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Rosenfeld, J. H., 2003, Economic potential of the Yucatan Block of Mexico, Guatemala, and Belize, *in* C. Bartolini, R. T. Buffler, and J. Blickwede, eds., The Circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics: AAPG Memoir 79, p. 340–348.

Economic Potential of the Yucatan Block of Mexico, Guatemala, and Belize

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ABSTRACT

The Yucatan Block is a rifted continental microplate covering 450,000 sq km in southern Mexico, northern Guatemala, and Belize. The crystalline basement is mantled by a Late Jurassic through Holocene carbonate/evaporite platform up to six-km thick. While the northern and western edges of the Yucatán Block have been passive margins since the Mesozoic, its southern margin was affected by Late Cretaceous suturing to the Chortis microplate, followed by Miocene to Holocene strike-slip faulting. Its eastern margin was modified by Paleogene strike slip against the Cuban Arc Terrane. The Yucatán Block has received very little terrigenous sedimentation since being isolated from nearby landmasses by the Jurassic separation of North and South America.

Major hydrocarbon production exists in Mexico from the area immediately west of the Yucatán Block in the Reforma Trend, Campeche Sound, and the Macuspana Basin. Oil has also been found west and south of the block in the Sierra de Chiapas of Guatemala and Mexico. Only one commercial oil accumulation has been found to date on the stable block itself (Xan field in Guatemala), and mineral exploration without commercial success has been limited to the small area of exposed crystalline basement in the Maya Mountains of Belize.

Based on current knowledge, it is the author's opinion that the economic potential of the Yucatán Block should not be discounted. Hydrocarbon and mineral exploration has been sporadic and generally low-tech, and there is a clear need for high-quality regional seismic data to reveal structural configuration and sedimentary architecture. Among the many geological factors to be understood are:

1) geometry of Triassic-Jurassic rift structures (horsts and grabens);
2) location and geometries of possible Jurassic and Cretaceous intraplatform hydrocarbon source basins, carbonate buildups, and structural traps in the evaporite/carbonate section;
3) paleoheatflow as it affected organic maturation;
4) effects within the block of tectonics along its margins (tilting, mass wasting, and foreland bulging); and
5) possible role of the Chicxulub K/T astrobleme in hydrocarbon and mineral occurrence.

INTRODUCTION

The onshore and offshore Yucatán Block covers approximately 450,000 km^2 of Mexico, Guatemala, and Belize (Figure 1). The block is a Paleozoic cratonic element whose edges have been extensively modified since it was isolated as a discrete microplate between spreading centers during the Jurassic separation of North and South America. Since the Late Jurassic, the Yucatán Block has been mantled by a variable thickness of carbonates and evaporites comprising the core of the Yucatán platform.

Nomenclature for this rather uniform depositional sequence (Figure 2) varies from country to country; *e.g.* the Hillbank, Yalbac, and Barton Creek Formations in Belize; the Cobán and Campur Formations in Guatemala; and the Cretácico Medio, Cretácico Superior, Icaiché, Chichén Itzá, and Carrillo Puerto Formations in Mexico. The platform carbonates continue to the west beyond the limits of the Yucatán Block into the Reforma Trend of Mexico and the Sierra de Chiapas of Mexico and Guatemala, where they are named the San Ricardo, Sierra Madre, and Ixcoy Formations.

The southern margin of the Yucatán Block is truncated by Tertiary through Holocene left-lateral displacement of the Chortís Block of Guatemala and Honduras along the Cuilco-Chixoy-Polochic and Motagua-Cabañas Fault Systems with pieces of the original Yucatán Block possibly dispersed along the Nicaragua Rise as far east as Jamaica. Its eastern edge, or Yucatán Borderland (Marton and Buffler, 1994), was dismembered by Paleogene strike-slip faults during the relative northward motion of Cuba, with displaced fragments of the original Yucatán Block incorporated into western Cuba (Iturralde-Vinent, 1994).

Deformational events that have influenced the petroleum and mineral resource potential of the Yucatán Block include:

1) Late Triassic to Middle Jurassic rifting (Marton and Buffler, 1994);
2) Late Cretaceous suturing along the southern margin of Yucatán (Beccaluva et al., 1995);
3) Cretaceous-Tertiary (K/T) asteroid or cometary impact (Sharpton et al, 1996); and
4) Cretaceous to Paleogene(?) westward tilting manifested by the shallow basement (<1 km) in eastern Yucatán (Marton and Buffler, 1994) and wells indicating deep basement (> 6 km) to the west (López-Ramos, 1973).

Depositional episodes related to these tectonic events include:

1) Early to Middle Jurassic red bed and eolian deposition;
2) Late Jurassic to Early Cretaceous marine transgression;
3) Late Jurassic through Holocene carbonate and evaporite (mainly gypsum-anhydrite) accumulation; and
4) Mass wasting and brecciation at the K/T boundary as a result of the Chicxulub impact event.

