A NEW FACIES MODEL FOR THE MISOA FORMATION (EOCENE), VENEZUELA'S MAIN OIL RESERVOIR

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The Misoa Formation has produced an estimated 13 billion barrels of oil, and contains a further 11 billion barrels of proved remaining reserves. The total represents approximately 50% of the proved reserves of the Maracaibo Basin, Venezuela's most productive region. In such a prolific formation, application of an inappropriate facies model to exploration and development can have huge financial consequences, in terms of misplaced wells, missed pools and miscalculated reserves.

A deltaic depositional model has been used for exploration and development drilling in the Misoa Formation since the 1960s. However, this deltaic interpretation is doubtful due to the lack of in situ *coal beds, palaeosols and other evidence for emergence diagnostic of delta plains. An alternative, tidal-shelf model is proposed here.*

INTRODUCTION

An appropriate facies model is essential for reliable reservoir prediction and, thus, cost-effective exploration and production. The Misoa Formation, which contains more recoverable oil than any other formation in the Maracaibo Basin, has traditionally been interpreted as deltaic since the 1960s (Brondijk, 1967a; Van Veen, 1972; Zamora, 1977; González de Juana *et al.*, 1980; Mathieu, 1989; Maguregui and Tyler, 1991; Lagazzi *et al.*, 1993; Ambrose *et al.*, 1995). However, the deltaic interpretation is suspect, because indicators of emergence characteristic of delta plains, such as coal beds, palaeosols, roots and desiccation cracks (e.g. Elliott, 1986), are absent. To escape this dilemma, the Misoa Formation would have to be entirely of delta-*front* origin; this is unlikely because modern delta fronts are generally just a few kilometres wide (in a downslope sense), whereas the Misoa Formation extends for more than 100 km in all directions (Fig. 1). Instead, an alternative, tidal-shelf model is proposed here, based on outcrop studies and published core descriptions. (All cores are held confidentially by the state-owned companies Maraven and Lagoven.) The new shelf model is profoundly important for future exploration and development in Lake Maracaibo, and in adjoining terrestrial concessions offered in the 1996 Venezuelan licensing round, the first offering in forty years. In particular, the predicted reservoir geometries are significantly different in the new model.

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As described in detail below, five facies can be recognized in most of the Misoa Formation outcrops in the Mérida Andes and Serranía de Trujillo mountain ranges, bordering the Maracaibo Basin: (1) mudstones; (2) mudstones containing strings of symmetrical sandstone ripples; (3) amalgamated sandy ripple strings with mud partings; (4) burrowed, tabular sandstone bodies, mostly 3- to10-m thick, made up of tabular cross-sets individually capped by symmetrical ripples; and (5) thin (cm) beds of pebble conglomerate. These facies can occur in any vertical order. Fossils include bivalves, gastropods and echinoids. Trace fossils in the sandstones (Facies 4) include *Arenicolites, Ophiomorpha, ?Skolithos* and *Thalassinoides*, defining a *Skolithos* ichnofacies.

Interpreting these facies, the depositional environment was below fair-weather wave base (i.e. offshore) in a large water body, based on: (1) the lack of evidence for emergence; and (2) the mudstones and tabular cross-bedding, which are uncharacteristic of a beach or shoreface. The echinoids and the *Skolithos* ichnofacies suggest a sea rather than a lake. The cross-sets capped by symmetrical ripples (Facies 4) are interpreted as stacked "event-beds" produced by migration of dunes during tide-enhanced storms. Combining these inferences, the Misoa Formation outcrops are interpreted as the distal, storm-influenced fringes of tidal-shelf sand sheets, analagous to the present-day NW European Shelf.

In the subsurface, beneath Lake Maracaibo and adjacent coastal areas, the Misoa Formation similarly lacks coal beds and other evidence for emergence, based on published descriptions of confidential cores. However, the sandstones show the following differences from those at outcrop: (a) they can be thicker; (b) they are less bioturbated, resulting in greater preservation of cross-stratification; and (c) they commonly contain mud drapes. These differences are interpreted to indicate a more proximal position within the tidal-shelf sand sheets, corresponding to the fair-weather-dune zone of modern analogues. Besides sheets, there is evidence for isolated sand ridges (as in modern tidal seas), inferred from published net sand maps and cross-sections based on well logs.

Hence, the tidal-shelf model is considered to be applicable to the bulk of the Misoa Formation, both at outcrop and in the subsurface. The antiquated deltaic model should therefore be abandoned. Sandstone reservoir geometries are predicted to be of two main kinds: (1) sheets, which possibly pinch and swell laterally due to dune topography; and (2) "shoestring" sand ridges.

PETROLEUM SIGNIFICANCE

Maracaibo Basin

The Maracaibo Basin is one of the oldest and most prolific producing hydrocarbon provinces in the world. Commercial production began in 1914 (González de Juana *et al.*, 1980). Cumulative production reached 33 billion barrels by 1991, and remaining recoverable reserves are estimated at 19 billion barrels (Talukdar and Marcano, 1994). Favourable factors include multiple reservoirs, including fractured Cretaceous limestones and numerous Tertiary sandstones, and an exceptional source rock, the Cretaceous La Luna Formation (Zambrano *et al.*, 1971; González de Juana *et al.*, 1980; James, 1990). Tectonically, the Maracaibo Basin evolved from a passive margin in the Cretaceous to a foreland basin in the Tertiary (Pindell and Barrett, 1990).

