High-impact palynology in petroleum geology: Applications from Venezuela (northern South America)

Valentí Rull

ABSTRACT

This article documents the application of high-impact palynology (HIP) in the Maracaibo Basin of Venezuela and its influence on such exploration and production aspects as regional planning and strategies, risk reduction, optimal drilling decisions and investment, petroleum-system modeling, new discoveries, and secondary recovery by fluid injection, among others. High-impact palynology has been defined as the coupling of high-resolution sequence biostratigraphy, multidisciplinary work, and the alignment of palynology with the attainment of business goals. The first part of this article explains the high-resolution ecostratigraphic methods used and the concept of integrated work applied. The second part of the article shows the results obtained in selected case studies, which illustrate the advantages of HIP. Among the most relevant studies are high-resolution ecostratigraphic frames at a basin level, timing between structural trap formation and oil migration, differentiation of petroleum systems in adjacent reservoirs, the concept of palynoblocks in structurally complex areas to estimate missing sections, stratigraphical models for exploratory wells with better predictions of target horizons, fine-scale reservoir correlations, and discovery of new reservoirs. The use of HIP in other areas is recommended, with palynology as a common in-house practice within multidisciplinary teams formed especially for each specific task.

INTRODUCTION

In the oil industry, palynology is a stratigraphic tool especially useful in the study of rocks deposited in continental, coastal, and shallow-marine settings. Palynological analyses are used mainly for chronostratigraphic correlations, paleoenvironmental studies, and the evaluation of potential source rocks. The integration of palynology with other geological disciplines, such as sedimentology,

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geophysics, geochemistry, and petrophysics, is needed for geological modeling and petroleum system studies, which in turn are essential for planning and developing better exploration strategies and for optimizing reservoir exploitation. Good examples of the benefit that palynology has provided to the oil industry through time are given by Hopping (1967) and McGregor et al. (1996).

The recent development of new geological concepts and methods, such as sequence stratigraphic analysis and high-resolution three-dimensional (3-D) seismic technology, has caused significant changes in stratigraphic work. In palynology, and in general in biostratigraphy, the classical qualitative or semiquantitative studies based on selected marker taxa have been enhanced with modern quantitative methods that use the whole palynological assemblage (including particulate organic matter), high-resolution sampling, and multivariate statistical methods (examples are presented in Jansonius and McGregor [1996] and Jones and Simmons [1999]). To refer to this new approach, Armentrout (1996) used the term "high-resolution sequence biostratigraphy" (HRSB). Biostratigraphy is no longer viewed as a service, as it was in the past, but as a part of integrated teamwork projects. The integration of HRSB with other disciplines to develop integrated geological teams has determined the alignment of biostratigraphy with the attainment of business goals, which is called by Payne et al. (1999) "high-impact biostratigraphy" (HIB).

The purpose of the present article is to document the application of high-impact palynology (HIP) approaches in the Maracaibo Basin (Venezuela) through the analysis of selected case studies. This is done to open to a wider audience of petroleum geologists and related professionals several of the potentialities that palynology can offer, as well as to encourage beginner biostratigraphers to use these methods. This article is not intended as a revision but as a methodological update.

The article is divided into two sections, one methodological and other practical. The first part introduces the methods used and their theoretical foundations. Emphasis is on ecostratigraphic methods, mainly palynocycles and ecologs, because they have been intensively used in the study area; however, other methods are also documented. The second part of the article illustrates the results obtained in selected case studies using ecostratigraphy and other quantitative methods and integrated work.

METHODOLOGICAL FRAMEWORK

Two main methodological aspects are discussed; one is conceptual, dealing with ecostratigraphy and other quantitative methodologies, and the other organizational, dealing with the functioning of exploration and production teams and tasks.

Ecostratigraphy

Ecostratigraphy is related to the nature of the fossil record. As a discipline based on organic evolution, which is directional and nonreversible, palynology considers the ranges of palynomorphs as chronostratigraphic markers. Indeed, global first and last appearances (FAD, LAD) are unique and have chronological meaning. These events, however, can be distorted locally by environmental factors (and, of course, diagenesis). For example, a LAD could result not from extinction but from the lack of suitable environments locally for fossil-producing organisms. Therefore, differences in the environmental tolerance of these organisms are potentially distorting the fossil record. As a result, in the classical biostratigraphic frame, fossils are commonly separated into chronological and environmental markers, the latter being commonly downgraded as less reliable or bad chronostratigraphic markers.

Modern biostratigraphic concepts, however, are changing this view. Martinsson (1973) introduced the concept of ecostratigraphy to develop a new approach that encompasses all the ecological (biotic and abiotic) aspects in stratigraphy. The basic premise is that evolution does not proceed on isolated taxa but in the frame of ecosystems and is, therefore, intimately associated with the ecological succession (Margalef, 1986). Environmental factors, far from being distorting signals, provide the basis for more accurate correlations (Brenner and McHargue, 1988). They are especially useful in three types of phenomena: (1) eustatically driven ecological events, (2) ecological events at a basin level (for example, regional anoxic and orogenic events), and (3) global climatic changes (Brenner and McHargue, 1988; Gladenkov, 1990; Olóriz et al., 1996). Events are restricted in space, but if the geographical domain in which they occur is known, a space-dependent stratigraphy is possible. In some cases, this stratigraphy could be local, but in others (for example, in eustatic and glacial cycles), it can have a worldwide extent.

Ecostratigraphy is a challenge for classical biostratigraphy, but it is a more realistic approach to the community behavior in time (Rull, 1997a). Evolutionary events are not neglected; on the contrary, they are placed in their correct context by recognizing that both evolutionary change and ecological succession are intermingled in the complex history of biotic systems through time (Margalef, 1986; Rull, 1990).

Ecostratigraphic techniques are synthetic, and commonly deal with multivariate statistics, because they consider ecosystems rather than individual taxa. Therefore, ecostratigraphic techniques need representative counts (Rull, 1987; Poumot, 1989) to estimate reliable fossil abundances and commonly deal with assemblage zones (Salvador, 1994). The two ecostratigraphic methods used in this article are palynocycles and ecologs, which are described in the following sections; other, nonecostratigraphic methods are also used and are explained in the corresponding examples.

Palynocycles

The term "palynocycle" was introduced by Poumot (1989), but the concept of palynological cycle was proposed by Van der Hammen (1957), who found a cyclic character in the palynological record of northern South America, related to astronomically driven climatic cycles. Poumot (1989) made a detailed paleoecological study of palynocycles, showing their dependence on the effect of eustatic events on coastal ecosystems. As a result, the sequential record of fossil pollen assemblages turned into a practical tool for the study of sea level oscillations and their phases, which are linked to particular depositional systems tracts. Five of these assemblages were important (Figure 1a).

1. Ferns. During the lowermost sea level phase, erosion and transport predominate, and the coastal pollen assemblages are dominated by fern spores from coastal swamps and inland forest, transported by rivers.
2. Palms. At the beginning of sea level rise, a peak of palm pollen is recorded, due to the ability of palms to colonize incipient prograding sandy accumulations.
3. Mangroves. In the maximum transgression, an increase of mangrove pollen is common, owing to the combination of a high and stable sea level and a wetter climate.
4. Open forests. The initial regressive stages are characterized by a maximum of pollen from back-mangrove open forests that expand because of climate cooling.
5. Herbs. Just before the lowest sea level position, a phase dominated by pollen of herbs indicates the reduction of the mangrove fringe and the recolonization of coastal terrains by herbaceous communities.

Rull and Poumot (1997) added three groups (forests, marine, and hinterland) for the Neotropics. Forests refer to coastal rain forests located behind the back-mangrove open forests, which began to develop between the palm and the mangrove phase, when both sea level and moisture were increasing. The marine group comprises dinoflagellate cysts and foraminiferal linings and commonly occurs slightly before or at the same time as the mangrove phase. Hinterland is a group constituted by pollen from inland and mountain communities (mainly savannas and mountain forests), whose maximum is recorded in coastal sediments when the sea level is reaching its lowermost position (before or at the same time as the herb group).

Palynocycles of the same nature, although with different floristic components because of biogeographical differences, have been recognized in the Paleogene and Neogene of tropical areas from Africa, Asia, and South America (Poumot, 1989; Poumot and Suc, 1994; Lorente and Contreras, 1997; Rull and Poumot, 1997; Van der Zwan and Brugman, 1999), reinforcing their global nature. Furthermore, several have been correlated with the second-, third-, and fourth-order global eustatic cycles of Haq et al. (1987).

Ecologs

Biologs are logs based on biological properties of fossils (Reyment, 1980). A special type of biolog is the ecolog, which considers relative frequencies of fossils in the assemblages, as well as physical and chemical properties of sediments in which they are included. Rull (1992) used two types of palynological ecologs, the paleovegetational index and the salinity index. The former is the ratio between the scores of two significant principal components representing different vegetation types. If this index is built using lower coastal plain and alluvial plain components, it can be considered a tidal limit index (TLI), roughly indicating the limit of the saline-water influence (Rull, 1997b). Using the coastal association as the numerator, high TLI values represent increased marine influence, whereas low TLI values indicate regression. Consequently, TLI maximums (M) should coincide with flooding surfaces, and

