breccias level because the source rocks are immature in this area, but the migration possibilities are good.

## Identification and Prioritization of Prospects (Drainage Areas)

The evaluation of drainage areas presented in this section corresponds to an analysis of reservoir rocks, sensu stricto; specifically, an estimation of the volume of migrated hydrocarbons trapped in Upper Cretaceous Breccia reservoirs (Figure 14).

The numerical simulation of the Upper Cretaceous Breccia reservoir permits an evaluation of the structural configuration at the top of the unit, as well as quantification of its hydraulic capacity to trap hydrocarbons, and finally, the quantification of theoretical volumetric capacity in these drainage areas. Figures 14 and 15 show the subdivision of drainage areas for the Breccia and its 3-D configuration. The blue lines trace the ascending migration pathways of the hydrocarbon fluids toward the crests of the structures.

An analysis of these volumetric estimates makes it possible to develop a preliminary prioritization of prospects, drainage areas, and hydrocarbon trapping areas. The prioritization is based on the capacity or the volume of stored hydrocarbons for each structure. Figure 15 depicts this prioritization by red zones numbered 1 to 5.

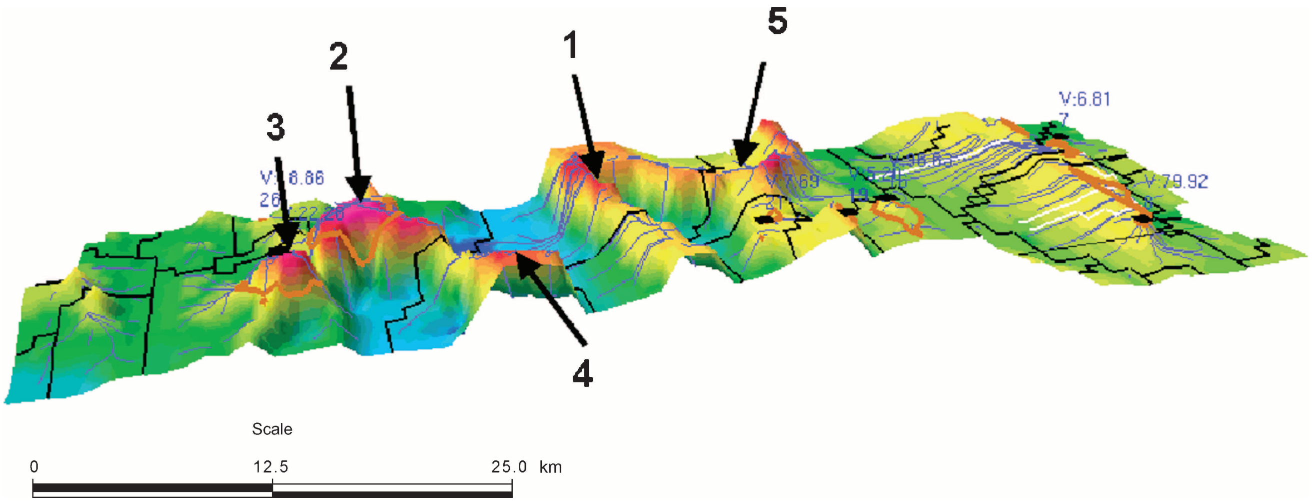

**FIGURE 15.** Structural configuration at the top of the Breccia delimiting hydrocarbon drainage areas. The highs are zones of trap development, of which the most important are numbered. Brown lines represent possible structural traps.