Misoa Formation

Of the 52 billion barrels of proved reserves (produced and remaining) in the Maracaibo Basin, approximately 50% occurs in the Misoa Formation, comprising 13 billion already produced and 11 billion remaining (Talukdar and Marcano, 1994, table 29.1). Misoa Formation reserves are distributed among 19 principal fields beneath Lake Maracaibo and adjacent coastal areas, including eight "giant" fields with individual reserves exceeding 500 million barrels (Talukdar and Marcano, 1994). Misoa Formation sandstones are

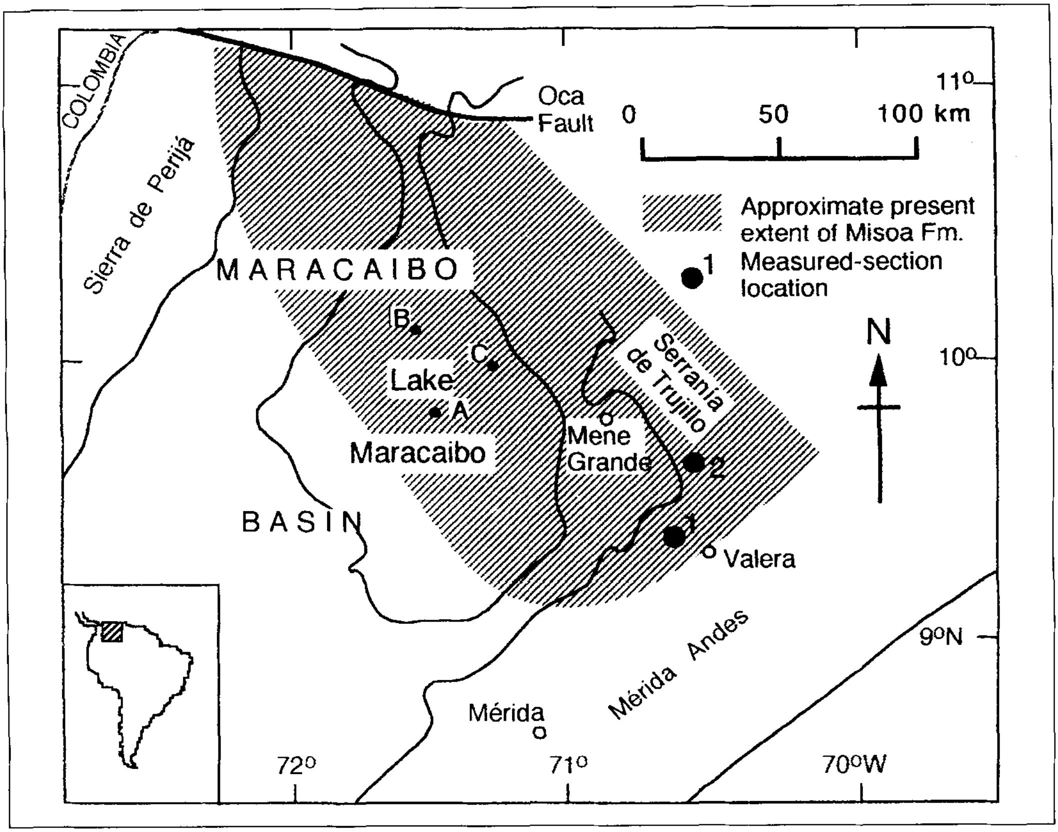


Fig. 1. Location map, showing the approximate present extent of the Misoa Formation (at outcrop in the Mérida Andes, Serranía de Trujillo and Sierra de Perijá mountains; in the subsurface beneath Lake Maracaibo and the adjacent plains). Numbers locate the two measured sections of Figs. 3 and 4. Letters indicate the locations of cores described in detail in the literature: A, central and B, northern Lake Maracaibo (Van Veen, 1972); C, *Lagunillas* field (Maguregui and Tyler, 1991; Ambrose *et al.*, 1995).

mostly "quartzose sandstones" and "subgreywackes" (van Andel, 1958), with excellent reservoir properties: average porosity among 263 samples from various fields is 20%, and average permeability among 178 samples is 240 millidarcies (Scherer, 1975, in González de Juana *et al.*, 1980).

With such large reserves remaining to be produced from the Misoa Formation, a reliable model of the depositional environment is critical, not only for development and to maximize recovery by efficient location of development wells, but also in exploration for additional reserves.

MISOA FORMATION: GENERAL GEOLOGY

Distribution

The Misoa Formation extends beneath much of Lake Maracaibo and the adjacent coastal plains, and crops out in the surrounding mountain ranges of the Mérida Andes, Serranía de Trujillo, and Sierra de Perijá (Fig. 1). Its overall geometry is a NE-thickening wedge, reaching a thickness of approximately 5 km in the type area in the Serranía de Trujillo (Brondijk, 1967a; González de Juana *et al.*, 1980). The NE limit of the Misoa Formation is unknown due to burial beneath the overthrust Lara Tectono-Sedimentary Complex (Stephan, 1985). The NW and SE limits are erosional truncations due to ongoing uplift in the Sierra de Perijá and Mérida Andes. The SW limit is poorly defined, because wells are few in southern Lake Maracaibo and in the plains NW of the lake: a pinchout is inferred by the Author beneath Lake Maracaibo, as is seen in a transect along the front of the Mérida Andes (Brondijk, 1967b, Fig. 2). In contrast, beneath the NW plains, the Misoa Formation grades laterally SWward into the Mirador Formation (Zambrano *et al.*, 1971, Lámina II).