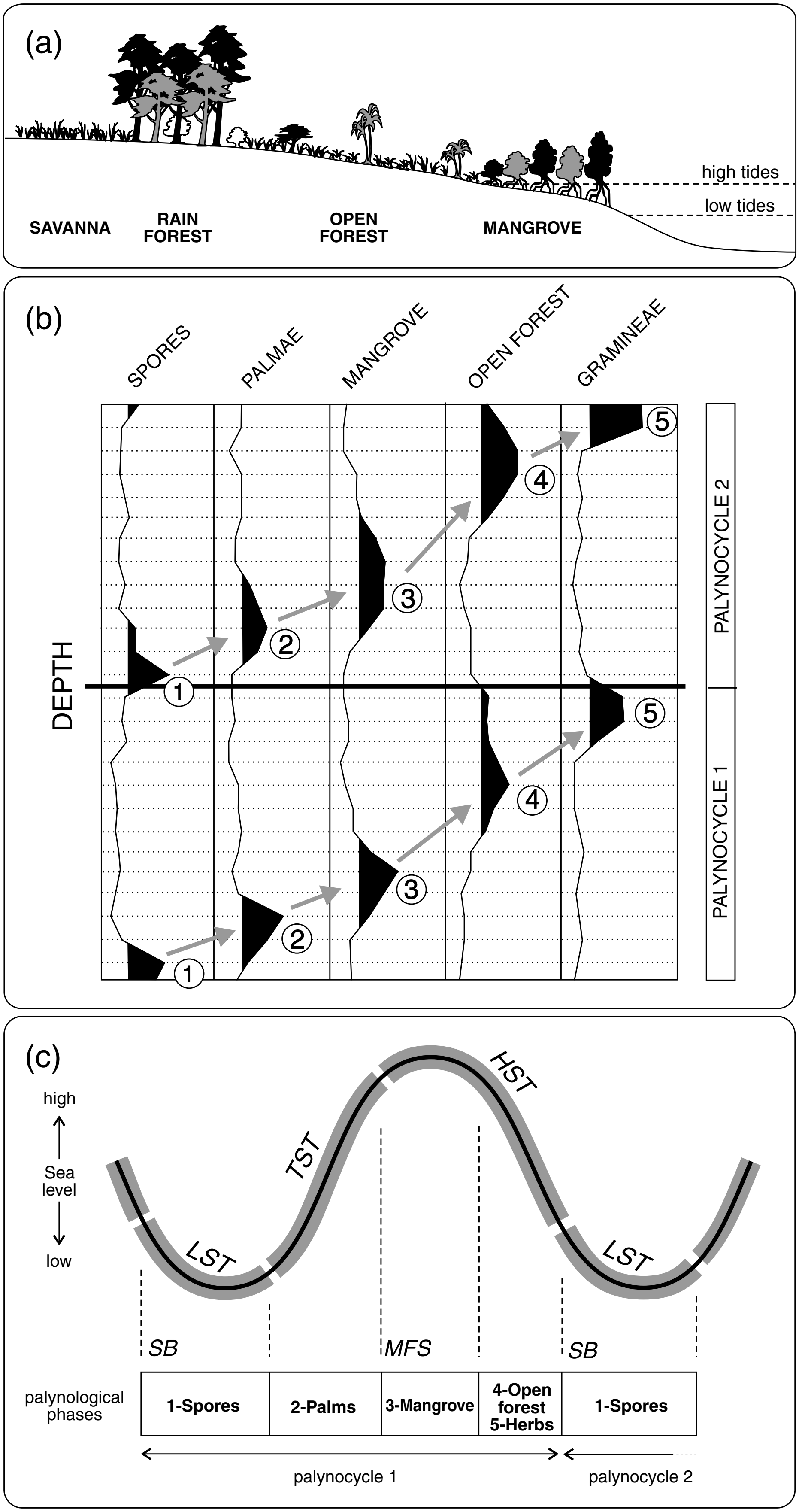


Figure 1. Original definition of palynocycles. (a) Generalized transect of coastal vegetation zones for the tropics of Asia and Africa (redrawn from Poumot, 1989). (b) Hypothetical example showing the stratigraphic expression of palynocycles (Rull and Poumot, 1997). Curves represent pollen percentages, and black areas are significant peaks or values above the mean. Only the five main phases (1–5) originally described by Poumot (1989) are depicted (see text for details). (c) Correspondence between the phases of the palynocycles and the depositional systems of the sequence stratigraphic analysis (Posamentier and Vail, 1988; Posamentier et al., 1988; Poumot, 1989; Homewood et al., 1992; Rull and Poumot, 1997). HST = highstand systems tract, TST = transgressive systems tract, LST = lowstand systems tract, SB = sequence boundary, MFS = maximum flooding surface.

TLI minimums (m) should represent sequence boundaries. The salinity index (SI) is the ratio between the relative frequencies of marine and freshwater fossil remains, commonly from planktonic organisms. The most common marine palynomorphs are organic-walled dinoflagellate cysts and foraminiferal linings. The common freshwater components are the colonial algae *Pediastrum* and *Botryococcus* (Chlorophyta). Because of the tolerance of some of these organisms to intermediate brackish waters, however, a simple statistical test (for example, linear correlation) should be done previously to choose the most suitable indicators (Rull, 1992, 1997b). High SI values are related to transgressions, and low values represent regressive phases. When used together, these two ecologs show close correspondence, supporting the validity of their theoretical foundations (Figure 2).

The two ecologs presented in this article have been especially useful in continental and coastal sediments, where the scarcity or absence of foraminifera, calcareous nannofossils, and other usual marine fossils has prevented the development of sequence-stratigraphic studies in the classical way (Rull, 1997b), but many others are possible and useful, depending on the biogeographical region and the problem under study. For example, Wiggins and Hill (1987) used the ecological shift plot, which is the ratio between pollen and spore characteristic of either warm or cold climatic extremes. Its application to the Tertiary of Alaska helped with regional basin correlations.

Integrated Work

Concerning the organizational aspects of petroleum exploration and exploitation, palynology (and biostratigraphy, in general) is no longer considered a lateral discipline or a service (either in-house or not). The aim of this article is not to erect a discussion on the historical causes for that; an excellent summary is in Payne et al. (1999). According to Payne et al. (1999), in the old model of perception of the geoscience community, much of the geological and petroleum-system

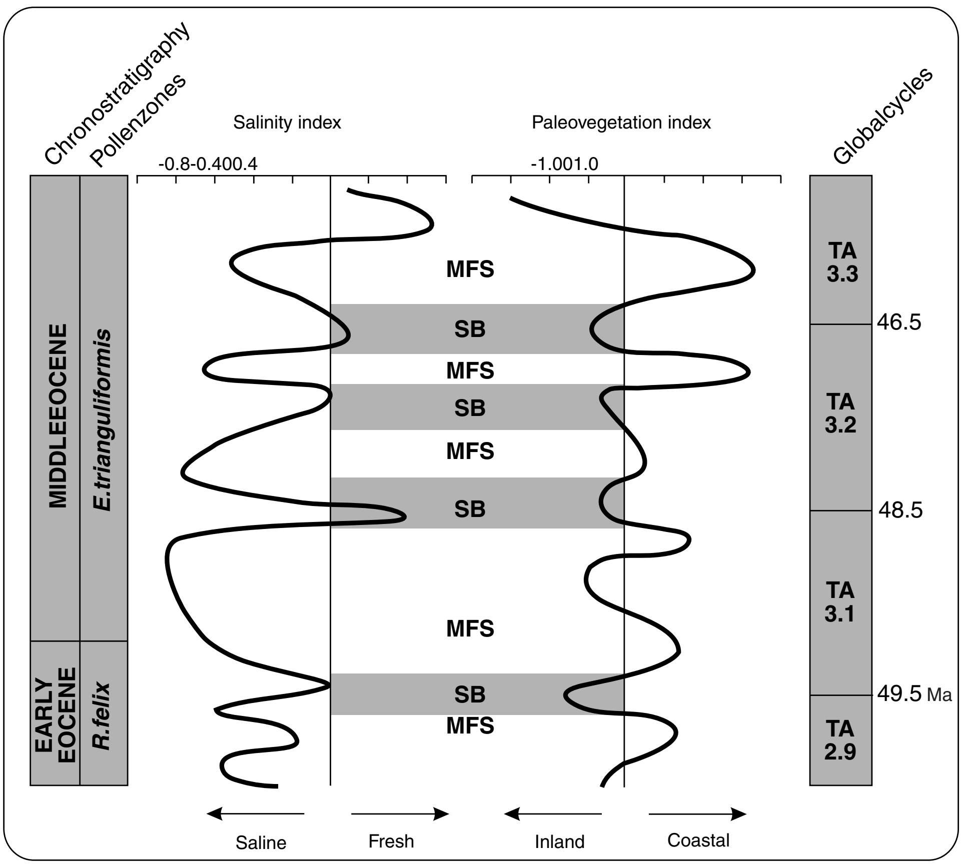


Figure 2. Comparison of paleovegetational and salinity indices in a Tertiary section from the Maracaibo Basin (modified from Rull, 1992). The salinity index used in this case was SI $= \ln[(F + 0.1)/(M + 0.1)]/e$, where F is the sum of freshwater fossils and M is the sum of the marine fossils. Therefore, negative values represent higher salinities, and negative peaks are maximums of marine influence. The paleovegetational index used was TLI $= \ln[(C + 0.1)/(I + 0.1)]/e$, where C is the scores of the principal component representing the most distal vegetation belt and I is the principal component associated with the innermost plant associations. By construction, the curves are inverse. The coincidence of inland ecosystems and freshwaters suggests sequence boundaries (SB), whereas the coupling of saline waters and shore plant communities indicates maximum flooding surfaces (MFS). TA = Tejas A.

modeling proceeded by itself, with only occasional biostratigraphic input. Biostratigraphy was considered a static science useful only as a chronostratigraphic tool in regional exploration and unreliable in establishing valid fine-resolution correlation frames at a reservoir scale. In part, this is due to the classic perception of biostratigraphy (see previous discussion), in which large-scale correlation potential is high but stratigraphic resolution is low. Quantitative high-resolution biostratigraphic methods, however, have been progressively established, determining an outstanding improvement in the subregional correlation power. This has increased the confidence in the biostratigraphic methods within the new geological framework and contributed to the incorporation of this discipline into integrated teamwork projects. In the new model (Payne et al., 1999), HIB is fully integrated into teamwork projects, with a continuous interaction and feedback, just as any other component of the geological study. In this way, the usefulness of biostratigraphy is largely enhanced, because the results are placed in the correct context, with subsequent benefits for petroleum geology. Moreover, biostratigraphers have additional stimulus for creativity provided by the existence of definite goals and questions to answer.

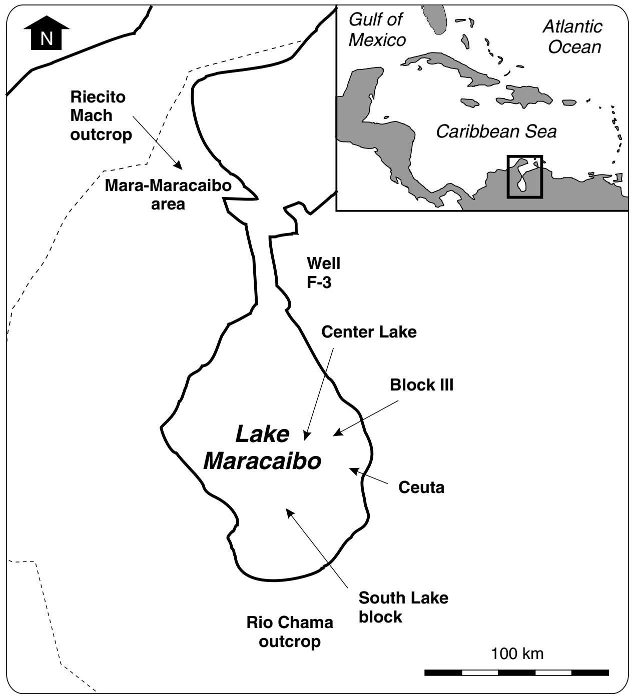


Figure 3. Map of the Lake Maracaibo area, indicating the sites and areas discussed in the case studies.

CASE STUDIES

Examples in this section are a selection from the routine work I developed during the last decade at Petróleos de Venezuela, S.A. (PDVSA) Exploration, Production, and Upgrading in the Maracaibo Basin (Figure 3), using high-impact palynology. The examples range from exploration planning of new areas to well-drilling control, including poorly documented aspects of the palynological work, such as, for example, fine-resolution reservoir correlation.

High-Resolution Stratigraphy at a Basin Level

A detailed and well-calibrated stratigraphic framework is essential for a realistic geological model. In the Maracaibo Basin, the classical palynological zonations based mainly on taxon-range and concurrent-range zones (Figures 4, 5), have been the base for a successful exploration history. With the growing use of sequence stratigraphy, the search for a palynological stratigraphy related to global eustatic cycles has led to the application of new techniques, such as, for example, Poumot's palynocycles. A first attempt was made by Rull and Poumot (1997) using late Eocene, Oligocene, and Miocene well sections. As a result, a preliminary subdivision into 21 palynocycles, corresponding to third-order eustatic cycles, was made (Figure 6). Further studies on well cores and outcrops reported additional third-order palynocycles from the Paleocene and early–middle Eocene (Rull, 1998, 2000). Furthermore, these studies ascertained numerous lower order palynocycles with a periodicity between 200 and 400 k.y. on average that were related to Milankovitch orbital cycles. More studies are needed for the establishment of a new palynostratigraphy of this type, but several tests in different areas and ages have shown that it has high potential (Rull and Lorente, 1999). In addition, palynocycle methodology has been used successfully in the Maracaibo Basin in tectonic interpretations (Lorente and Contreras, 1997) and high-resolution reservoir correlation (Gamero et al., 1997), as can be seen in more detail in further examples.