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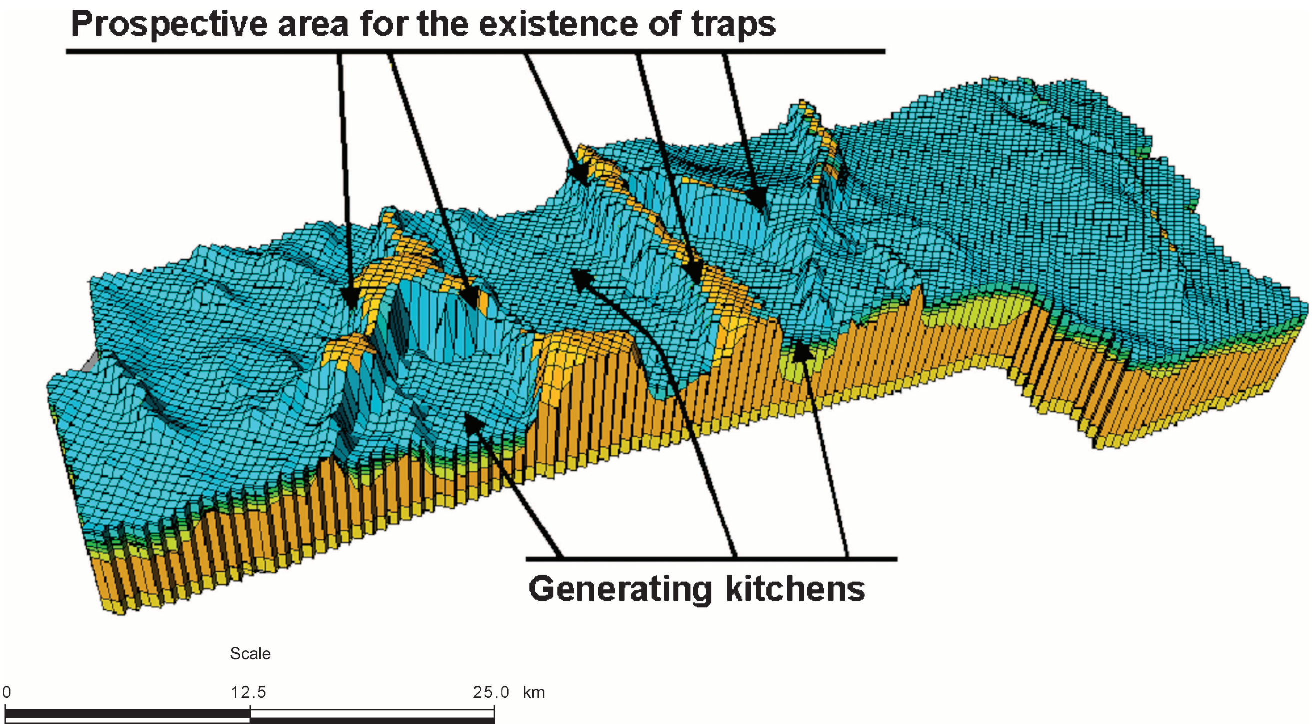

**Figure 16.** The 3-D configuration of the Breccia stratigraphic horizon (in blue) in relation to the intrusions of Callovian salt (golden yellow). The geometries of these two units are fundamentally deterministic in the formation of hydrocarbon traps. The arrangement of generative kitchens in related subbasins and the geometry of the reservoir horizons allow the determination of the most important prospective locations for exploratory wells.

These selected storage or trap areas share the characteristic of being adjacent to the most favorable basins (generating kitchens). The natural drainage areas are shown in Figure 14.

## Timing of Petroleum System Elements and Processes - General Integration

### *Elements of the Petroleum Systems of the Kayab Area*

A petroleum system consists of both elements (source rock, reservoir rock, accumulated sedimentary section, and trap seal) and processes (generation, expulsion, migration-accumulation of hydrocarbons, and trap formation). The petroleum system elements and processes identified in the Kayab area are described in the following paragraphs.

### *Source Rocks*

The recognized source rocks in the Kayab area are of Tithonian (average TOC of 5%) and Oxfordian age. Based on lithologic characteristics in neighboring areas, the Kimmeridgian may also generate hydrocarbons. Therefore, the Tithonian, Kimmeridgian, and Oxfordian strata are considered to be the source rocks for the Kayab study area.

The numerical simulation has indicated adequate TR values for the Upper Jurassic strata to have reached maturity in the deepest subbasins of the southwestern Kayab seismic volume. Along with the geodynamic and thermal history of the area, this indicates both generation and expulsion of hydrocarbons. The salt bodies bounding the generating subbasins guided the migrating hydrocarbons (see geological sections 3, 11).

### *The Buried Sedimentary Sequence*

Units in this sequence considered to contain potentially important source rocks are the Jurassic and perhaps some Cretaceous marine lithologies. As discussed in the preceding paragraphs, the Upper Jurassic is already proven to have generating potential. These units, plus the overlying Cenozoic rocks, reach an aggregate thickness of nearly 8000 m (26,247 ft). Therefore, the Tithonian–Kimmeridgian–Oxfordian is at sufficient depth in the southwestern Kayab area to have reached the oil-generating window (see 3-D sections and models).