Tertiary sedimentation marked the return of carbonate platform deposition with the local exception of the Macuspana Basin. Despite thick sedimentary section and hydrocarbon production in Guatemala, most of the Yucatán Block has no regional seismic coverage. Exploration wells are sparse (less than one well per 20,000 km^2), irregularly distributed, and

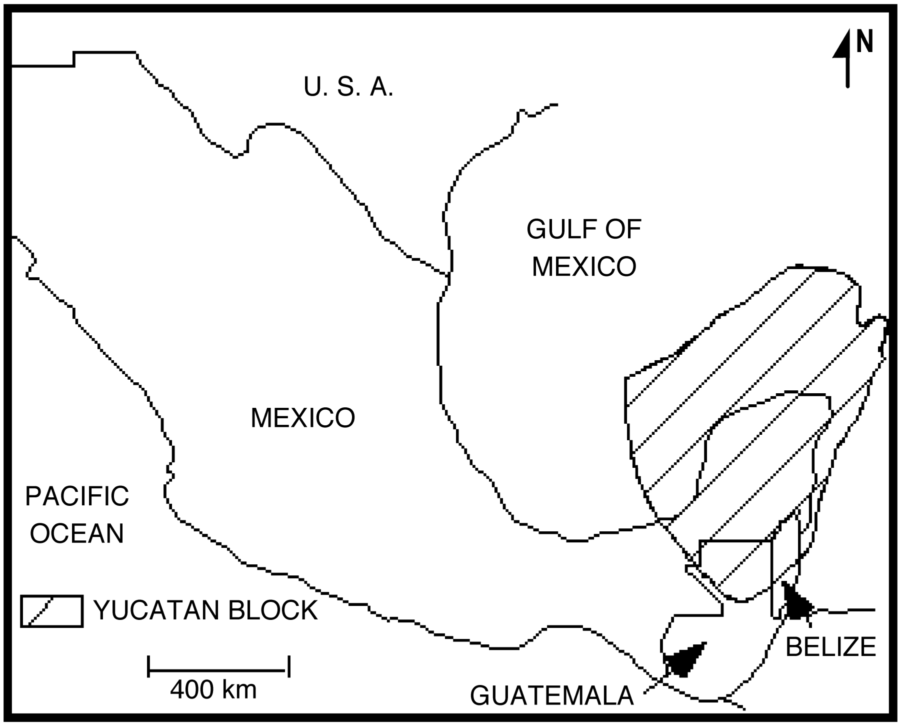

Figure 1. Location map of the Yucatán Block in Mexico, Guatemala, and Belize.