Correlations and Reservoir Tracking

The following example shows how ecostratigraphy enhances the stratigraphic resolution, improving regional correlations and reservoir tracking. In the Mara-Maracaibo area, Eocene sediments are remarkably

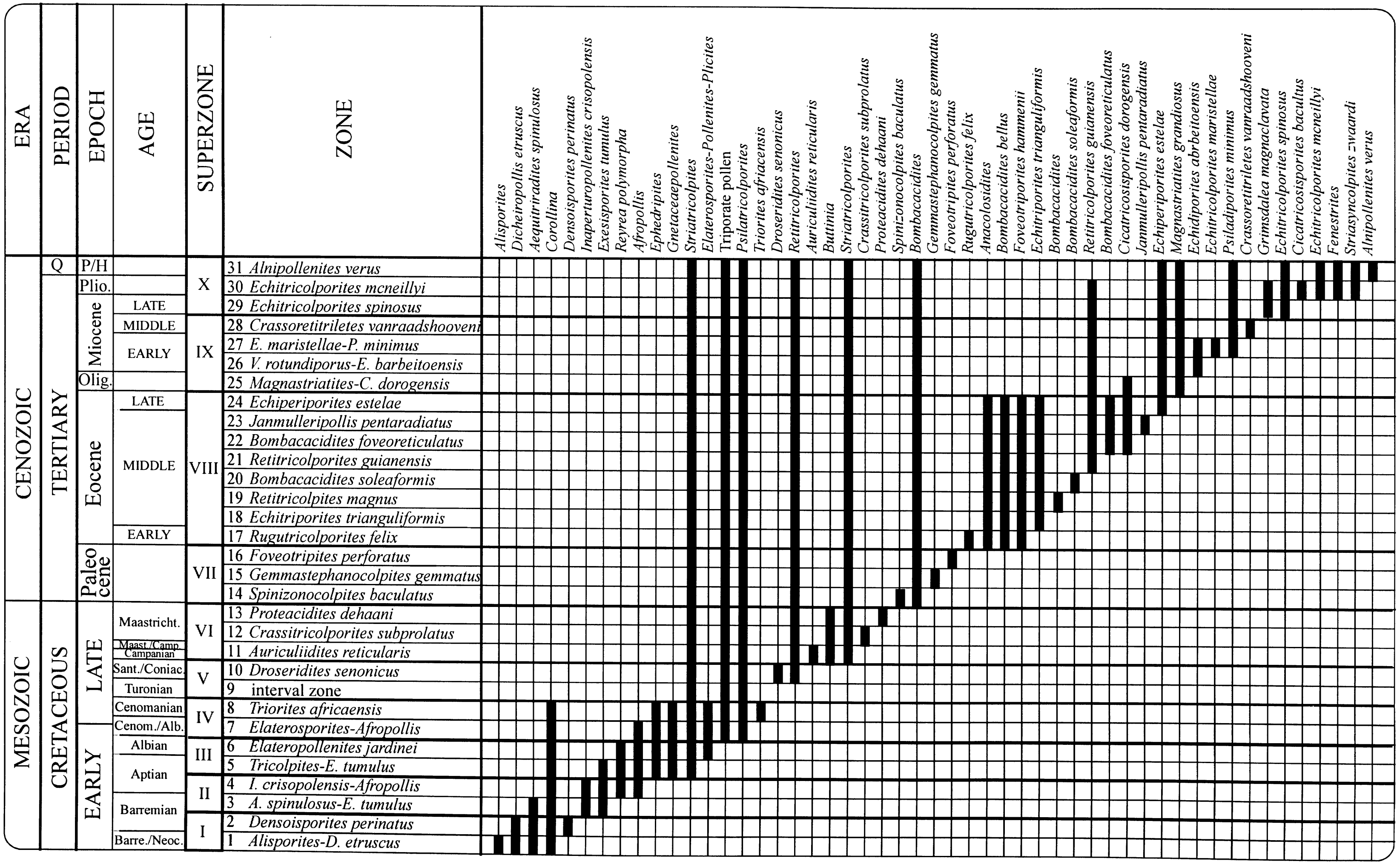


Figure 4. Ranges of the key sporomorph markers for the Late Cretaceous and the Cenozoic in northern South America (redrawn from Muller et al., 1987).

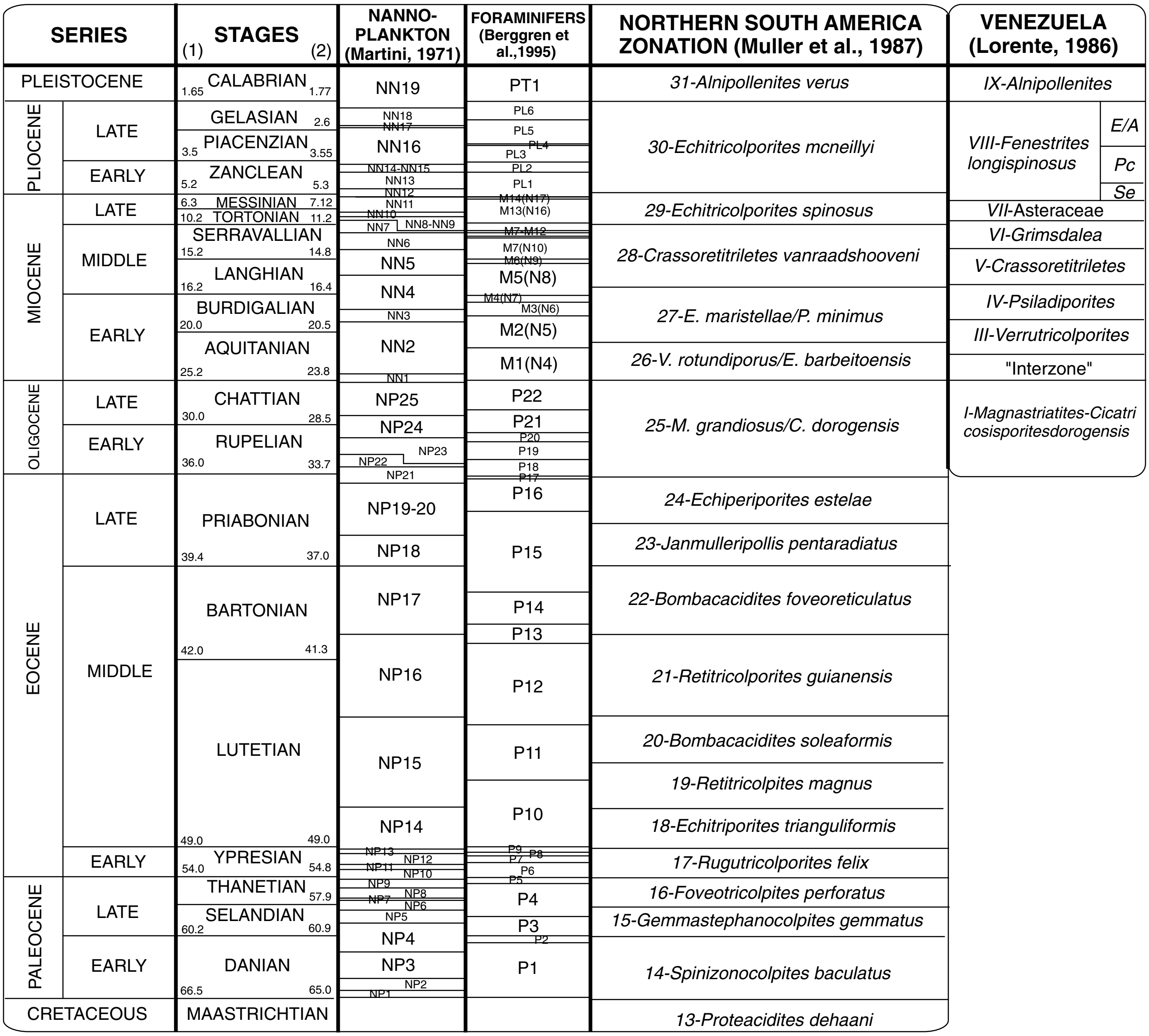
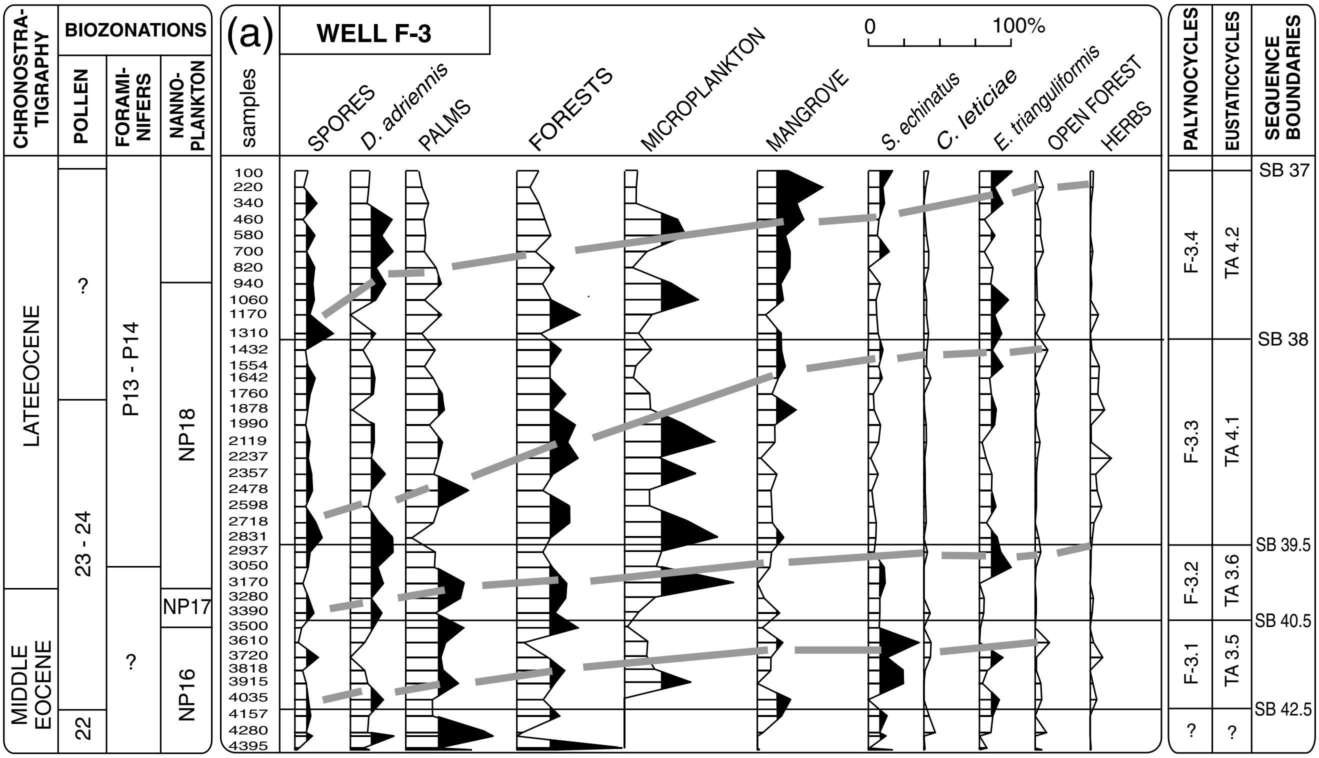


Figure 5. Chronostratigraphic equivalence of the palynological zonations for northern South America and Venezuela (modified from Lorente et al., 1997). Ages of stage boundaries (in Ma) are according to (1) Haq et al. (1987) and (2) Berggren et al. (1995).

thick, especially in the early Eocene, which encompass some of the prospective Tertiary reservoirs in the region. Correlation and well-drilling control have commonly been handicapped, however, by the lack of sufficient biostratigraphic resolution. Eocene sediments were deposited in continental and transitional environments and are commonly devoid of planktonic foraminifera and calcareous nannoplankton. The classical palynological zonation was not detailed enough to resolve stratigraphy at the reservoir scale. Indeed, the

Figure 6. Application of Poumot's palynocycles methodology to the Maracaibo Basin (Rull and Poumot, 1997). (a) Example of well F-3 (Figure 3). Biozones used correspond to Figure 5. Eustatic cycles and sequence boundaries (in Ma) are according to Haq et al. (1987). The original phases of palynocycles as described by Poumot (1989) are in capital letters. Other intermediate phases were represented by single-taxa groups (*Deltoidospora adriennis, Spinizonocolpites echinatus, Clavatricolporites leticiae,* and *Echitriporites trianguliformis*) that are abundant but of doubtful or unknown ecological affinity. Their situation within the sequence is tentative. (b) Palynocycles obtained in the four wells (M-1 and F-1 to F-3) studied by Rull and Poumot (1997). The composite column of all the palynocycles found is called "general" and is correlated with the Tertiary global eustatic cycles of Haq et al. (1987), at right.