### *Reservoir Rocks and Trap Seals*

This study considers that the reservoir rocks are contained within the Cretaceous section, particularly the Upper Cretaceous Breccia. In consideration of the calcareous nature of the Lower Cretaceous rocks and

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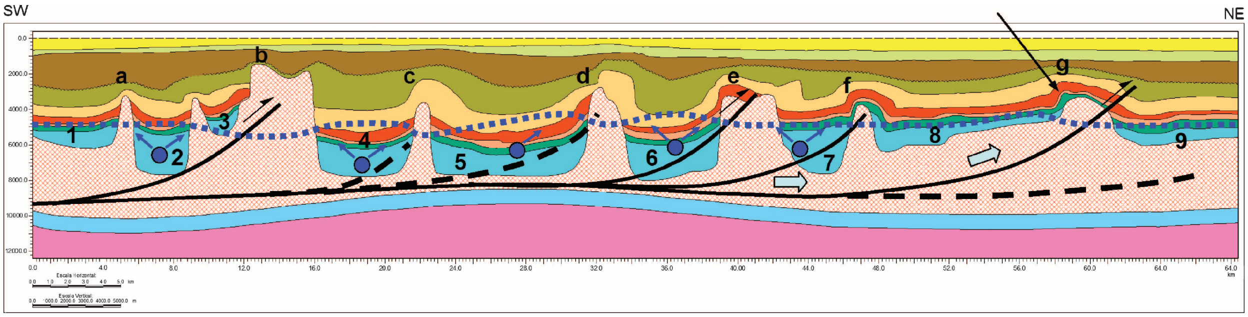

**FIGURE 17.** Representative geological section for the Kayab area. The areas of greatest thermal maturity correspond to the deepest subbasins with the thickest buried sedimentary accumulations. The blue line in the structural section represents the top oil window. The blue points are the pods of active source rocks in subbasins.

the fracturing they have undoubtedly undergone because of tectonic deformation, these are also considered to be potential reservoirs.

Cretaceous Breccia and limestones are regionally extensive and would be present throughout the study area according to seismic data and sparse subsurface control. The structural configuration of the Breccia horizon, resulting from both compression and salt movement, has favorable hydrocarbon migration and trapping characteristics. Migration pathways are provided by the inherent fracture systems. Seals over the anticlinal highs consist of Cenozoic rocks or salt intrusions (Figures 16, 17). An analysis of this information yields preliminary drilling locations for structures that may contain hydrocarbons, particularly those that are adjacent to the deepest generating subbasins in Kayab.

Regionally distributed Paleocene argillaceous strata, along with diapiric salt, comprise the most important seal rocks for traps in the Kayab area.

## *Processes in the Petroleum Systems of the Kayab Area*

### *Generation and Expulsion of Hydrocarbons*

According to the geological model in Temispack, it is probable that organic facies in the Tithonian, Oxfordian, and possibly Kimmeridgian in the southwestern Kayab area have undergone adequate heating for hydrocarbon maturation. This may be deduced because the entire sedimentary column, including the mentioned section, has a thickness exceeding 8000 m (26,247 ft). Therefore, the generating kitchens would lie between 4500 and 8000 m (14,764 and 26,247 ft) deep, as seen on structural sections of the area.

The numerical simulation of maturation provides important information about the thermal evolution of the oil window in several of the deepest or most subsided subbasins (Figures 16, 17). In this structural context, the positions of the autochthonous and allochthonous salt bodies as they relate to the adjacent sedimentary series are also important because of their influence on kerogen maturation. The salt has high thermal conductivity (6.4 W/m/°C) relative to the other lithologies of the geological model and transmits heat into the overlying sedimentary accumulations, although the presence of salt appears to retard maturation laterally.

The second most important area is in northeastern Kayab (e.g., Tunich) because it is smaller and has undergone less subsidence (Figure 17). This leads us to propose that the area of greater hydrocarbon generation with lower trapping risk is in the southwestern half of the Kayab seismic volume, whereas the part corresponding to the large Tunich structure is less prospective.

### *Migration and Trapping of Hydrocarbons*

The hydrocarbon migration and trapping processes may be tied to structuring in the generating subbasins between the salt intrusions and anticlines. The upward flow along migration pathways may move through the flanks of anticlines near salt walls, with the anticlinal crests and upper flanks trapping the migrated hydrocarbons. Salt walls bordering the sedimentary sequences could guide the migrating hydrocarbons toward traps in the upper parts of these structures (Figure 17).