No type section has been described for the Misoa Formation, but Brondijk (1967a) nominated a composite reference section comprising three river sections in the NW Serranía de Trujillo. Access to these sections is difficult, and detailed sedimentological studies have not been conducted. However, a new road across this sector of the Serranía, along the Río Misoa valley, exposes excellent roadcuts, which have been studied sedimentologically (Lagazzi *et al.*, 1993).

Age and stratigraphy (Fig. 2)

The age of the Misoa Formation is Early to Middle Eocene, based on foraminifera and palynomorphs (Brondijk, 1967a; Van Veen, 1972; Muller *et al.*, 1987). In the Serranía de Trujillo, the formation is conformably underlain and overlain by marine shales (Trujillo and Paují Formations). In contrast, in the subsurface the Misoa Formation is bounded by unconformities, with marine sandstones, shales and limestones of the Guasare Formation below, and marine strata of the La Rosa Formation above.

In the subsurface, the Misoa Formation is divided by oil companies into two intervals, "C" overlain by "B", each of which is further subdivided on the basis of well-log correlations (Walton, 1967).

Lithology

Although sandstones and shales are dominant, the Misoa Formation contains some limestone beds in its lower portion in the Serranía de Trujillo (Brondijk, 1967a). These bioclastic limestones, up to 2-m thick, contain red algae, benthonic foraminifera and molluscs. The limestones are "seldom encountered" beneath Lake Maracaibo (Brondijk, 1967a, p. 7), and being a minor component of the formation, are not considered further here. However, it is worth noting that the limestones are fully consistent with the marine-shelf origin proposed for the Misoa Formation in this paper.

MISOA FORMATION FACIES AT OUTCROP

The following facies descriptions and interpretations are based on the Author's visits to numerous sections throughout the Mérida Andes and Serranía de Trujillo, including parts of the reference sections and the new roadcuts in the Río Misoa valley. Two sections were logged at the centimetre scale, one in the SE Serranía de Trujillo near Agua Viva, and another in the Mérida Andes near Valera (Figs. 3 and 4, drafted at reduced scale). The Agua Viva section is laterally equivalent to the lowermost beds of the Misoa Formation of the subsurface (basal "C"), according to Lagazzi *et al.* (1993). In contrast, the Valera section represents the very top of the Misoa Formation, immediately below the Caús Formation (Fig. 3). Thus, the two illustrated sections are stratigraphically far apart. A sedimentological log of the Agua Viva section was also illustrated by Lagazzi *et al.* (1993).

Based on all but one of the sections visited, five facies can be discriminated in the Misoa Formation at outcrop. The facies are described individually below, and certain

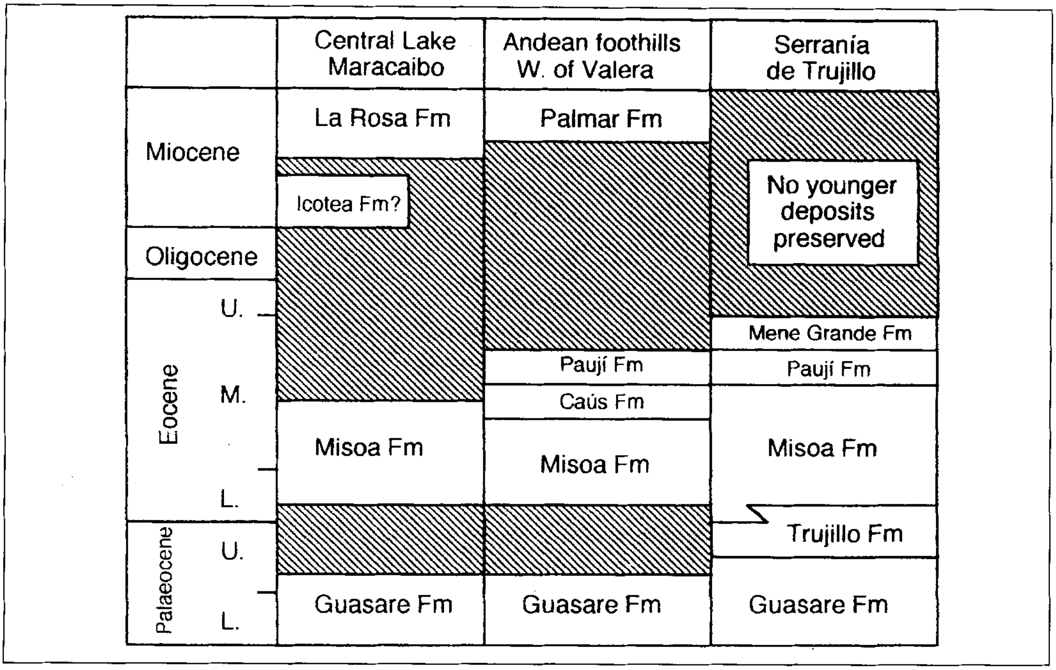


Fig. 2. Stratigraphic context of the Misoa Formation. Stratigraphy from Brondijk (1967a) and Zambrano *et al.* (1971). Age ranges are from González de Juana *et al.* (1980) and Muller *et al.* (1987). The central column corresponds to the region of Locality 1.

interpretations are deduced for each of the facies in turn, while a more complete environmental interpretation is given at the end, considering all five facies together.