(b)

		PALYNOCYCLES M-1	F-3	F-2	F-1	GENERAL	EUSTATIC CYCLES		SB
MIOCENE	LATE			F-2.9		PCY23	TB3	3.3	6.3
				F-2.8		PCY24		3.2	8.2
				F-2.7		PCY22		3.1	10.5
	MIDDLE						TB2		12.5
					F-1.4	PCY21		2.5	13.8
					F-1.3	PCY20		2.4	15.5
					F-1.2	PCY19		2.3	16.5
	EARLY				F-1.1	PCY18		2.2	17.5
									21.0
							TB1		22.0
				F-2.6		PCY15		1.4	25.5
OLIGOCENE				F-2.5		PCY14		1.3	26.5
				F-2.4		PCY13		1.2	28.4
				F-2.3		PCY12		1.1	30.0
				F-2.2		PCY11	TA4	4.5	33.0
				F-2.1		PCY10		4.4	36.0
EOCENE	LATE								37.0
			F-3.4			PCY8		4.2	38.0
			F-3.3			PCY7		4.1	49.5
	MIDDLE		F-3.2			PCY6	TA3	3.6	40.5
			F-3.1			PCY5		3.5	42.5
		M-1.4				PCY4		3.4	44.0
		M-1.3				PCY3		3.3	46.5
		M-1.2				PCY2		3.2	48.5
		M-1.1				PCY1		3.1	

early Eocene was represented by a single pollen zone, *Rugutricolporites felix* (Muller et al., 1987), accounting for almost 5 m.y. (Figure 5). Several attempts to subdivide this zone were made, but the chronostratigraphic value of the resulting assemblage subzones was doubtful (Barbeito et al., 1985). As a result, the accuracy in the stratigraphic location of the reservoirs within the early Eocene interval was not always satisfactory, and errors in correlation and reservoir tracking due to lateral facies shifts were not uncommon.

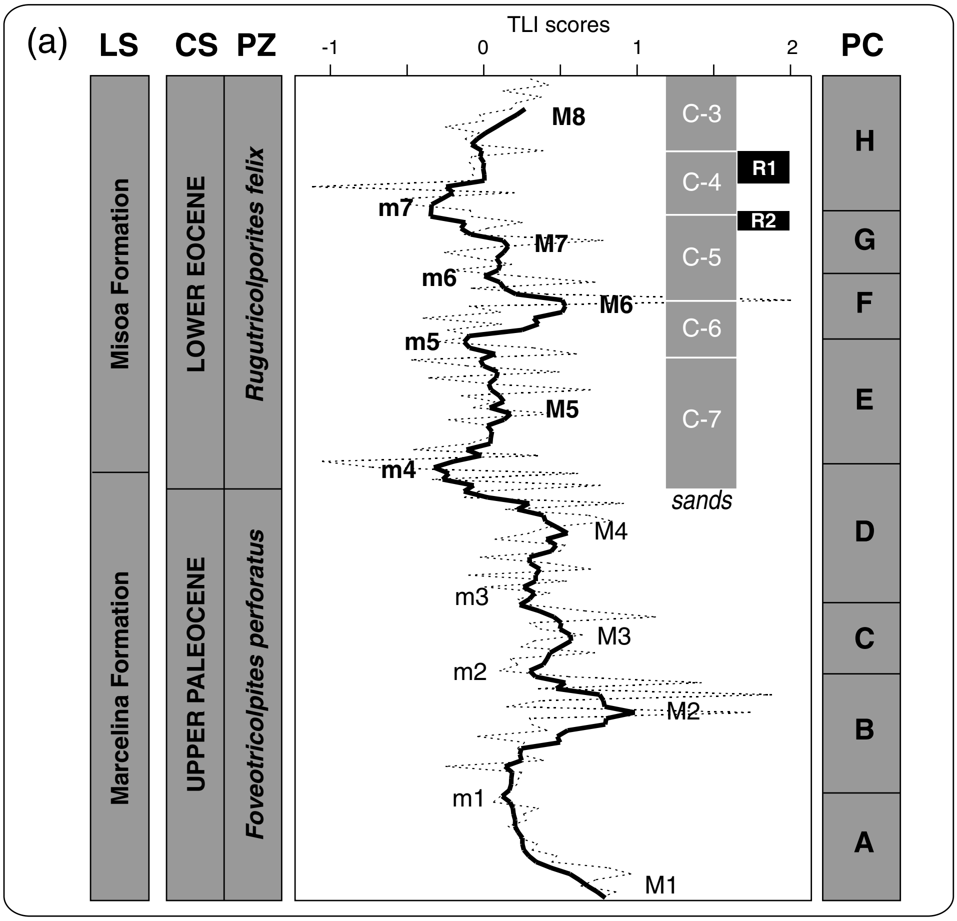
To improve the stratigraphic resolution, part of the Riecito Maché composite outcrop (Figure 3) was reinterpreted using ecostratigraphic techniques. The section studied embraces the late Paleocene–early Eocene and has enough sample density and sufficient pollen counts for ecostratigraphic purposes (Rull, 1999). Rull (1999) compared the results obtained using Poumot's palynocycles and a TLI ecolog. Both methods resolved the same cycles, which were correlated with third-order global eustatic sea level cycles (Rull, 2000). At least eight palynological cycles could be determined, of which four, E–H, correspond to the early Eocene and were correlated with the regional Eocene sand stratigraphy of the Maracaibo Basin, as well as with reservoirs of particular interest in the Mara-Maracaibo area (Figure 7). In this way, sands C-3 and C-4 correspond to palynocycle H, sand C-5 corresponds to palynocycle G and the upper half of F, sand C-6 is close to the boundary between palynocycles E and F, and sand C-7 coincides with the major part of palynocycle F and the top of D. Reservoirs 1 and 2 (R1 and R2) are located on the top of C-4 and C-5, respectively, which are associated with the minimum 7 (m7, the third minimum after the upper Paleocene–lower Eocene boundary), in the transition between palynological cycles G and H. Reservoir 1 is at the beginning of palynocycle H, in which palm pollen dominates (Rull, 2000) (Figure 4), and is therefore associated with a transgressive systems tract (TST). Reservoir 2 is at the end of cycle G, characterized by a peak of pollen from hinterland forests and spores (Rull, 2000) (Figure 4), which is typical of lowstand systems tracts (Figure 1). Fourth- and fifth-order palynocycles allowed higher resolution in this correlation frame. Indeed, palynocycles G and H could be subdivided into two and four minor cycles, respectively (Rull, 2000) (Figure 5). Reservoir 1 corresponds to the lower half of the second minor palynocycle of H (Figure 7), associated with prograding phases (1–3) that are characterized by sand bars and beaches linked to the initial steps of sea level rise (Poumot, 1989). Similarly, R2 coincides with the end of the second palynocycle of G (Rull, 2000) (Figure 5); its sands were probably deposited in continental environments. These fourth- and fifth-order palynocycles have an average duration of about 200 k.y.; hence, the related depositional units are most probably parasequences.

The application of this high-resolution correlation design contributed to the improvement of exploration practices in the Mara-Maracaibo area in several ways. From a regional perspective, it defined more precisely the stratigraphic interval of interest and made it easily detectable in seismic lines and electric logs. This furnished better tools for both planning and control of exploratory drilling. Indeed, prospect proposals were more accurate, and, therefore, exploratory risk was reduced. Furthermore, operational drilling costs diminished because of a better fit between predicted and actual well stratigraphy, as well as a more confident appraisal of the reservoir depth. Additional benefits, not yet realized, would rely on (1) the possibility of reconsideration of former field development strategies, in the light of the new stratigraphic knowledge, and (2) the usefulness of low-order cyclicity in fine-resolution reservoir correlation and its application to secondary recovery practices.

The Timing between Trap Formation and Oil Migration

A good example of integrated work with explicit goals is provided by the exploratory survey of the northern Andean foothills. At the beginning, extensive field campaigns yielded enough samples for a broad litho-bio-chronostratigraphic picture of the area, allowing evaluation of some exploratory possibilities and constraints (Boesi et al., 1985). Potential Cretaceous and Tertiary source rocks, reservoirs, and seals were identified as input for petroleum-system modeling. Because this is a structurally complex area, however, the timing between trap-forming tectonic events and oil migration was considered a critical parameter. If migration had occurred first, there would be no need to continue exploration. Previous geochemical and structural studies suggested that both oil migration and structure formation, associated with the initiation of the latest Andean uplift, began in the Miocene (González de Juana et al., 1980; Blaser and White, 1984). Therefore, the existence of suitable traps before oil migration was questionable.

A subproject was designed to evaluate this risk, involving structural, sedimentological, geochemical, and biostratigraphic expertise. Geochemical studies showed that there was no new evidence against the



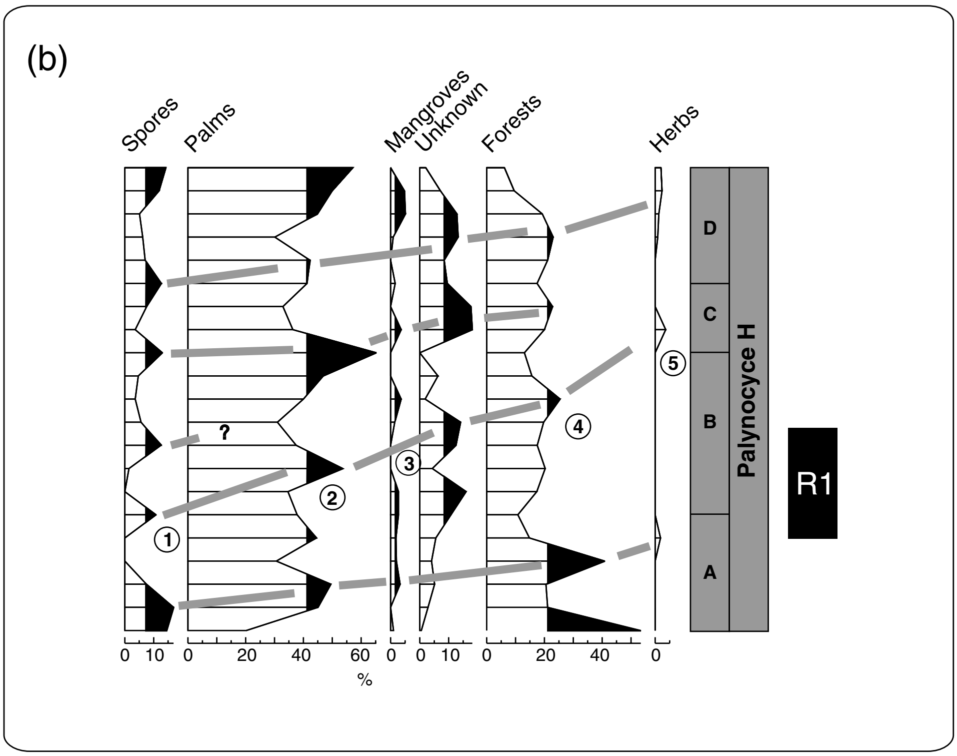


Figure 7. Palynocycles and ecologs in the Riecito Maché outcrop (Rull, 2000). (a) Tidal limit index (TLI) correlated with other stratigraphic features. Dotted line = raw data; solid line = six-point polynomial smoothing. Maximums (M1–M8) and minimums (m1–m7) of the smoothed curve are noted. C-3–C-7 = early Eocene sand bodies commonly used in the Maracaibo Basin. R1–R2 = position of reservoirs of interest in the Mara-Maracaibo area. LS = lithostratigraphy; CS = chronostratigraphy; PZ = pollen zones of Muller et al. (1987); PC = palynocycles, according to Rull (2000). (b) Decomposition of third-order palynocycle H into lower order palynocycles A–D using the original phases of Poumot, which are indicated only for palynocycle H-B, as an example. R1 = reservoir 1.