These migration pathways are visualized through simulations of the drainage areas. As already mentioned, these illustrations show the most probable zones of accumulation based on the geometries of the horizons, including permeability barriers and porous levels based on lithofacies distribution (Figures 14, 15).

### *Trap Formation*

Trap formation is tied directly to the sedimentary and tectonic evolution of the entire basin, i.e., textures and sedimentary structures that produce adequate porosity and permeability, and geological structuring, including fracturing and faulting.

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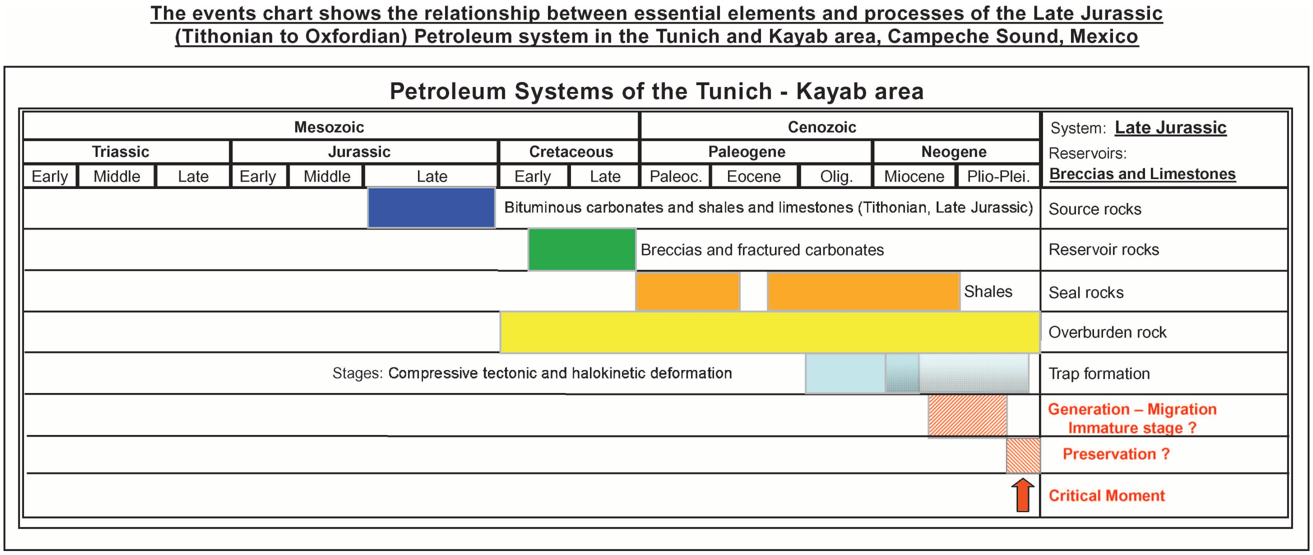

**FIGURE 18.** Timing diagram of petroleum system elements and processes for the Upper Jurassic sequence (Tithonian, Kimmeridgian, and Oxfordian) in the southwestern Kayab area.

Structural controls on traps in the study area are considered to result mainly from the compression that affected the Jurassic through the Paleogene section, followed by halokinesis and extensional deformation culminating with the Neogene filling of the basin (see geological sections in Figures 16, 17).

Consideration of the data obtained from the geological interpretation and the numerical simulation is of fundamental importance because this defines structural trapping styles and allows the selection of the best locations for exploratory wells having objectives in the anticlinal culminations (fault-propagation folds) or on fold flanks where salt has occupied or broken through the upper part of the structures.

In general terms, the tectonic vector of the compressional phase was oriented southwest–northeast, and the folded structures are generally oriented northwest–southeast. The economic significance of these trends is their parallel alignment to systems in the Ku-Maloob-Zaap and Cantarell province. These aligned structures have now been related to source rocks, petroleum charge systems, migration pathways, and trapping structures for the entire Campeche Sound petroleum province. This preliminary working hypothesis implies that a large part of the petroleum charge of the known fields in Campeche Sound has resulted from long-distance lateral migration originating in generating basins located toward the southwest (i.e., mature zones in Zazil-Ha, southern Kayab, the Coatzacoalcos marine province, etc.), where kerogen is more thermally mature. The migration scenario for Kayab would, therefore, be primarily vertical, with a second phase of migration by lateral flow from deeper reservoirs across spill points toward shallower structures, i.e., the Ku-Maloob-Zaap and Cantarell complexes. Only in this manner can the amount of hydrocarbons produced in Campeche Sound be explained because the local source rocks and vertical migration cannot account for this vast petroleum charge. This hypothesis may be corroborated by additional integrated studies or through detailed syntheses of the existing, active petroleum systems within a regional context.