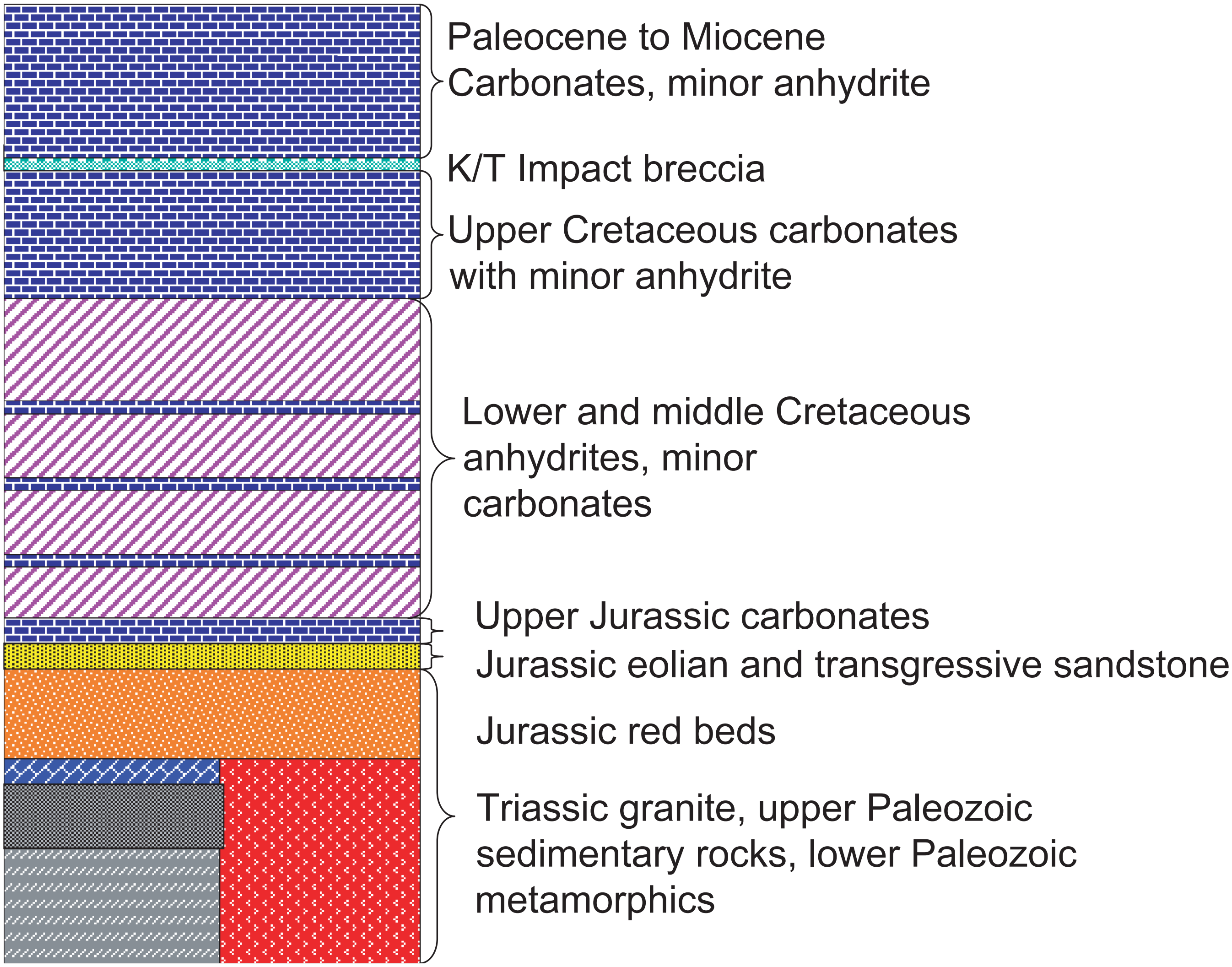

Figure 2. Generalized stratigraphic column for the Yucatán Block.

mostly drilled without seismic control (Figure 3). Prospecting for metallic minerals has not been feasible beneath the generally featureless surface carbonates.

HYDROCARBONS

The presence of one or more hydrocarbon systems in the Yucatán Block is known from the occurrence of oil in Guatemala and Belize. What are these systems, how robust are they, and how areally extensive might they be? Some of the possibilities are discussed below.

Rift Play

Drilling in Mexico and Belize and outcrops in the Maya Mountains indicate that the crystalline crust is generally granitic with pre-Pennsylvanian metasedimentary and metavolcanic components (López-Ramos, 1973; Steiner and Walker, 1996). These authors also mention low-grade Pennsylvanian and Permian metasedimentary rocks encountered by drilling and in outcrop. This basement complex corresponds to the hinterland of the Ouachita belt of Arkansas, Oklahoma, and Texas, and may be the ''Llanoria'' of Flawn et al. (1961). The continental basement of Yucatán is stretched, since much of the block is covered by sedimentary overburden as much as six km in thickness; an impossibility on unstretched continental crust at isostatic equilibrium.

Linear gravity anomalies within the Yucatán Block suggest that this crustal stretching produced a series of horsts and grabens in this continental block between the Gulf of Mexico and the Proto-Caribbean Sea spreading ridges in the Jurassic (Marton and Buffler, 1994). Few wells drilled in the Yucatán Block have reached Jurassic rocks or basement. However, a 36-m-thick section of Jurassic dolomite was described by López-Ramos (1973) at the depth of 3140 m in the Yucatán-1 well (Figure 3).

The horsts would have been source areas for terrigenous clastics that accumulated in the adjacent grabens, and for the Oxfordian eolian and transgressive marine sandstone found in the Ek-Balam field of Campeche Sound (Guzmán-Vega and Mello, 1999). This is analogous to the depositional sequence in the contemporaneous Norphlet and Smackover Formations of the northern Gulf of Mexico. These grabens would also have been the preferred routes for Late Jurassic to Early Cretaceous marine transgression on the Yucatán Block. Transgressive marine deposits in these grabens would consist of sandstone and marl. The configuration and orientation of these proposed rift basins remains uncertain.

The hydrocarbon source potential of this sequence is confirmed by the presence of light oil in the Eagle-1 well of Belize (Figure 3) whose biomarkers suggest derivation from Late Jurassic or Early Cretaceous marl (J. Zumberge, personal communication, 2000). Exploration objectives of this play would be the synrift and early post-rift sandstones on the flanks and crests of horst blocks, and carbonates deposited during transgression and platform building (Figure 4).