Miocene as the time for oil migration; therefore, the key parameter became the initiation of the latest Andean orogeny. Efforts were concentrated in the post-Eocene section of the Rio Chama outcrop (Figure 3), which was intensively resampled for foraminifera, palynology, and sedimentology (Higgs and Mederos, 1992). These three disciplines intersected in finding reworked Cretaceous and Eocene elements in almost all the samples of the Oligocene part of the Rio Chama Formation. Biostratigraphic evidence mainly consisted of the late Maastrichtian pollen form-species *Proteacidites dehaani* and the Eocene markers *Echitriporites trianguliformis* and *Rugutricolporites felix*, together with common Cretaceous foraminifera and chert fragments from the Cretaceous La Luna Formation (Pittelli and Rull, 1993; Rull, 1997c). This substantiates the presence of upstream Cretaceous and Eocene outcrops in a higher topographical position. Furthermore, sedimentological analysis documented a shift in paleocurrents, which began to flow from the south-southeast in the Oligocene (Higgs and Mederos, 1992). Therefore, consistent indications existed of highlands situated in the same position as the present Andes, suggesting that mountain building had already begun. This supported the possibility of structural-trap formation before oil migration and encouraged continuing exploration. The area is now under exploitation.

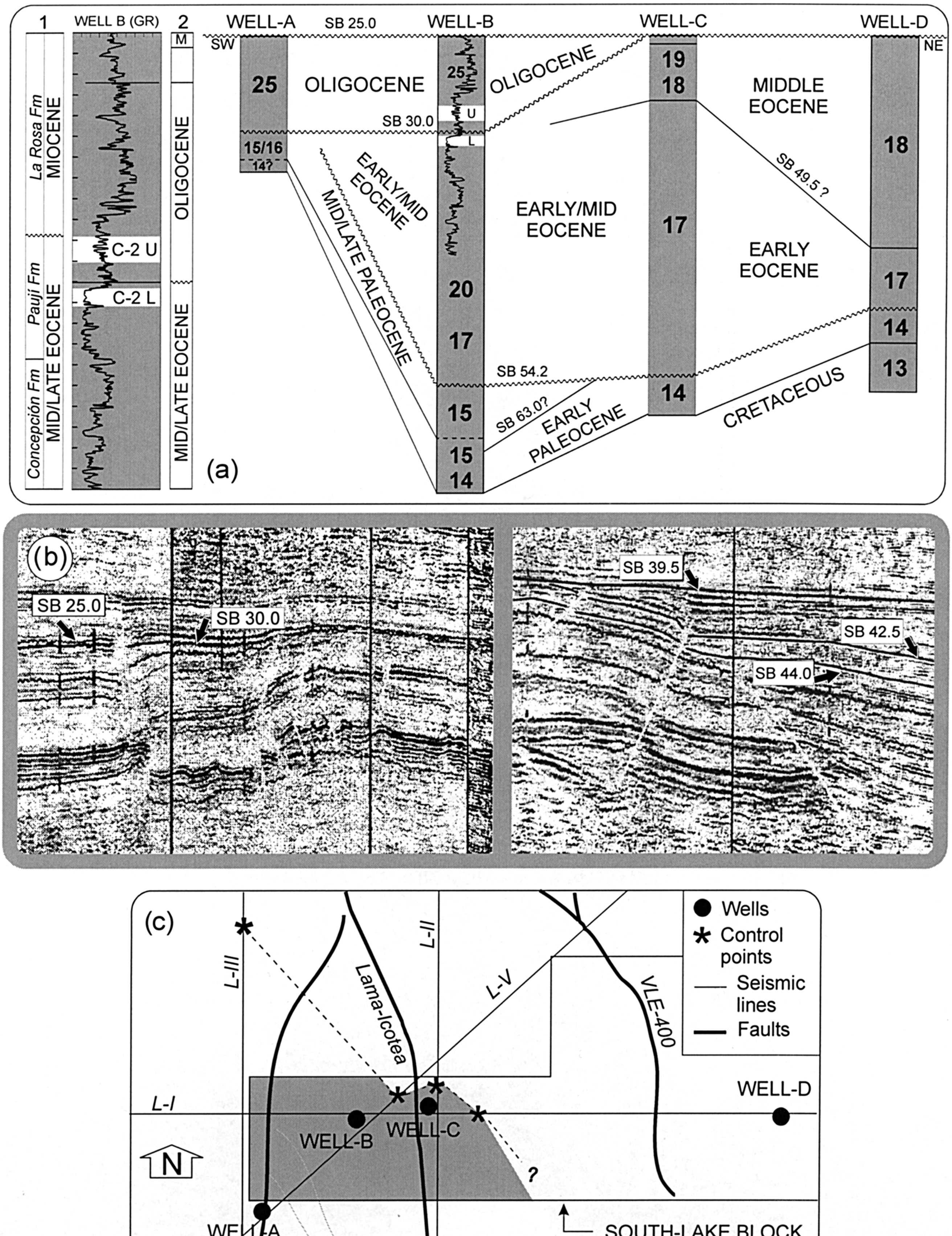
Stratigraphic Traps and Petroleum Systems Differentiation

One of the contributions of sequence stratigraphy analysis to exploration is a better understanding of the origin, types, and distribution of stratigraphic traps, which are commonly associated with sedimentary wedges and erosional surfaces. High-resolution palynology integrated into a multidisciplinary team whose goal was the stratigraphic reinterpretation of the south lake area in a sequence stratigraphic context determined a change in the traditional exploratory concepts and practices. In the South Lake block (Figure 3), the two known oil-bearing reservoirs of the Tertiary (C-2 upper and C-2 lower) had been traditionally considered to lie in middle–upper Eocene sediments, close to the top of the Eocene (Figure 8). The top Eocene is an outstanding stratigraphic regional marker across the whole basin, characterized by the unconformable Eocene–Miocene contact (González de Juana et al., 1980). Because Oligocene sediments had not been identified so far in the south lake area (because of the lack of intensive biostratigraphic studies), this regional picture was assumed also to be valid for the South Lake block. Therefore, seismic and log correlations were constrained by this view, and exploration strategies followed the traditional scheme based on the search for structural traps only.

During the last decade, however, some new findings questioned this model. On the one hand, Oligocene sediments were undoubtedly identified in well A, situated in an adjacent block at the south, using palynology and calcareous nannoplankton (Rojas et al., 1997). On the other hand, the reinterpretation of several seismic transects crossing the South Lake block led to the finding of a wedge that, owing to its stratigraphical position, was most probably Oligocene in age (Molano and Araujo, 1997). A multidisciplinary approach was thus undertaken to evaluate new possible stratigraphic interpretations. The first significant result was the confirmation of the Oligocene age for the wedge observed in the seismic lines. Indeed, the high-resolution palynological analysis carried out in well B identified Oligocene sediments in an interval previously interpreted as Miocene (Figure 8). The boundaries of this Oligocene interval coincided with the seismic markers interpreted as the sequence boundaries (SB) 25.0 and 30.0, which could be traced in several seismic transects and mapped (Figure 8). Further palynological analysis along a major east-west transect enabled calibration of Paleocene and Eocene seismic markers. In this way, a new stratigraphic picture emerged in which wedges limited by erosional surfaces were the rule (Figure 8).

Three main units were recognized: a Paleocene wedge sharpening toward the east; an Eocene pinching out toward the west; and the Oligocene wedge, facing to the east again. This stratigraphic arrangement was interpreted as the result of successive tectonic events at a regional level determining the tilting of the basin in opposite directions, interrupted by phases of uplift and/or low sea levels, which promoted erosion. In this

Figure 8. Tertiary stratigraphy in the South Lake block. (a) Palynostratigraphical section of a northeast-southwest transect and detailed chronostratigraphy of well B (1 = traditional interpretation; 2 = interpretation after the study reported in this article). Palynological zones (14–25) are according to Muller et al. (1987), as detailed in Figures 4 and 5. Ages of sequence boundaries are according to Haq et al. (1987). (b) Seismic interpretation showing the palynologically dated sequence boundaries (modified from Molano and Araujo, 1997). (c) Map of the Oligocene wedge in the South Lake block. L-I–L-V are the seismic lines used to locate the control points (stars).



1
WELL B (GR)
2
La Rosa Fm
MIOCENE
Pauji Fm
Concepción Fm
MID/LATE EOCENE
C-2 U
C-2 L
M
OLIGOCENE
MID/LATE EOCENE
(a)
WELL-A
SB 25.0
WELL-B
WELL-C
WELL-D
SW
NE
25
OLIGOCENE
SB 30.0
15/16
14?
U
L
EARLY/MID EOCENE
MID/LATE PALEOCENE
EARLY/MID EOCENE
20
17
15
15
14
SB 54.2
SB 63.0?
EARLY PALEOCENE
19
18
17
14
MIDDLE EOCENE
SB 49.5 ?
EARLY EOCENE
CRETACEOUS
18
17
14
13
(b)
SB 25.0
SB 30.0
SB 39.5
SB 42.5
SB 44.0
(c)
L-III
L-II
L-V
L-I
Lama-Icotea
VLE-400
Wells
Control points
Seismic lines
Faults
WELL-D
WELL-B
WELL-C
WELL-A
N
?
SOUTH-LAKE BLOCK