## The Timing of Elements and Processes in the Kayab Area Petroleum System

The following integrated picture has been established for the elements and processes of the Tithonian, Oxfordian, and Kimmeridgian petroleum systems in the Kayab area (Figure 18). During the Paleogene compression, anticlinal structures formed that may have served as hydrocarbon traps for the Cretaceous carbonate reservoir sequence. This was followed by the halokinetic deformation of the initial traps.

Because of the great thickness of siliciclastic sediments accumulated during the Neogene, the Mesozoic sedimentary section was buried sufficiently to initiate generation and expulsion of hydrocarbons from the source rocks, which migrated toward the reservoirs and traps. Generation and expulsion occurred toward the end of the Neogene, especially the Pliocene to Holocene. Tithonian, and perhaps Oxfordian, petroleum systems are still active. Figure 18 shows the timing of the petroleum elements and processes in the southwestern and northeastern parts of the Kayab area.

In summary, geological petroleum risks in the southwestern Kayab area appear to be low, whereas these same risks are higher for the Tunich area in the northeastern part of Kayab.

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# CONCLUSIONS

Tectonic evolution roughly corresponds with a phase of compressional deformation, a phase of halokinesis, and a phase of deposition and subsequent basin fill during the Paleogene and Neogene.

The 3-D model of the petroleum systems was done in Temispack, highlighting the subbasins with petroleum economic interest, hydrocarbon-generating sedimentary sequences, and possible relationships to trapping structures.

A preliminary visualization of the Kayab area suggests that this region has a very good chance of becoming an important heavy petroleum province in the near future because it contains two active petroleum systems (Tithonian and Oxfordian). The prediction of heavy oil derives from the fact that source rocks are in the early stage of thermal maturity. These petroleum systems charge the structures in southwestern Kayab by vertical migration and also charge the actual productive Cantarell and Ku-Maloob-Zaap area by long-distance lateral migration. Exploration studies scheduled for the near future may more precisely document these conclusions.

According to the sparse kinetic data and numerical modeling of the Tithonian source rocks, petroleum generation began at an $R_o$ of 0.45% (slightly more than 70°C). At $R_o$ greater than 1.0%, gas will be generated. During the early stages of kerogen maturity, heavy, high-sulfur oil may have been generated from the Tithonian. For $R_o$ between 0.57 and 0.81–0.9%, paraffinic, naphthenic, and normal aromatic oils were generated from the type 2 kerogen.

Hydrocarbon expulsion would have begun from the source rocks at a TR of 0.3. When related to temperature, the expulsion of heavy, sulfur-rich oils began at 85°C.

Numerical models and simulations of petroleum system processes and elements can generate more precise concepts and permit the visualization of the parameters and dynamics that culminated in the existence of petroleum fields. This knowledge then allows the development of strategies for petroleum exploration, field development, and new reserve additions because of a better understanding of the geological and physical-chemical parameters, thereby reducing technical risk.

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# REFERENCES CITED

Ángeles, A. F. J., 1982, Estudio sedimentario y diagenético del Campo Abkatún: Sociedad Geofísica Mexicana, VI Convención Nacional, Resúmenes, no. 6, p. 108.

Ángeles, A. F. J., 1988, Estudio estratigráfico-sedimentológico del Jurásico Superior en la Sonda de Campeche: Ingeniería Petrolera, v. 28, no. 1, p. 45–55.

Ángeles, A. F. J., 1993, Breve historia de la Sonda de Campeche: Gaceta de la Asociación Mexicana de Geólogos Petroleros, v. 2, p. 3–4.

Ángeles, A. F. J., 1996a, Estratigrafía del Jurásico Superior del Subsuelo en la Sonda de Campeche (Golfo de México): Tesis de Maestría, Escuela Superior de Ingeniería y Arquitectura (ESIA), Instituto Politécnico Nacional, 93 p.

Ángeles, A. F. J., 1996b, Unidades generadoras del Jurásico Superior en la Sonda de Campeche: Memorias, V Congreso Latinoamericano de Geoquímica Orgánica (Cancún), p. 144–146.