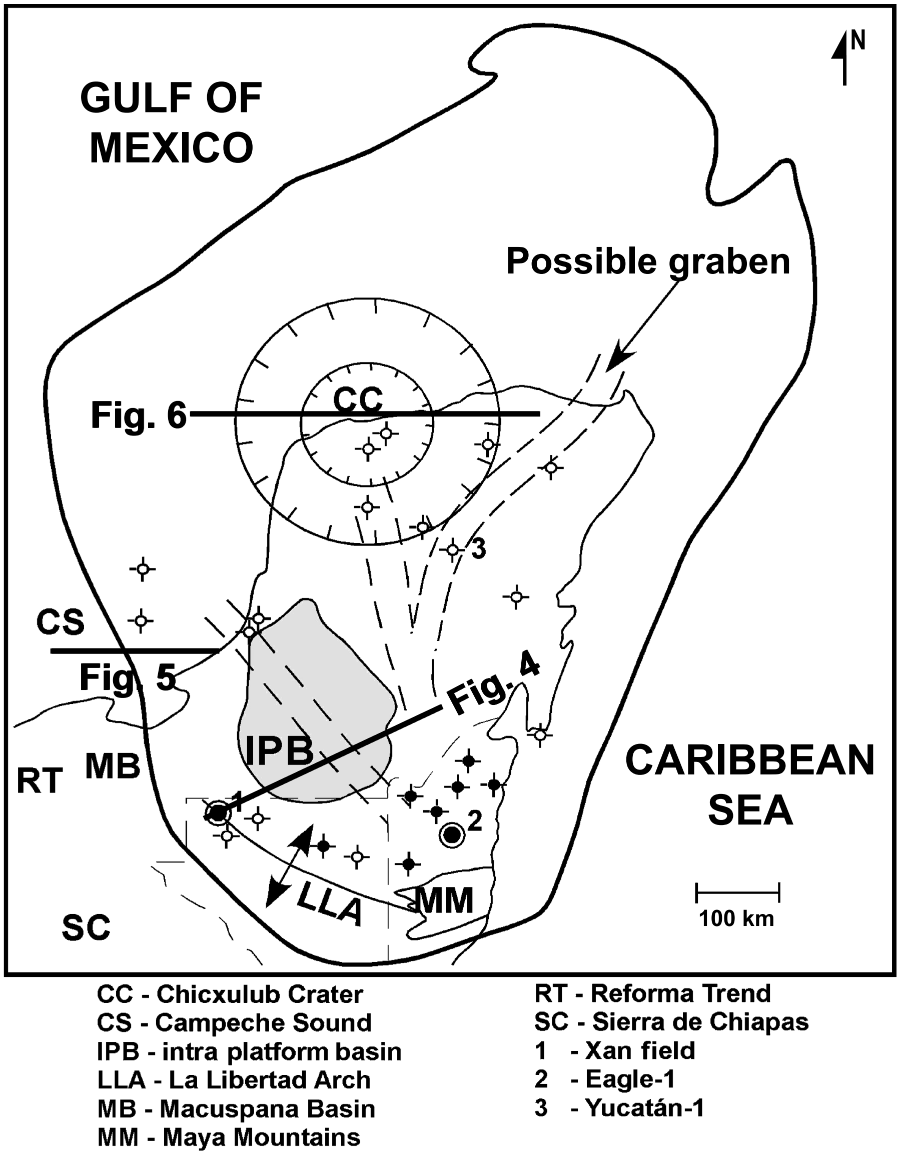

Figure 3. Geological elements of the Yucatán Block. CC = Chicxulub Crater, CS = Campeche Sound, IPB = Intraplatform Basin, LLA = La Libertad Arch, MB = Macuspana Basin, MM = Maya Mountains, RT = Reforma Trend, SC = Sierra de Chiapas, 1 = Xan field, 2 = Eagle-1 well, 3 = Yucatán-1 well. Numbered lines show approximate locations of Figures 3, 4, and 5.

Intraplatform Basin Play

Xan field on the central Yucatán Block in Guatemala (reserves of ~100 million barrels of oil) is on the curvilinear La Libertad Arch south of the 150- to 200-km-diameter gravity low (López-Ramos, 1973) outlined in Figure 3. This field produces 16° API gravity oil from vuggy dolomite in a carbonate buildup of Turonian age. The reservoir is sealed by anhydrite and overlies organic-rich, oil-prone Cenomanian carbonate source rocks. The broad negative gravity anomaly may represent a temporally persistent intraplatform basin with a central concentration of source rocks ringed by carbonate buildups or calcarenite banks of the Xan type (Figure 4). The author speculates that this may be a "steer's head" basin formed by subsidence over a major graben or failed rift. Hydrocarbon migration out of this basin would be radial, but westward tilt of the Yucatán Block would favor eastward hydrocarbon migration across a wide, unexplored swath of Mexico, Guatemala, and Belize.