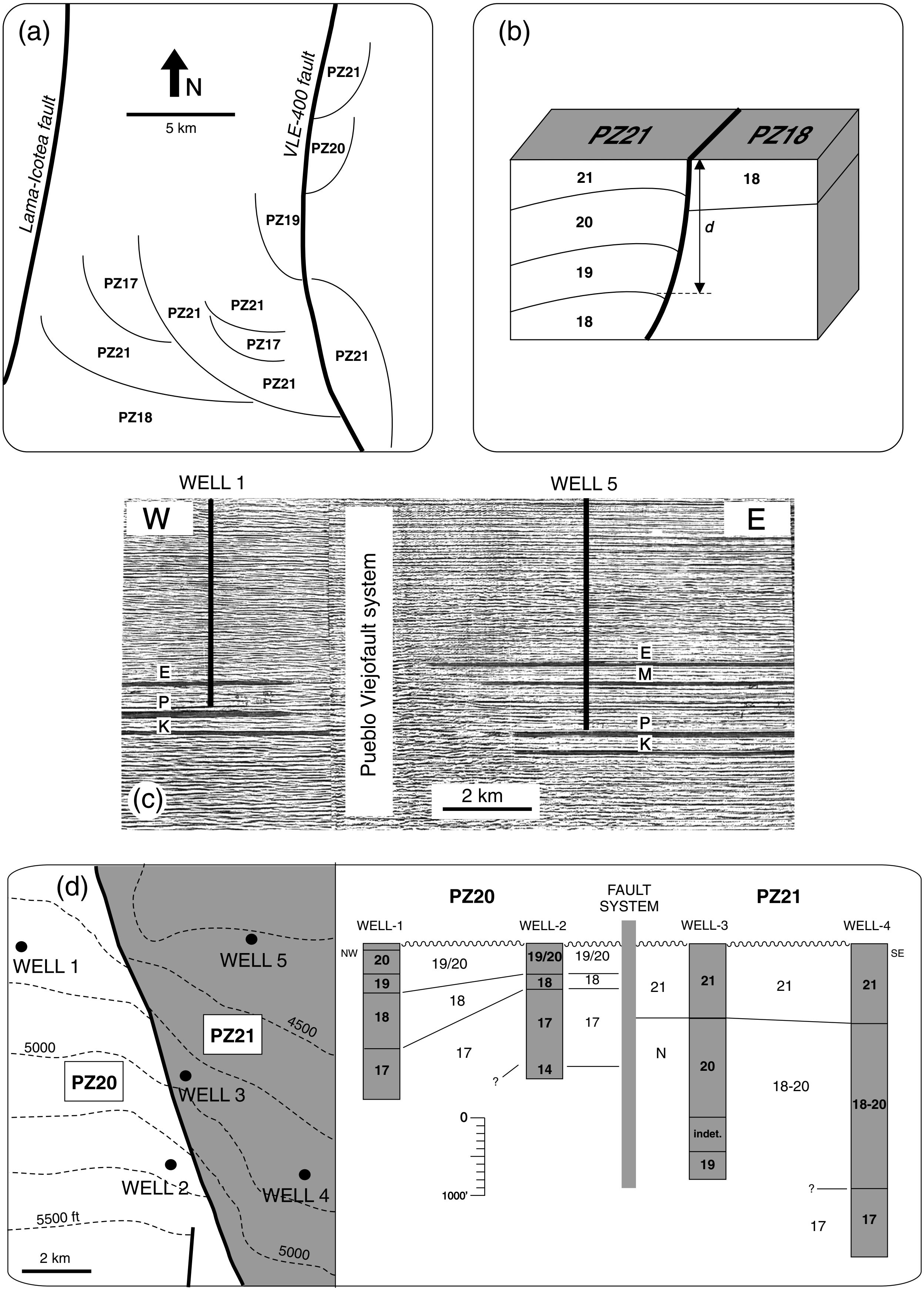
framework, the two reservoirs previously found in the area were in two different sedimentary units (Figure 8), C-2 upper in the Oligocene and C-2 lower in the Eocene. Furthermore, geochemical analysis showed that their hydrocarbons were different in composition (35° and 28° API, respectively) and origin. As a consequence, the oil accumulations were interpreted to belong to two different stratigraphically segregated petroleum systems, one developed to the east in the Eocene stratigraphic unit and the other to the west within Oligocene sediments. This was confirmed further by the production results of the block situated at the southwest of the South Lake block, in which the petroleum system corresponding to the Oligocene unit was identified and characterized. Nowadays, the Eocene of the South Lake block is being intensively restudied from an exploratory point of view, using a combined structural/stratigraphic approach in the search for traps.

Concept and Use of Palynoblocks: Paleostructures, Burial History, and Reservoir Prediction

A palynoblock is a tectonic block, that is, limited by faults, characterized by the occurrence of a single palynological zone in its top, and designated according to this palynological zone. For example, PZ17 denotes a palynoblock topped by palynological zone 17 (Rull and Lorente, 1997). The original definition uses the zonation of Muller et al. (1987), but any other scheme can be applied. Similarly, palynostratigraphic units other than zones (for instance, superzones, subzones, etc.) can be employed. As a consequence, a palynoblock is a concept holding both tectonic and chronostratigraphic attributes, with interesting but still largely unexplored applications. For instance, a palynoblock mapping of a given area provides an immediate chronological picture in space, and the interpretation of the relative movement of tectonic blocks can be straightforward. This has been of great help to infer the tectonic evolution of the central area of the Maracaibo Basin during the Paleocene, which is characterized by the alternation of several extensive and compressive events that reactivated and inverted preexisting structures (Arminio and Growcott, 1996; Rull and Lorente, 1997). Other applications to oil geology are discussed in more detail in the following case studies.

In the Maracaibo Basin, an outstanding regional peneplanation subsurface exists in the unconformable contact between the middle Eocene and the lower Miocene. Upper Eocene and Oligocene sediments are missing (González de Juana et al., 1980); however, the extent of the gap has not been settled and is still controversial. In a regional survey carried out by Rull and Lorente (1997) in the central area of the basin, five subsurficial palynoblocks, PZ17–PZ21, were defined and mapped (Figure 9). The maximum diachronism of the subsurface, that is, the maximum difference in age between the palynoblocks, was estimated at 10 m.y. (see Figure 9). This suggests the existence of a significant paleorelief before the terminal Eocene erosive event. To quantify the magnitude of the eroded sediments, it was assumed that missing sections in older palynoblocks (those topped by older pollen zones) are similar in thickness to sediments preserved in the younger ones. In this way, the missing section in a given palynoblock could be estimated as the difference in depth between its top and the corresponding isochronous boundary in an adjacent palynoblock (Figure 9). The actual estimates range between about 250 and 1700 m in palynoblocks PZ21 and PZ17, respectively. The real values, however, should be larger, because the upper part of the top palynological zone of each palynoblock has probably been eroded as well. Furthermore, using the average sedimentation rates for the middle Eocene (~160 m/m.y.) and the duration of palynological zones 23–25 (about 13 m.y.), the thickness of the upper Eocene–Oligocene section can be estimated to about 2000 m. Therefore, the total thickness of the missing section would range between 2250 and 3700 m, depending on the palynoblock considered. These results were of immediate utility in the understanding of petroleum systems, via the reconstruction of burial history. Indeed, dissimilar thermal gradients and kerogen maturation patterns in different palynoblocks were explained by differences in the sedimentary gaps, which could be quantified using the palynoblock methodology. This provides more accurate

Figure 9. Application examples of palynoblocks in the central Lake Maracaibo (a, b) and Ceuta areas (c, d). Palynological zones, in numbers, are according to Figure 5. (a) Map of the Eocene subsurface palynoblocks defined in the central Lake Maracaibo area. (b) Schematic picture of the contact between two hypothetical palynoblocks (PZ18 and PZ21), illustrating the minimum estimation for the missing section d. (c) Seismic interpretation of an east-west transect across the Pueblo Viejo fault system in Ceuta. E = top Eocene; M = top of Misoa Formation (early–middle Eocene); P = top Paleocene; K = top Cretaceous. (d) Map and schematic palynostratigraphic correlation of Eocene palynoblocks at both sides of the Pueblo Viejo fault system in Ceuta.


(a)
Lama-Icotea fault
VLE-400 fault
N
5 km
PZ21
PZ20
PZ19
PZ17
PZ21
PZ21
PZ17
PZ21
PZ21
PZ21
PZ18
(b)
PZ21
PZ18
21
20
19
18
18
d
WELL 1
WELL 5
W
E
E
P
K
E
M
P
K
Pueblo Viejofault system
(c)
2 km
(d)
WELL 1
WELL 5
PZ21
4500
5000
PZ20
WELL 3
WELL 2
WELL 4
5500 ft
5000
2 km
PZ20
FAULT SYSTEM
PZ21
WELL-1
WELL-2
WELL-3
WELL-4
NW
SE
20
19
18
17
19/20
18
17
19/20
18
17
14
?
19/20
18
17
21
N
21
20
indet.
19
21
18-20
21
18-20
?
17
17
0
1000'

input parameters for geochemical modeling and resource evaluation, which increases the confidence of the results and diminishes the exploratory risk.

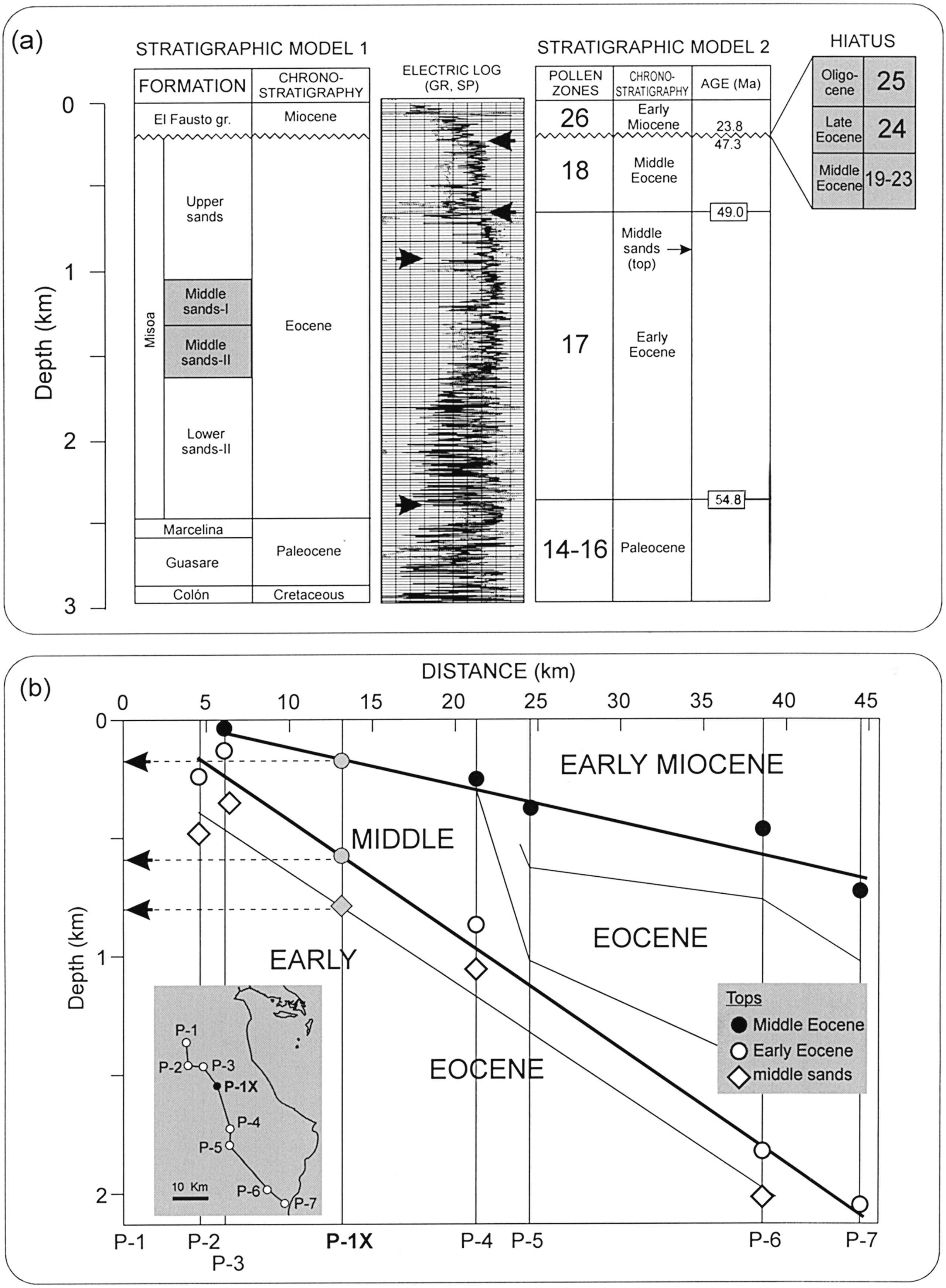
Another example from the Ceuta area (Figure 3) shows the application of the palynoblock concept to a reservoir scale. The interpretation of an east-west seismic transect crossing the Pueblo Viejo fault system exposed a thickening of Eocene strata in the eastern side (Figure 9). This thickening was especially evident in the middle Eocene, which contains several important reservoirs within the B sands. A multidisciplinary project involving the palynological study of the middle Eocene (zones 18–22) in several key wells was carried out to elucidate the exploratory significance of this seismic feature. That project discovered that the east side of the fault system was a PZ21 palynoblock, younger than PZ20, located at the west side. This indicates that the western block had been topographically more elevated before the peneplanation, which removed zones 21 and younger from the top. A further intrablock detailed study showed that the thickening observed in seismic lines at the east was due to a greater thickness of palynological zones 18–20, indicating that faulting was active during their sedimentation. Therefore, the thicker reservoirs within B sands should be expected to be on the east side of the fault, that is, in the younger palynoblock. Similar case studies from the same region yielded the same results, allowing confirmation of two rules in the exploration of highly tectonized areas: (1) the contact between two palynoblocks is a good area for prospecting because faulting can provide sealing, and (2) thicker reservoirs can be expected in the younger palynoblocks.