Facies 1

This facies consists of mudstones, in units 0.5- to 5-m thick, with up to 20% siltstone and sandstone intercalated as horizontal streaks (1-5 mm) and trains of connected, symmetrical ripples (1-5 cm). Millimetre-scale lamination is generally visible, slightly to strongly disrupted by burrows, which include *Arenicolites*. Scarce bivalves were observed in the present study, and echinoid fragments were found at Río San Miguel near Menė Grande.

Interpreting these characteristics, Facies 1 was deposited in a permanent water body (lake or sea), as shown by the lack of desiccation cracks or other indicators of emergence. Salinity indicators are absent, except in those intervals with echinoids, which indicate fully marine conditions. Ripple symmetry indicates the influence of waves, implying that the ripple strings represent storm beds. Combining these inferences, the most likely depositional environment for Facies 1 is the distal part of a storm-influenced marine shelf, below fair-weather wave base and above storm wave base.

Facies 2

The main difference from Facies 1 is a higher proportion (20-70%) of sandstone streaks and ripples. Some sandstone intercalations are thicker (5-10 cm) and can be capped by symmetrical ripples of longer (dm) wavelength (e.g. Lagazzi *et al.*, 1993, Fig. 24). The interpreted environment is the same as for Facies 1, but more proximal.

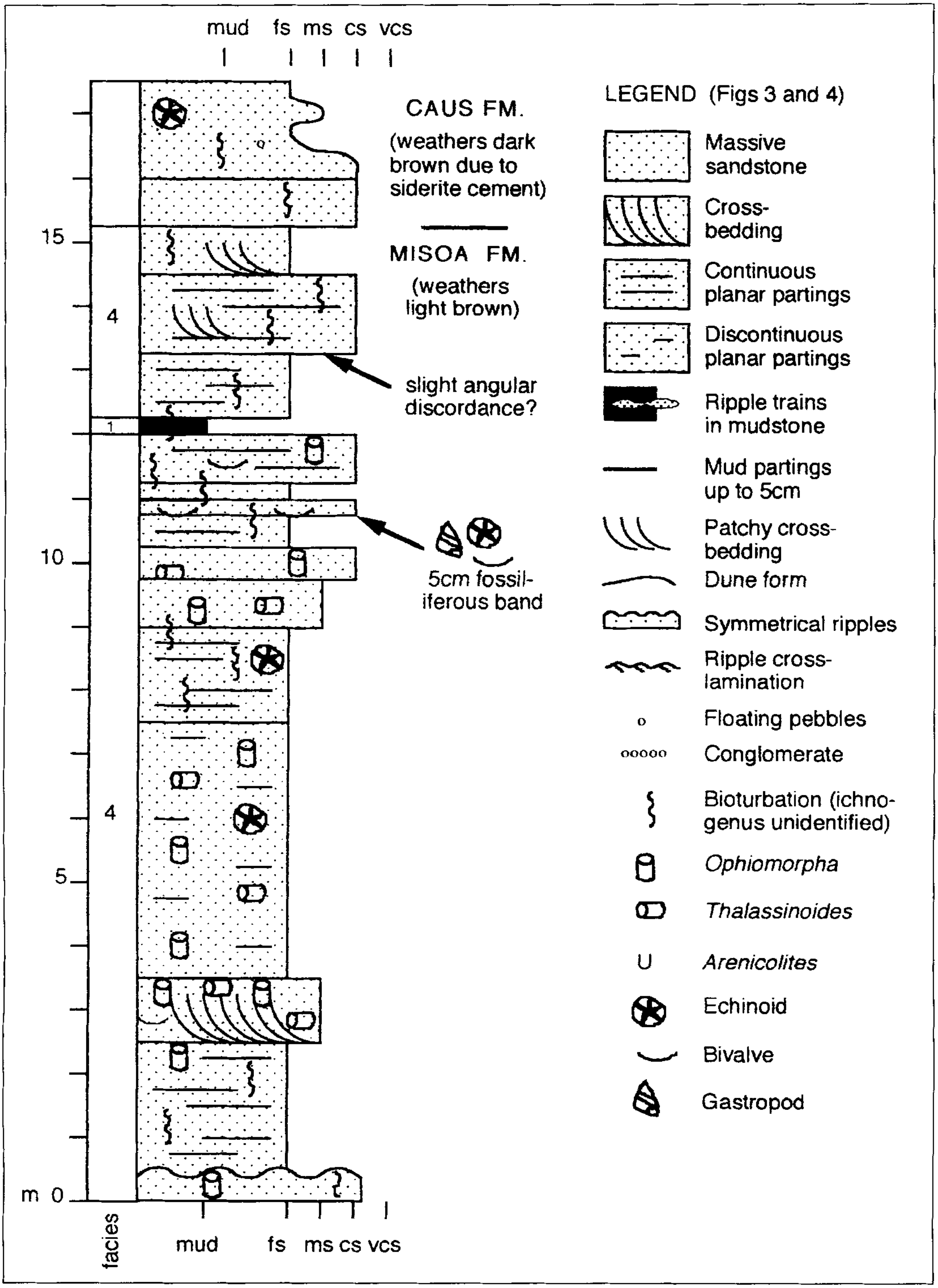


Fig. 3. Sedimentological log of the Misoa Formation and part of the overlying Caús Formation. The section is a roadcut on the Valera-Isnotú road, 5 km east of Isnotú (Locality 1 in Fig. 1).