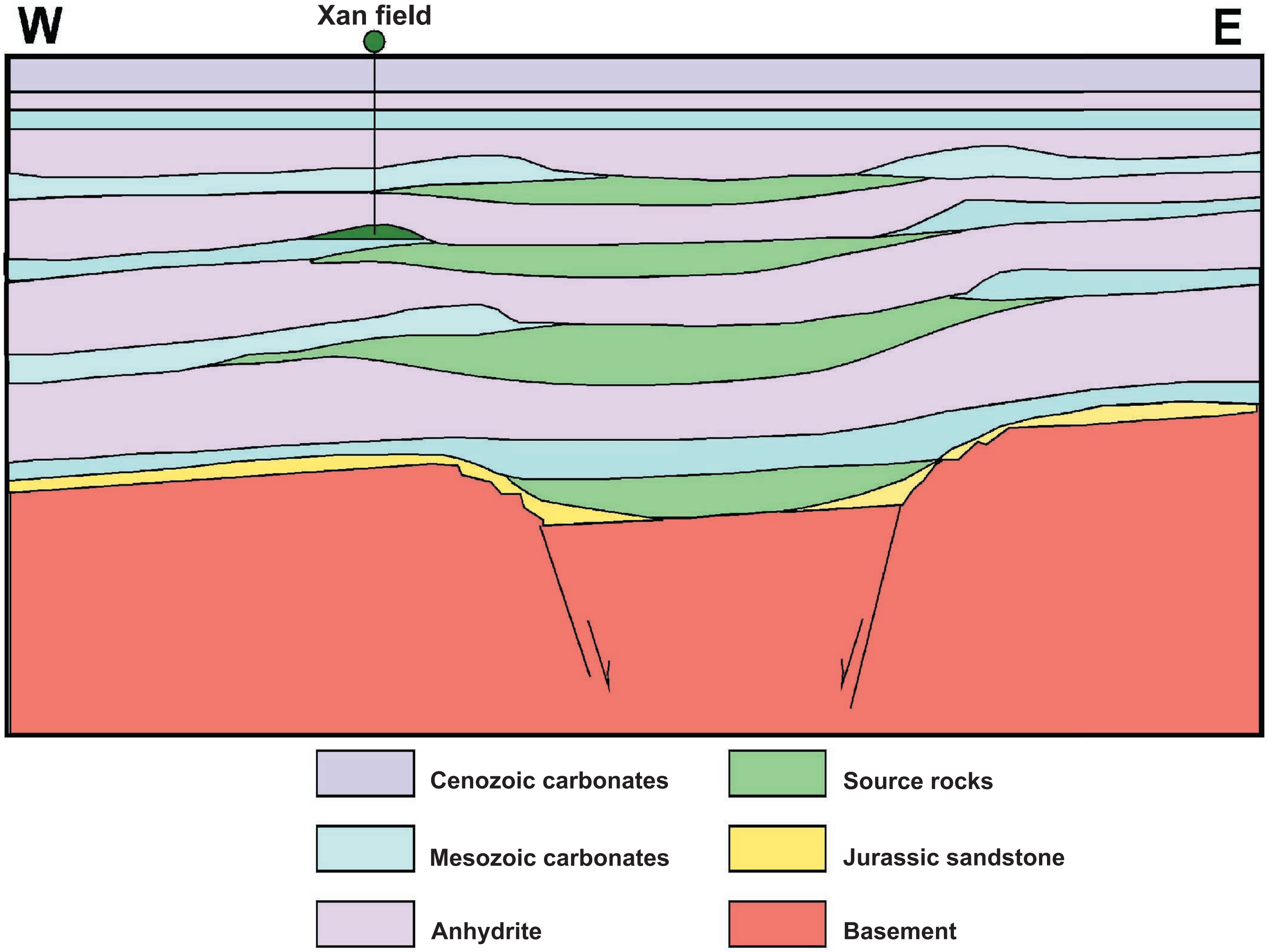

Figure 4. **Diagrammatic southwest-to-northeast-oriented section across a gravity low that may represent an intraplatform basin and underlying rift illustrating the possible distribution of source rocks, carbonate buildups, and anhydrite seals, as typified by the Xan oilfield of Guatemala.**

Eastward oil migration was confirmed in the Eagle-1 well of Belize, where 39° API gravity oil flowed from Lower Cretaceous carbonates just above the crystalline basement at a depth of 600 m. Several other wells in northern Belize (Figure 3) also had oil shows (unpublished oil company data). Relatively shallow burial depth and low organic contents of the Mesozoic strata in Belize are insufficient for hydrocarbon generation, indicating that the Eagle-1 oil had its origin in a relatively distant hydrocarbon generation kitchen regionally downdip in Mexico and/or Guatemala.

It is probable that the Xan reservoir is not the only carbonate buildup on the inner platform of the Yucatán Block. This facies tract is characterized by laterally extensive, eustatically controlled alternations of carbonate and anhydrite along migration pathways radiating from the proposed intraplatform basin (Figure 4). This framework is similar to that of the supergiant oil accumulations on the Arabian platform where oil generated in the intraplatform Hanifa Basin is trapped among cyclic carbonates and anhydrites of the Arab Formation beneath the massive Hith Anhydrite (Wilson, 1985).

Lateral Migration of Hydrocarbons from the Gulf of Mexico

The hydrocarbon accumulations of Campeche Sound (>30 billion barrels of oil) and the Macuspana Basin (>10 trillion cubic feet of gas) indicate the presence of a massive hydrocarbon charge in the area bordering the western Yucatán Block. The westward tilt of Yucatán creates a favorable geometry for capturing hydrocarbons that either have bypassed or spilled from traps in Campeche Sound and the Macuspana Basin. These hydrocarbons could be trapped in carbonate buildups in the platform sequence, or at porosity pinch outs among anhydrite layers that thicken and coalesce towards the central platform (Figure 5).