Ángeles, A. F. J., and M. E. Ortuño, 1994, Estudio estratigráfico sedimentológico del Cretácico en la Sonda de Campeche: Sociedad Geológica Mexicana (SGM), XII Convención Nacional, Resúmenes, no. 12, p. 8–9.

Ángeles, A. F. J, J. R. Núñez, and M. J. M. Quezada, 1992, Evolución tectónica de la Sonda de Campeche, estilos estructurales resultantes y su implicación en la generación y acumulación de Hidrocarburos: II Simposio de la Asociación Mexicana de Geólogos Petroleros e Instituto Mexicano del Petróleo, p. 12–13.

Araujo, M. J., L. M. A. Basáñez, and M. A. D. Márquez, 1986, Estudio estratigráfico-sedimentológico de las rocas del Jurásico en el prospecto Área Marina de Campeche (C-5008) inédito: Instituto Mexicano del Petróleo, 92 p.

Bañuelos, M. O., 1993, Roca almacén del Mioceno y Plio-Pleistoceno en la Sonda de Campeche: I Simposio de Geología de Subsuelo, Asociación Mexicana de Geólogos Petroleros, p. 84–91.

Bello, M. R., 1991, Estudio estratigráfico-sedimentológico del Cretácico Superior en la Sonda de Campeche: Instituto Mexicano del Petróleo, Reporte Interno Inédito, Proyecto CAO-3512, 110 p.

García, H. J., 1993, Roca almacenadora Jurásico Superior Oxfordiano: I Simposio de Geología de Subsuelo, Asociación Mexicana de Geólogos Petroleros, p. 49–50.

Guzmán, V. M. A., and M. R. Mello, 1999, Origin of oil in the Sureste Basin, Mexico: AAPG Bulletin, v. 83, no. 7, p. 1068–1095.

Guzmán, V. M. A., L. O. Castro, J. R. R. Román, M. L. M. Medrano, and L. C. Valdez, 2001, El origen del petróleo en las subprovincias Mexicanas del Golfo de México: Boletín de la Asociacion Mexicana de Geologos Petroleros, v. 49, no. 1 and 2, p. 31–46.

Hernández, G. S., 1993, Subsistema almacenador en los horizontes Cretácico Superior y Eoceno Medio de la

TOC
Start
Search

Región Marina: Primer Simposio de Geología de Subsuelo, Asociación Mexicana de Geólogos Petroleros, p. 79–83.

Holguín, Q. N., and I. M. A. Romero, 1982, Estudio geoquímico de pozos de exploración en la Sonda de Campeche-Plataforma de Yucatán: Instituto Mexicano del Petróleo, Reporte Interno Inédito, Proyecto C-1142, 60 p.

Holguín, Q. N., et al., 2005, Estudio regional de manifestaciones superficiales de aceite y gas en el sur del Golfo de México, su origen e implicaciones exploratorias: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 52, no. 1, p. 20–41.

Instituto Mexicano del Petróleo (IMP), 2000, Atlas de las cuencas sedimentarias terciarias y mesozoicas de México: Internal Report, 320 p.

Medrano, M. L. M., and I. M. A. Romero, 1993, Caracterización geoquímica de las rocas generadoras de los sistemas petrolíferos del Jurásico Superior en el área Marina de Campeche: I Simposio de Geología de Subsuelo, Asociación Mexicana de Geólogos Petroleros (AMGP), p. 5–16.

Medrano, M. M. L., I. M. A. Romero, and V. R. Maldonado, 1996, Los subsistemas generadores de la Sonda de Campeche, México: Memorias, V Congreso Latinoamericano de Geoquímica Orgánica (Cancún), p. 85–90.

Meneses, G. J., 1980, Geología de la Sonda de Campeche: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 32, no. 1, p. 1–26.

Mitra, S., G. C. Figueroa, J. H. García, and A. M. Alvarado, 2005, Three-dimensional structural model of the Cantarell and Sihil structures, Campeche Bay province, Mexico: AAPG Bulletin, v. 89, p. 1–26.

Mitra, S., J. A. D. González, J. G. Hernández, S. H. García, and S. Banerjee, 2006, Structural geometry and evolution of the Ku, Zaap and Maloob structures, Campeche Bay, Mexico: AAPG Bulletin, v. 90, p. 1565–1584.

Ornelas, M., S. Franco, N. Aguilera, H. Alzaga, H. A. Escamilla, and M. Granados, 1994, (res) Secuencias bioestratigráficas del Kimmeridgiano-Tithoniano en pozos de la zona marina de Campeche Sureste de México: Sociedad Geofísica Mexicana, XII Convención Nacional, Resúmenes, no. 12, p. 197.