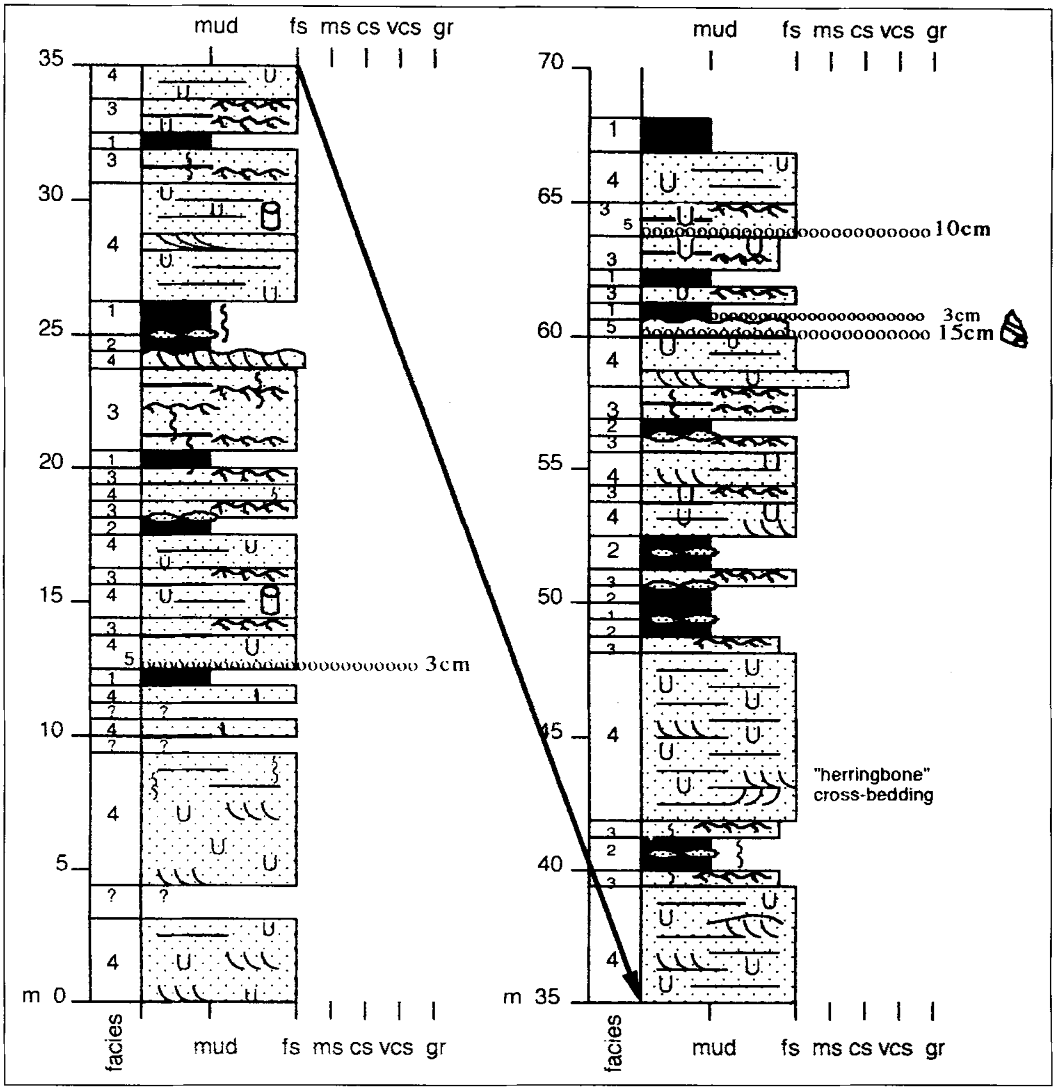


Fig. 4. Sedimentological log of the Misoa Formation. The section is a roadcut 5 km north of the Agua Viva checkpoint (*"alcabala"*) of the Guardia Nacional, on the road to Carora (Locality 2 in Fig. 1). For legend, see Fig. 3.

Facies 3

The proportion of ripple-strings is even higher (70-100%), such that amalgamation of ripple strings is common, forming decimetre- and metre-scale sandy units with thin (<5 cm) mudstone partings. The interpreted environment is the same as for Facies 1 and 2, only yet more proximal.