Enhanced Palynosteering and Well-Drilling Control Improvement

Well-site biostratigraphy is a long-established tool for the stratigraphic control of drilling (for example, determination of the stratigraphic position of the drill bit, coring and casing points, and total depths), which contributes to lower drilling costs (Payne et al., 1999). Commonly, wells are monitored during their drilling by comparison with a stratigraphic model based on previous studies (including biostratigraphy) in other wells of the same area, as well as seismic interpretations. Currently, the biostratigraphy contributes to the model by identifying certain key horizons, such as, for example, formation tops, which should successively be found during the drilling. This contribution can be notably enhanced, however, as noted in the following example.

In the Mara area (Figure 3), a first stratigraphic model for the exploratory well P-1X was based on extrapolations from regional seismic lines because no wells existed in the vicinity (5 km or less). The exploratory objective of the well was the so-called middle Eocene sands, situated at about 1050 m depth, according to the first stratigraphic model (Figure 10). The evaluation of the palynological information existent in neighbor fields from the same region, however, showed interesting and useful spatial trends. Indeed, both the early and middle Eocene tops showed a roughly linear descending trend (in depth) in the northwest-southeast direction (Figure 10b). The top of the middle Eocene sands followed the same tendency and was consistently situated 150–180 m below the middle Eocene top. The exploratory well P-1X was situated in the middle of these trends, and, therefore, these three datums were estimated by linear interpolation. Furthermore, the depth and stratigraphic extension of the Eocene–Miocene unconformity was predicted using the same palynological studies. By comparison with the regional data, this hiatus should omit palynological zones 19–25, representing most of the middle Eocene, the late Eocene, and the entire Oligocene (approximately 23 m.y.). Finally, the Paleocene and Cretaceous tops were also prognosticated, using the known depths of their corresponding palynological zones (Figure 5) measured in wells from neighboring fields. This furnished a palynological stratigraphic model that fit almost exactly with the observed tops during the drilling (Figure 10). Especially useful was the accuracy in the determination of the top of target sands before the previously expected depth and the absence of Cretaceous rocks in the section penetrated, contrary to the prediction of the first model. From an economic point of view, the application of the palynological model resulted in a lower investment (otherwise, additional drilling would be necessary to reach the Cretaceous) and a reduced

Figure 10. Example of enhanced palynosteering and well-drilling control. (a) Stratigraphic models proposed before the drilling of well P-1X as compared with the final electric log. Model 1 was based on regional seismic interpretation and model 2 on palynology (details in the text). Actual tops are indicated in the log by arrows. Ages according to Berggren et al. (1995). (b) Graphical display of the palynological method for estimating the tops of the middle Eocene, the early Eocene, and the target sands in well P-1X, using linear interpolation. Estimated depths of the tops (gray symbols) are indicated with arrows in the depth scale.


(a)
STRATIGRAPHIC MODEL 1
FORMATION
CHRONO-STRATIGRAPHY
El Fausto gr.
Miocene
Upper sands
Middle sands-I
Middle sands-II
Lower sands-II
Misoa
Eocene
Marcelina
Guasare
Paleocene
Colón
Cretaceous
Depth (km)
0
1
2
3
ELECTRIC LOG (GR, SP)
STRATIGRAPHIC MODEL 2
POLLEN ZONES
CHRONO-STRATIGRAPHY
AGE (Ma)
26
Early Miocene
23.8
47.3
18
Middle Eocene
49.0
Middle sands (top)
17
Early Eocene
54.8
14-16
Paleocene
HIATUS
Oligo-cene
25
Late Eocene
24
Middle Eocene
19-23
(b)
DISTANCE (km)
0
5
10
15
20
25
30
35
40
45
Depth (km)
0
1
2
EARLY MIOCENE
MIDDLE
EOCENE
EARLY
EOCENE
Tops
Middle Eocene
Early Eocene
middle sands
P-1
P-2
P-3
P-1X
P-4
P-5
P-6
P-7
10 Km

exploratory risk. Indeed, the calibration of the time/depth curve considering the tops identified and the extension and duration of the Eocene–Miocene hiatus resulted in a more precise knowledge of thermal and maturity properties in depth, thus helping in the identification of the more prospective sand intervals.

Reservoir Correlation and Enhanced Recovery

Intrareservoir correlations are particularly difficult in fields with complex lithostratigraphy and/or strong tectonic influence, where the internal reservoir architecture is disturbed by faults and frequent lateral facies shifts. In these cases, ecostratigraphic methods can provide a detailed chronostratigraphic and paleoenvironmental frame as the basis for high-resolution sequence-stratigraphic interpretations. The following example shows the contribution of this biostratigraphic approach to a multidisciplinary study (including seismic reinterpretation, sedimentology, petrophysics, and palynology) of enhanced recovery.

The studied reservoir is in block III of Lake Maracaibo (Figure 3) and produces medium petroleum (19° API), mainly from the massive lower B sands of the Misoa Formation (middle Eocene). Of the total estimated reserves of the reservoir, less than 15% have been produced during the last 45 yr (Gamero et al., 1997). A program of secondary recovery was initiated recently to increase the productivity. As a part of it, a novel geological model based on 3-D seismic data caused a change in the strategy for reservoir management and recommended the injection of water to stimulate production (González et al., 1996). The lower B sands, however, comprise two different units (B-6 and B-7), and the question of reservoir continuity through them remained open. A detailed study of cores embracing both units was undertaken in a joint palynological-sedimentological subproject. A middle Eocene palynocycle containing the palynological zones 18 (upper part), 19, and 20 (lower part) was identified (Figure 11a). The maximum of mangroves coincided with the maximum salinity index, thus indicating a maximum flooding surface (MFS), which was dated as 43.0 Ma (Rull, 1998). The boundaries of the palynocycle were SB 42.5 (upper) and SB 44.0 (lower). The MFS 43.0 was located in a shale layer situated in the contact between upper and lower B sands and is a regional correlation datum, which can be traced across the whole block using the electric logs (Figure 11b). Furthermore, this shale layer constitutes an effective sealing layer for lower B sand reservoirs. Sands B-6 and B-7 were separated by the SB 44.0, which is a major boundary identified in the whole Maracaibo Basin (Ghosh et al., 1997). As a consequence, these two sand units were deposited in different sequences and were interpreted as independent flux units and, therefore, as different reservoir compartments (Gamero et al., 1997). This new sedimentological model notably impacted the decisions in the water injection project, which is now successfully implemented.

High-Resolution Palynology and a New Discovery

The application of high-resolution ecostratigraphic studies together with the use of the palynoblock concept allowed calibration and reinterpretation of seismic profiles and the finding of unknown oil accumulations. In the Center Lake area (Figure 3), it had been traditionally accepted that all the reservoirs were within the C sands. In the general stratigraphic column of the Maracaibo Basin, the C sands underlay the B sands, extending from the early Eocene to the base of the middle Eocene (González de Juana et al., 1980). In the study area, however, most of the middle Eocene sediments had been eroded, and, therefore, the B sands were apparently absent (Figure 12a).

Using this assumption, a study was initiated to correlate the reservoirs of the Center Lake block, as in the example previously analyzed from block III. A very detailed core sampling program was carried out for the palynological study to obtain fine-resolution correlations. The general palynostratigraphy indicated a thickening of the middle Eocene sediments toward an assumed depocenter situated at the north, beyond the boundaries of the block. This fit well with the Eocene paleogeographic scheme for the Maracaibo Basin known so far, and the trend was accepted to establish log correlations. The accurate palynological analysis of the southernmost well H, however, revealed a stratigraphic anomaly. Indeed, palynological zones 17 (early Eocene) and 18 (base of the middle Eocene) were in a lower stratigraphic position than in other wells, and a new palynological zone (19, middle Eocene) was determined below the Eocene–Miocene unconformity (Figure 12a). This strongly suggested the presence of a body of B sands, which was further confirmed by seismic and log reinterpretation (Figure 12b, c). After an integrated teamwork task, the final model considered the existence of a normal fault between wells G and H, which separate two subsurface palynoblocks (PZ18 and PZ19, respectively). In palynoblock PZ19, the body of B sands was more than 100 m thick, and it was