Ornelas, S. M., F. N. Aguilera, N. S. Franco, M. M. Granado, and M. R. Bello, 1991, Determinación de los límites Oxfordiano-Kimmeridgiano-Tithoniano en pozos de la Zona Marina de Campeche, Plataforma Continental de México: Instituto Mexicano del Petróleo, Reporte Interno Inédito, Proyecto CAO-551, 125 p.

Ortega, L. S., M. L. Medrano, and V. L. Clara, 1995, Definición de los límites reales de generación de las rocas del Tithoniano de las cuencas del Sureste, Sonda Marina de Campeche: Instituto Mexicano del Petróleo, Reporte Interno Inédito, Proyecto CAB-0501, 128 p.

Ortuño, A. S., C. Romero M., J. Rosales R., and E. Bahena R., 2004, Modelado de prospectos en el área de Kayab: Reporte Interno Inédito, Instituto Mexicano del Petróleo, 160 p.

Ramírez, C. L., A. J. Mendoza, G. R. del Valle, and R. P. Gómez, 1996, Mapping salt structure and subsalt imaging in Campeche Bay Mexico, using seismic inversion modeling and prestack attributes: Society of Exploration Geophyscists Expanded Abstracts 15, 588 p.

Región Marina Noreste (RMNE), 2002, Sistemas petroleros terciarios en el área de Tunich-Chilam: PEMEX, Exploración y Producción (PEP), Reporte Interno Inédito, Petróleos Mexicanos (PEMEX), 120 p.

Romero, M. A., J. Hegre, and R. Maldonado, 1996, Modelado 1D Genex en el área marina de Campeche: Memorias, V Congreso Latinoamericano de Geoquímica Orgánica, Cancún, Quintana Roo, México, p. 55–56.

Romero, M. A., L. Medrano, and R. Maldonado, 2001, Subsistemas Generadores de la Región Marina de Campeche: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. 49, nos. 1–2, p. 105–115.

Romero, I. M., C. Cassaigneau, M. Flores, A. Vassayre, R. Navarro, and J. Gaulier, 2004, Future exploration strategy of a frontier offshore Campeche area provided by basin modeling: AAPG International Conference, Cancún, Quintana Roo, México, p. 112–113.

Rudkiewicz, J. L., M. Vandenbroucke, H. L. B. Penteado, F. Brigaud, A. Vear, J. Wendebourg, and S. Düppenbecker, 2000, Integrated basin modeling helps to decipher petroleum systems, *in* M. R. Mello and B. J. Katz, eds., Petroleum systems of south Atlantic margins: AAPG Memoir 73, p. 27–40.

Salomón, M. L., 1999, Modelado estructural de las fallas y su importancia en la exploración de hidrocarburos en el Golfo de México: Biblioteca Instituto Mexicano del Petróleo, TN 872, S35 1999, 85 p.

Santamaría, O. D., 2000, Organic geochemistry of Tithonian source rocks and associated oils from the Sonda de Campeche, México: Ph. D. dissertation, University of Aachen, Germany, 190 p.

Santamaría, O. D., and B. Horsfield, 2000, La Evolución Térmica de las Rocas Generadoras del Tithoniano en el Área Marina de Campeche, México: Boletín Asociación Mexicana de Geólogos Petroleros, v. 49, nos. 1–2, p. 116–136.

Schneider, F., S. Wolf, I. Faille, and D. Pot, 2000, A 3D-basin model for hydrocarbon potential evaluation: Application to Congo offshore: Oil and Gas Science and Technology, Revue de l'Institut Français du Pétrole, v. 55, no. 1, p. 3–13.

Stover, S. C., S. Ge, P. Weimer, and B. C. McBride, 2001, The effects of salt evolution, structural development, and fault propagation on late Mesozoic–Cenozoic oil migration: A two dimensional fluid-flow study along a megaregional profile in the northern Gulf of Mexico Basin: AAPG Bulletin, v. 85, no. 11, p. 1945–1966.

Ungerer, P., J. Burrus, B. Doligez, P. Y. Chenet, and F. Bessis, 1990, Basin evaluation by integrated two-dimensional modeling of heat transfer, fluid flow, hydrocarbon generation and migration: AAPG Bulletin, v. 74, no. 3, p. 309–335.