Facies 4

Facies 4 consists of tabular (non-channelled) sandstone bodies mostly 3- to 10-m thick, which are the most distinctive feature of the Misoa Formation at outcrop (Fig. 5a). The sand is generally very-fine or fine grained. Internally, the sand bodies consist of subtabular, asymptotic cross-sets, 5- to 70-cm thick. Set boundaries are expressed as parting surfaces and, like the cross-stratification, are partly to completely erased by bioturbation. Cross-lamina azimuths are difficult to determine because of bioturbation and the two-dimensional nature of the exposures, but appear relatively constant within any sand body; in one case, however, two successive cross-sets show apparently opposed cross-laminae, forming "herringbone" cross-bedding (Fig. 4 at 43 m; Fig. 5b). Thin (<5 cm), discontinuous mudstone layers separate some sets, generally overlying symmetrical ripples (of short or long wavelength) developed at the top of the underlying cross-set. Trace fossils include *Arenicolites, Ophiomorpha* and *Thalassinoides*, defining a "*Skolithos* ichnofacies" (Pemberton *et al.*, 1992). Long, vertical tubes previously identified as *Skolithos* (Van Veen, 1972; Lagazzi *et al.*, 1993) are in some cases linked at the base, forming a "U" (i.e. *Arenicolites*); thus, *Skolithos* awaits confirmation. Fossils include bivalves and gastropods (Fig. 3 at 11 m; Fig. 4 at 60 m). Moulds of whole echinoids are common in the Valera section (Fig. 3).

Turning to interpretation, the *Skolithos* ichnofauna suggests normal marine salinities (Pemberton *et al.*, 1992), while intervals with echinoids are definitely marine. Facies 4 sand bodies are inferred to have accumulated episodically, as successive "event-beds", as indicated by the rippled bed tops and mudstone partings, which suggest breaks in deposition. A complete event-bed is visualized as comprising one or more cross-sets, capped by symmetrical ripples; the ripples were susceptible to erosion during the next "event". The ripple symmetry implies that the "events" were storms. The presence of high-angle cross-bedding, instead of hummocky cross-bedding typical of storm beds (Dott and Bourgeois, 1982), suggests that the storm currents were supplemented by tidal currents (Johnson and Baldwin, 1986). Comparable tide-storm interactive systems have been inferred in the literature for numerous formations worldwide (summary in Johnson and Baldwin, 1986).

Facies 5

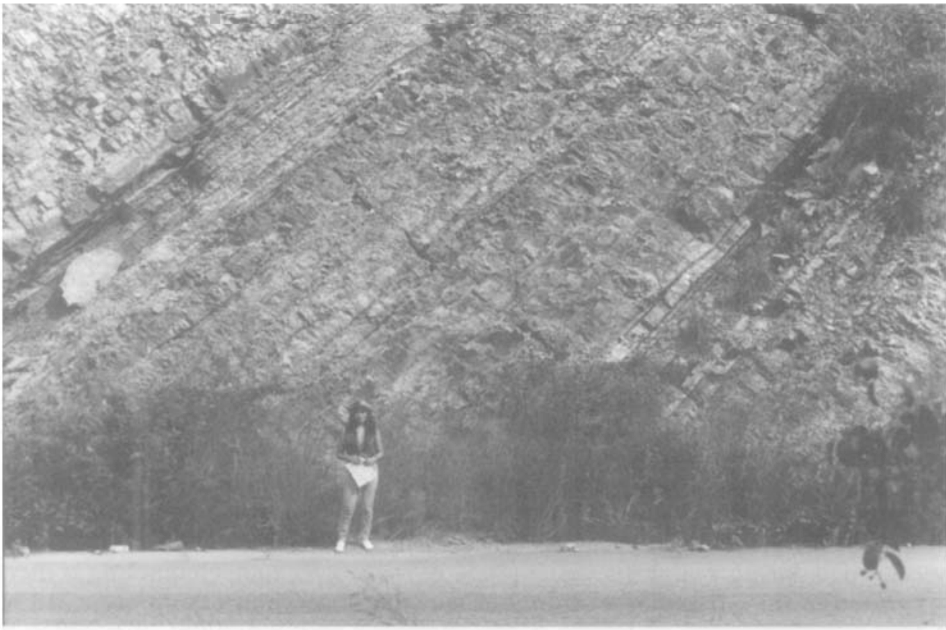
This facies consists of thin beds of pebble conglomerate. Four beds ranging from 3- to 15-cm thick occur in the Agua Viva section (Fig. 4). The beds can occur at any position within a sand body (at the top, base or internally), or may be encased in mudstone (Fig. 4 at 61 m). Pebbles are of two varieties: (1) chert, ranging from hard and black to powdery and white; and (2) quartzite.

Facies successions

The five facies alternate vertically in an apparently random manner (Figs. 3 and 4). As a result, sand bodies can appear to have sharp or gradational bases, and sharp or gradational tops (Fig. 6). Outcrop examples with gradational bases and sharp tops, forming coarsening-up successions, have been reported previously (Van Veen, 1972; Lagazzi *et al.*, 1993), but are only one of four possible configurations ("Type 1" in Fig. 6).