Astrobleme Related Hydrocarbon System

The K/T impact at Chicxulub, with a final crater diameter estimated to be 200 to 300 km (Figure 3), is among the largest preserved impact features on earth (Sharpton et al, 1996). A compelling case has been made for the impact origin of K/T dolomitic breccia reservoirs in the giant and supergiant Campeche Sound fields (Grajales-Nishimura et al., 2000). The possible existence of an impact-related hydrocarbon system within the Yucatán Block is discussed below.

Several wells were drilled into and around the impact crater prior to 1970. Some of these wells (López-Ramos, 1973) penetrated igneous rocks and breccias, originally thought to be of volcanic origin, that have since been determined to be melt rock formed by the Chicxulub impact (Sharpton et al., 1996). The wells outside the crater's rim penetrated the typical interbedded carbonate-anhydrite sequence of the Yucatán Block (Figure 6). Although a hydrocarbon system would not be expected to survive within the crater, conditions around its periphery may have been conducive to hydrocarbon generation and accumulation.

Hydrocarbon Generation

The Yucatán-1 well penetrated Paleozoic volcanic basement at a depth of 3200 m. The low geothermal gradient in the overlying carbonates and anhydrite may have precluded hydrocarbon generation from any possible Mesozoic source rocks in that area. Therefore, hydrocarbon presence in the area could depend upon local, impact-induced heating caused by:

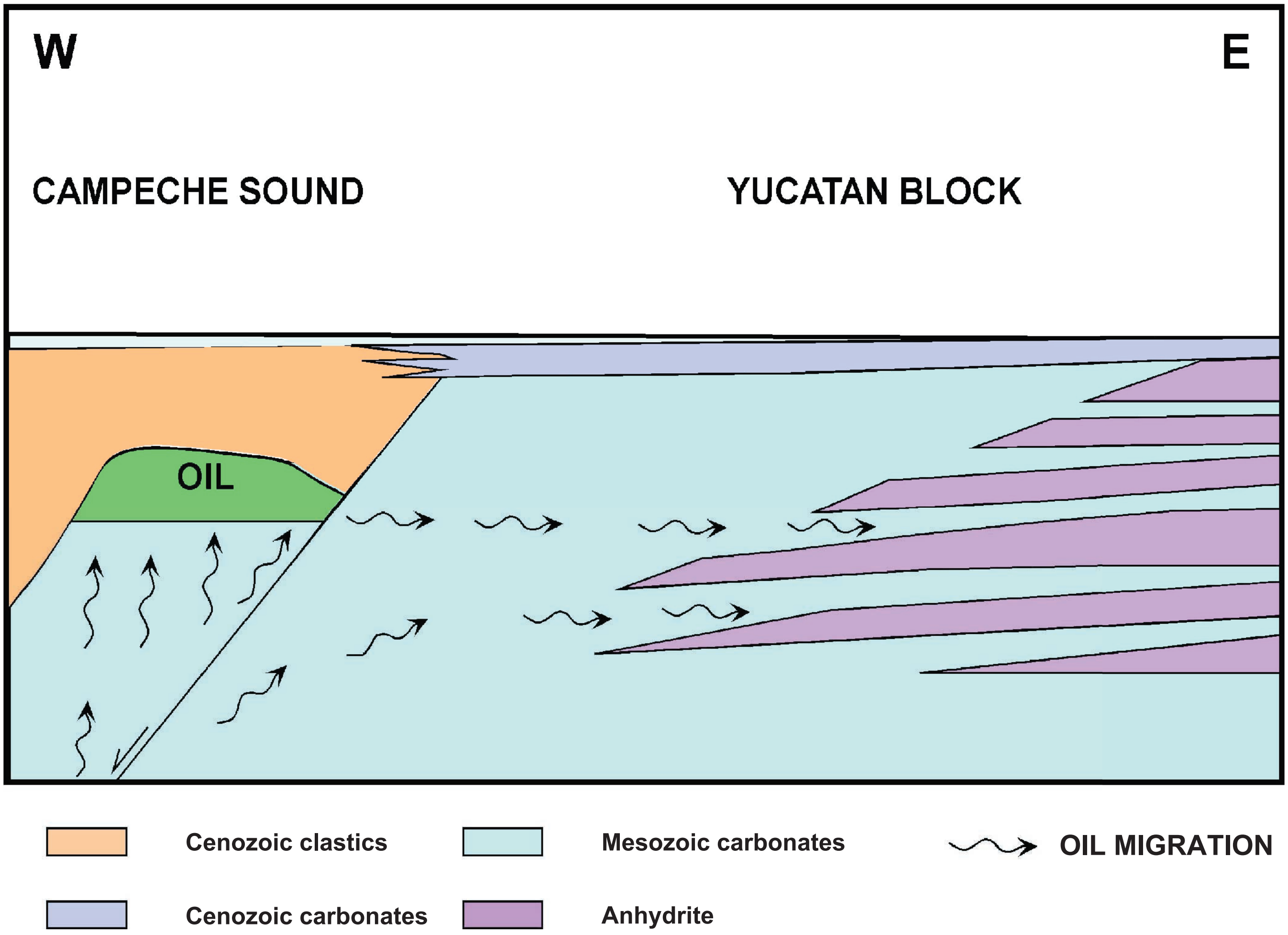

Figure 5. Diagrammatic west-to-east-oriented section showing the possible migration of hydrocarbons from Campeche Sound into the western margin of the Yucatán Block.