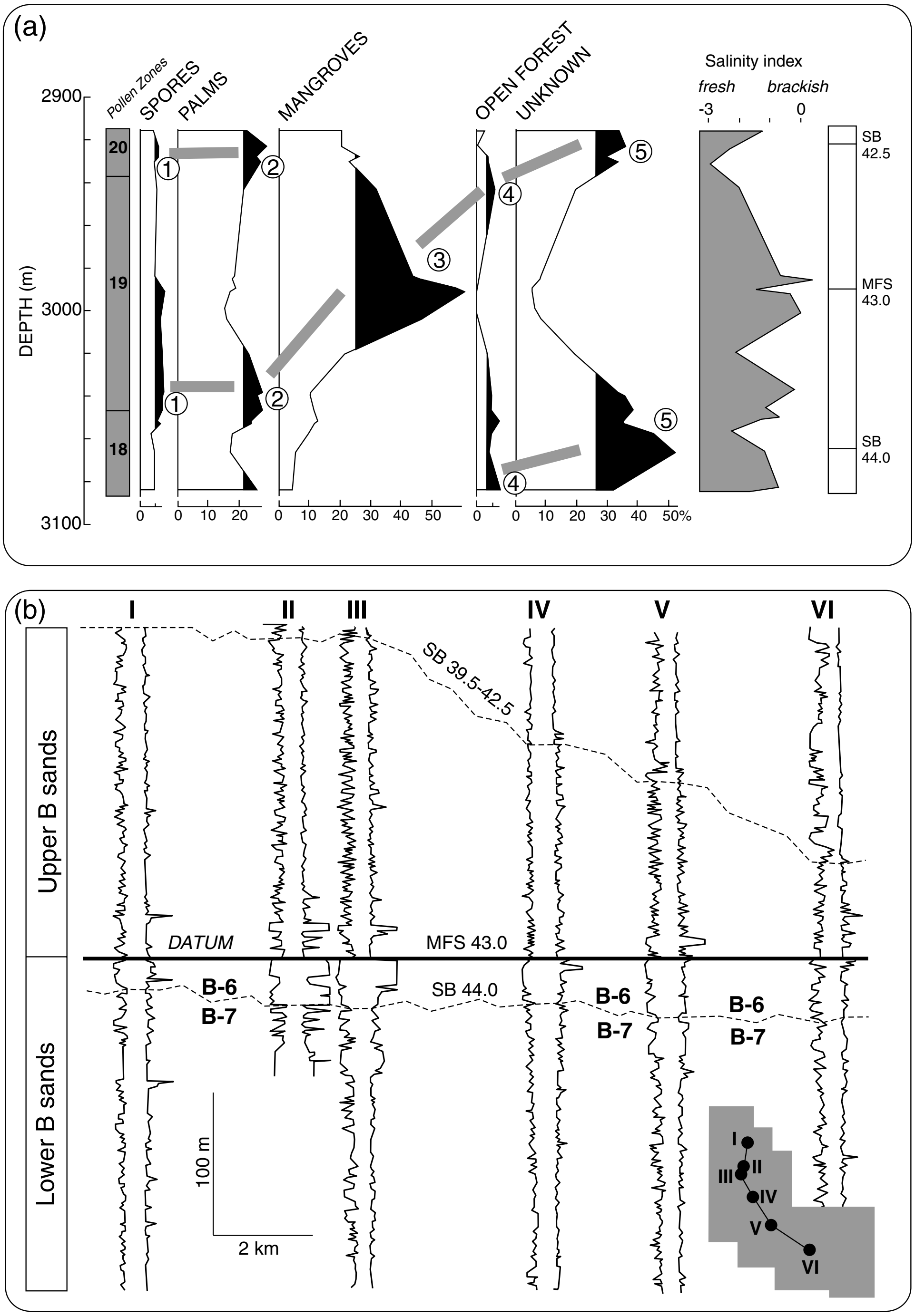


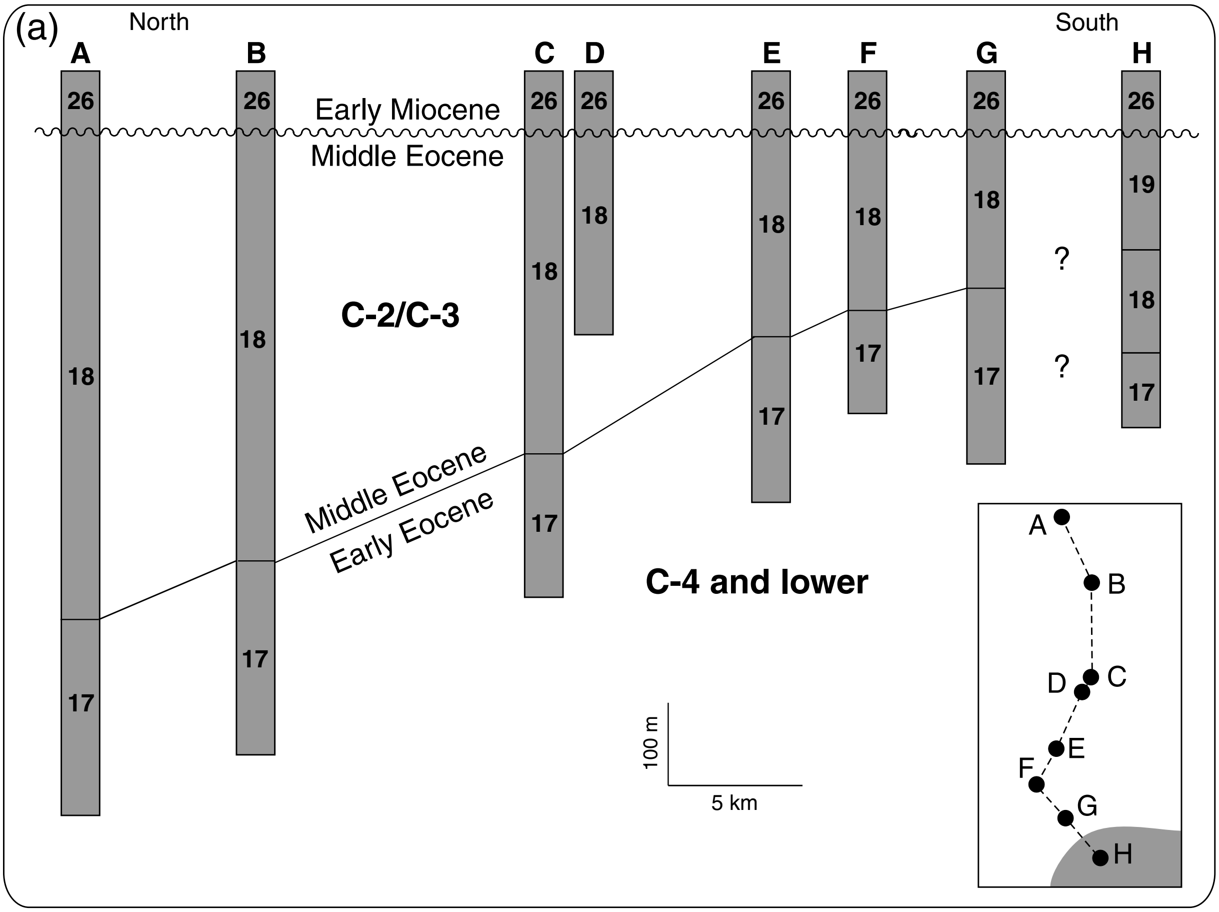
Figure 11. Reservoir correlations in block III, Lake Maracaibo. (a) Example of palynocycle found in core samples (modified from Rull, 1998). The unknown group is dominated by *Echitriporites trianguliformis,* an extinct form-species with unknown botanical affinity, possibly related to continental plants intolerant of high temperatures (Rull, 1999). Pollen zones of Muller et al. (1987) are indicated at the left side (see also Figure 5), and the salinity index according to Rull (1992, 1997b) is at the right side. Values of -3 indicate fresh water, and values around zero are typical of brackish water. Note the absence of fully marine water (values up to $+3$) throughout the section. Ages follow the calibration of Berggren et al. (1995). (b) Log correlation across block III using the key horizons provided by palynology (modified from Gamero et al., 1997) and the shale containing the MFS 43.0 as the datum. Sand units B-6 and B-7 are indicated. Inset is a sketch map of block III.

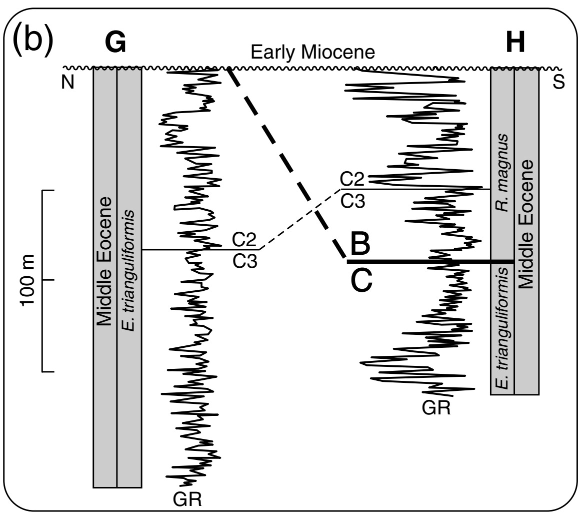
considered worth evaluating for light oil. The drilling was successful, and the production of the area increased by about 4000 bbl/day.

CONCLUSIONS AND FINAL COMMENTS

During the last decade, the use of HIP procedures, that is, the integration of ecostratigraphic and fine-resolution techniques with other geological work and the alignment of palynology with the attainment of business goals, has enhanced exploration and exploitation results in the Tertiary of the Venezuelan Maracaibo Basin. Selected case studies from my own experience show how HIP has contributed to exploration and production results, decisions, and planning.

The development of a high-resolution ecostratigraphic frame at a basin level is a long-term project initiated in 1995 on Paleocene, Eocene, Oligocene, and Miocene sediments. So far, a preliminary subdivision





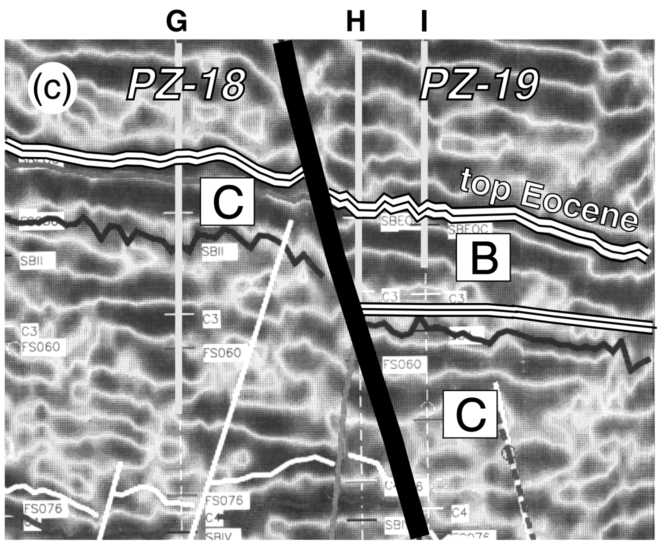


Figure 12. Case study of a new discovery using high-resolution palynostratigraphy and seismic and log reinterpretation. (a) General Eocene palynostratigraphy of a north-south transect in the Center Lake block. Palynological zones (17–19) are according to Figure 5. Letters A–H represent wells. Note the anomalous occurrence of zone 19 in well H. (b) Detail showing the different correlations of sand bodies in gamma-ray logs from wells G and H before (thin lines, C2 and C3) and after (thick lines, B, C) the high-resolution palynological study. (c) Magnified 3-D seismic image with the final interpretation in which normal faulting (thick line) separates two palynoblocks (PZ-18 and PZ-19), with different stratigraphies below the Eocene–Miocene unconformity (top Eocene).

into third- and fourth-order cycles has provided a useful correlation tool that has been applied with success to tectonic interpretations and reservoir correlation. In the Mara-Maracaibo area northwest of the basin, the use of ecostratigraphic tools such as palynocycles and ecologs helped to define more precisely the intervals that have exploratory interest and made them easily detectable in logs and seismic data. In this way, exploratory risk and operational costs diminished, because of a better fit between predicted and actual well stratigraphy. In the northern Andean foothills, integrated petroleum system studies (field sampling, seismic, sedimentology, mineralogy, palynology, foraminiferal analysis) revealed that the formation of structural traps could have begun in the Oligocene, before the timing of oil migration (Miocene), thus encouraging the exploration of new areas in this region. In the south of Lake Maracaibo, the involvement of high-resolution palynostratigraphy in multidisciplinary teamwork analysis (seismic, petrophysics, geochemistry, palynology) allowed differentiation of two petroleum systems in adjacent reservoirs and contributed to a change from exploration practices based on the search for structural traps to a new approach based on combined structural/stratigraphic oil accumulations.

The concept of palynoblocks was developed to identify palynologically the tectonic blocks, and it helped in understanding the tectonic evolution in structurally complex areas, such as, for example, central Lake Maracaibo. Furthermore, the magnitude of missing sediments due to an Eocene–Oligocene erosive event was estimated as an input for burial history reconstructions and geochemical models. Another location at the northwest of the basin was selected as an example of improvements in well-drilling control by enhanced palynosteering. During the drilling of an exploratory well, the use of a palynologically derived stratigraphic model or prognosis resulted in a lower investment and reduced exploratory risk.

Finally, two examples are related to fine-resolution reservoir correlation. The first one, from the eastern part of Lake Maracaibo, shows how palynology, used together with sedimentology, petrophysics, and geochemistry, contributed to the establishment of a new geologic model to support the strategy of secondary recovery by water injection. The second, a multidisciplinary study initially directed at reservoir correlation, yielded a new discovery after high-resolution palynological analysis and seismic and log reinterpretation.

In summary, HIP has been demonstrated as a tool necessary to improve both exploration and production achievements in the Maracaibo Basin. Analogous results could be expected in other areas with similar sedimentary characteristics. The maximum efficiency of high-impact procedures is attained when palynological analysis is carried out in-house, as part of multidisciplinary teams specially formed for each specific task.

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