INTERPRETED DEPOSITIONAL ENVIRONMENT

Considering the facies together, the lack of evidence for emergence suggests that the Misoa Formation was deposited in a permanent water body (sea or lake). A sea is the more likely: the rare intervals with echinoids are definitely marine, while the *Skolithos* ichnofacies characterizing much of the formation is probably marine. Deposition below fair-weather wave base can be inferred from: (1) the presence of mudstone beds, requiring periods of negligible bottom-currents; and (2) the tabular-cross-bedded nature of the sandstones, which contrasts with the parallel-, low-angle-, or trough cross-stratification characteristic



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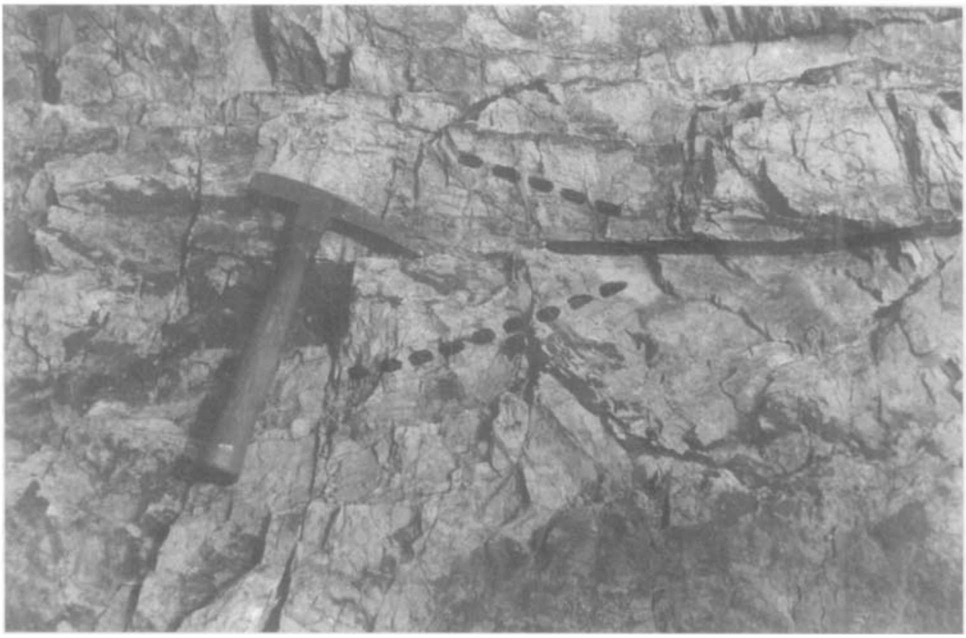

5b

Fig. 5a. Typical Misoa Formation sandstone body (Facies 4) at the Agua Viva section (Fig. 4, 32.5-40.0 m). Right way up. Internal parting surfaces are sub-parallel, indicating that the constituent beds are essentially tabular, although degraded dune forms are locally visible (e.g. about 1 cm "NW" of person's head). (b) Herringbone cross-bedding at the Agua Viva section (Fig. 4 at 43 m). The horizontal parting surface, highlighted by the solid black line, separates cross-sets with oppositely dipping cross-laminae (parallel to the dashed lines). The cross-stratification is partially erased by vertical cylindrical burrows, which are difficult to see in this photograph (*see text*).

of the foreshore and shoreface. On the other hand, deposition above storm wave base is indicated by the pervasive symmetrical ripples. Sand bodies of Facies 4 are interpreted as amalgamated event-beds produced by tide-enhanced storms. The same storms may have produced the ripple strings of Facies 3, 2 and 1, which are interpreted as increasingly distal equivalents. Thus, the various Misoa Formation facies are interpreted to represent successive positions along tidal-shelf sand sheets influenced by storms (Fig. 7), similar to Anderton's (1976) model for the PreCambrian Jura Quartzite in the Dalradian Supergroup of Scotland. This model is based on modern tidal-current transport paths on the present-day NW European Shelf, which produce sand sheets showing "downdrift" fining and zonation of bedforms (Belderson *et al.*, 1982; Stride *et al.*, 1982). During periods when the tidal currents are aided by other currents, such as storms, the bedform zones migrate downdrift, temporarily occupying more-distal positions (Stride *et al.*, 1982).

In the tidal-shelf model, Facies 4 event-beds correspond to the "climbing dunes" zone of Anderton (1976), representing a storm-provoked excursion of dunes into an otherwise mud-depositing region (Fig. 7). Individual event-beds should therefore contain multiple (climbing) cross-sets, but these have not yet been confirmed in the field, probably due to masking by bioturbation. At the end of each event, the dunes were subdued by waves, leaving a more or less tabular bed with a wave-rippled upper surface. According to Anderton (1976), climbing dunes can be deposited either on the flat sea floor, or in channels eroded during a slightly earlier phase of the storm; such channeling is therefore to be expected in the Misoa Formation, but was not observed in the present study.

The thin conglomerates of Facies 5 are attributed to winnowing of pebbles in the (upcurrent) fair-weather dune-belt during severe storms (Fig. 7), providing pebbles for transport and deposition downcurrent.

The dominance of unidirectional palaeocurrents in any one sand body is consistent with other ancient analogues (Anderton, 1976; Levell, 1980), and with the unidirectionality of net sand transport in modern analogues (Belderson *et al.*, 1982). The occurrence of herringbone cross-bedding confirms the influence of tides, and could indicate intertonguing of two sand sheets derived from opposite directions, at a "bedload convergence" (Johnson *et al.*, 1982).