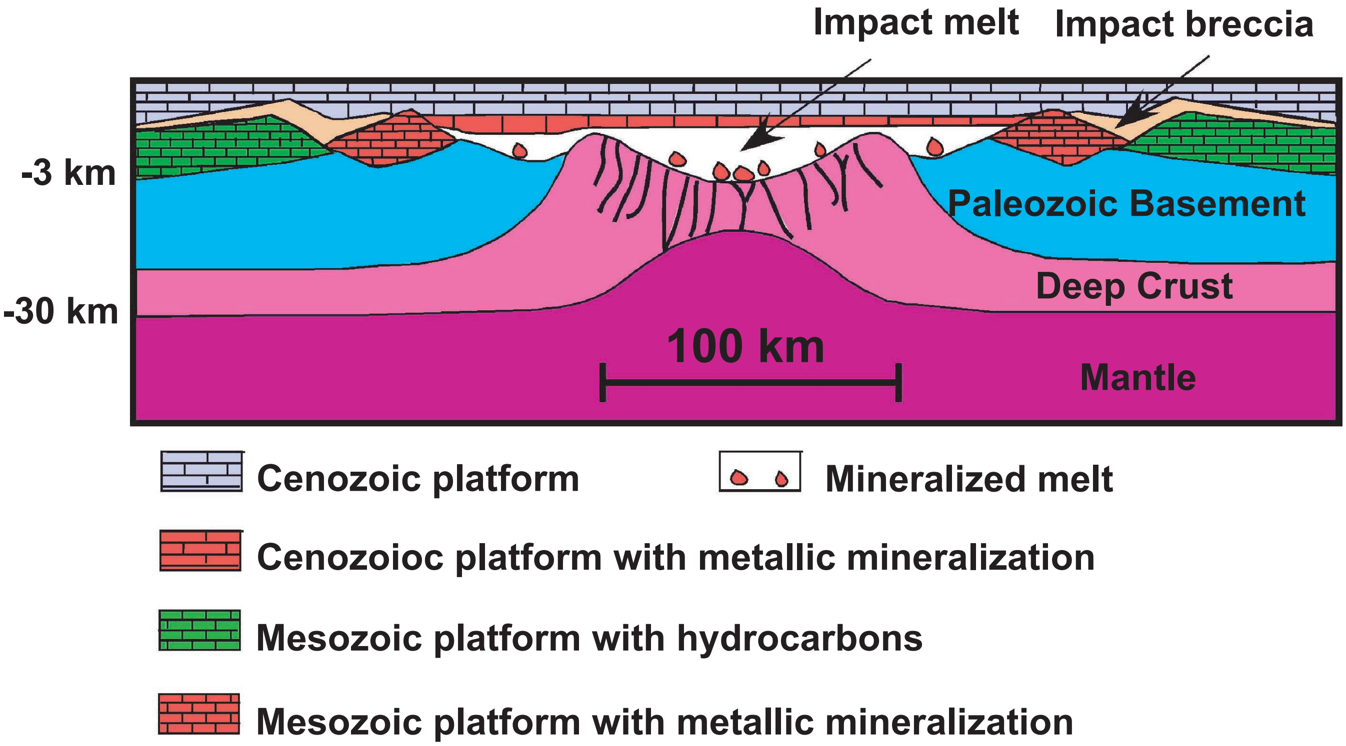

Figure 6. Diagrammatic west-to-east-oriented section across the Chicxulub impact crater with possible locations of metallic ores and hydrocarbon resources. Note the representation of ore bodies in the impact melt and in carbonate-hosted hydrothermal systems adjacent to and immediately overlying the central crater. Carbonates beyond the outer crater may be hydrocarbon-bearing with seals comprising faults, interbedded anhydrites, and the overlying impact breccia. Adapted from Sharpton et al, 1994.

1) heat radiating from impact induced melts and increased geothermal gradient caused by the rapid uplift of deep crustal layers;
2) ''kneading'' of a large rock volume by the passage of very high-amplitude impact-induced seismic waves;
3) friction along rapidly moving kilometer-scale fault/slide blocks during crater collapse; and
4) heat transfer by post-impact hydrothermal systems.

Reservoirs

Dolomite interbedded with anhydrite is well documented in the target section. The dolomite should be extensively fractured over a wide area around the crater, thereby enhancing any matrix porosity.

Traps

Faulted and tilted strata around the periphery of the post-collapse crater could provide structural traps (Figure 6).

Seals

Interbedded anhydrites, although initially fractured, would quickly heal to form internal seals for the interbedded dolomite reservoirs. Top seal rocks would consist of micritic platform carbonates, intraplatform evaporites, and/or impact breccia similar to welded volcanic tuff (Figure 6). Lateral seals would consist of faults and major fractures made impermeable by fault gouge and frictional melt (pseudotachylite) found as meter-scale dikes in well-exposed major impact structures (Peredery and Morrison, 1984), and by precipitation of hydrothermal minerals in open fractures.

Metallic Minerals

Mineralization at meteor impact sites is well documented, the most notable example being the Precambrian Sudbury Crater in Ontario, Canada, containing an estimated 1.65 billion metric tons of ore, averaging 1.2% Ni and 1.05% Cu (Masaitis and Grieve, 1994). The metals originated as an immiscible sulfide segregation in the impact melt. An additional 6 million metric tons of hydrothermal ore, averaging 4.4% Zn, 1.4% Cu, and 1.2% Pb, also occur in a thin, post-impact carbonate. The pre-erosion Sudbury and the buried Chicxulub impact craters are nearly the same size (200 to 300 km in diameter), and it is conceivable that a quantity of metal similar to that of Sudbury is present in the Chicxulub melt sheet at mineable depths between one and three km. (Figure 6).

A second, and perhaps even more extensive objective, would be mineralized veins, stockworks, and replacement bodies created by a robust hydrothermal system in the thick carbonates around and above the transient crater. This system may have persisted for thousands of years following the impact. Elements of this system would include:

1) a cylinder of fractured and uplifted deep crustal rocks about 100 km in diameter;
2) a cauldron of cooling melt and hot rock in the central impact area exposed to a constant influx of seawater;
3) formation of hydrothermal brine, rich in dissolved chlorides derived primarily from seawater and sulfides derived from reduced sulfate from seawater and anhydrite;
4) deep convection through the abundant fracture systems;
5) dissolution of available metallic ions from fractured wall rocks of the system as soluble chloride and sulfide complexes;
6) precipitation of metallic sulfides from cooling and oxidizing metal-bearing brine in fractures in and around the crater; and
7) metallogenetic zonation as the hydrothermal system cooled.

The economic potential of such ore bodies would depend on their present-day depth and the feasibility of mining in an environment with abundant ground water.

CONCLUSIONS

The basic structural framework and stratigraphic architecture of the Yucatán Block are poorly understood. This is a complex geological province mantled by a deceptively simple carbonate platform. This perceived "simplicity" may lead to the conclusion that existing exploration work has sufficiently revealed the salient geological characteristics of the province, and that these indicate high exploration risk.

On the positive side, there are at least two documented oil types generated on the Yucatán Block: one from Middle Cretaceous restricted-marine source rocks found at Xan field, and another, in the Eagle-1 well, generated from Upper Jurassic to Lower Cretaceous marl. Hydrocarbons may also have migrated into the western edge of the block from the Campeche and Macuspana Trends.

Although the Yucatán Block may contain important hydrocarbon and metallic resources, surface conditions provide little help to the subsurface explorer. On the contrary, the surface presents challenges to exploration because of its featureless geology, thick vegetation, high velocity rocks, thick caliche crust, shallow caverns, karst topography, environmentally sensitive areas, abundant archeological sites, and poor infrastructure. Therefore, the discovery of economic resources will require careful application of state-of-the-art seismic and potential field geophysical methods, and drilling technology.

In order to properly evaluate the economic potential of the Yucatán Block, the following steps are recommended:

1) Assemble, integrate, and interpret all available geological, geophysical, and geochemical information from the Yucatán Block in Mexico, Guatemala, and Belize.
2) Acquire a grid of deep-imaging seismic data to be integrated with modern potential field (gravity, magnetic, and magneto-telluric) and well data in order to provide an accurate regional framework for the Yucatán Block.
3) Evaluate samples from the deep-drilling program at Chicxulub undertaken by the International Continental Scientific Drilling Program (IGCP) and the Universidad Nacional Autónoma de México in early 2002, and incorporate the data obtained into the regional framework.
4) Perform electromagnetic and/or induced polarization surveys over the onshore portion of the Chicxulub crater to determine where large metallic concentrations might exist.
5) Carry out detailed seismic surveys over selected areas determined to have exploration potential.
6) Drill economically feasible and environmentally manageable hydrocarbon and mineral prospects.

ACKNOWLEDGMENTS

Many geoscientists and companies have expended both energy and financial resources in order to provide the basis for our current understanding of the Yucatán Block. The author acknowledges, among others, the contributions of Ernesto López-Ramos, Francisco Viniegra, Antonio Camargo, Glen Penfield, Virgil Sharpton, and Richard Buffler.

Among companies whose investments in the exploration of Yucatan resulted in the acquisition of critical data are Petroleos Mexicanos, Texaco, Amoco, Shell, Gulf, Phillips, Sohio, Esso, Marathon, and Anschutz.

The author thanks Veritas Geophysical Company for support during the preparation of this work. This paper has benefited from discussions with Hector Palafox of the Instituto Mexicano del Petroleo. Arthur Berman, a friend and colleague, was generous with his time and knowledge during this work. Constructive comments of Ronald Phair and others were very helpful during the final preparation of the manuscript.

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