The variability among vertical facies successions suggests that the migration history of the sand sheets was variable. For example, sand sheets with gradational bases (Types 1 and 4 in Fig. 6) are interpreted to reflect gradual progradation of the sand body, due either to a relative sea-level fall, or an increase in sediment supply controlled by climate, tectonics or an autocyclic mechanism such as delta switching. In contrast, a *sharp* base suggests either: (1) that the sand body was established abruptly, perhaps by a change in tidal circulation caused by a storm-induced change in geography; or (2) that the advance of the sand body was a response to forced regression (*cf* Plint, 1991). The tops of sand sheets can likewise be gradational or sharp, both of which reflect abandonment, either due to geographic reorganization or due to drowning by a rise in relative sea level. Anderton (1976) also reported apparently random interbedding of facies in the Jura Quartzite; as possible causes, he suggested changes in water depth and variations in tidal regime due to minor changes in geography. Similarly, Hein (1987) reported poor definition of sequences in tidal-shelf deposits of the Lower Cambrian Gog Group.

COMPARISONS WITH THE SUBSURFACE

Published descriptions of Misoa Formation cores from Lake Maracaibo and adjacent coastal areas reveal the following similarities to the outcrops:

1. The overall facies association consists of metre-scale alternations of sandstones and mudstones containing sand ripples (Van Veen, 1972; Maguregui and Tyler, 1991; Lagazzi *et al.*, 1993; Ambrose *et al.*, 1995).

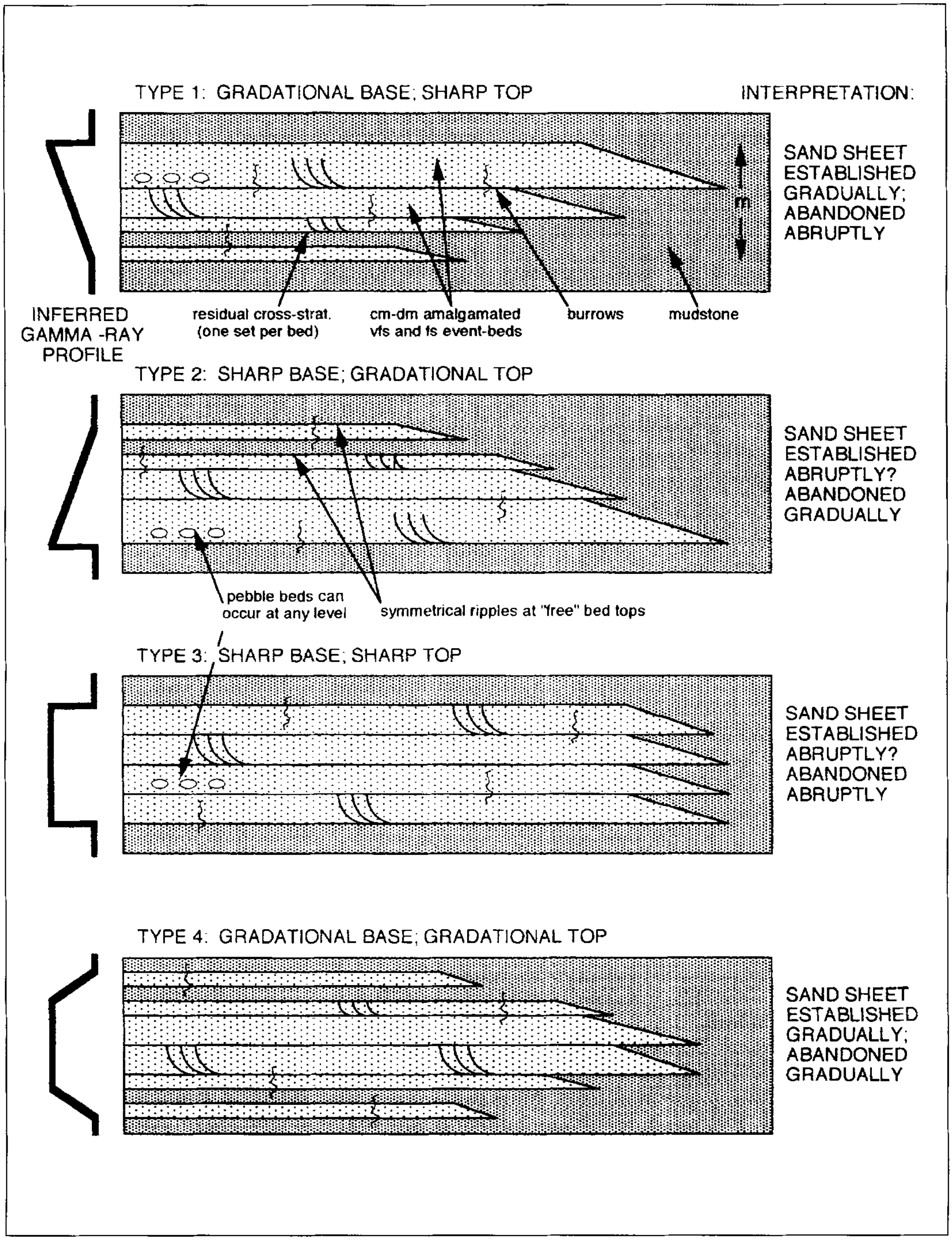

Fig. 6. Variability of Misoa Formation vertical successions at outcrop, interpreted in terms of migration behaviour of tide-influenced shelf sand sheets. No horizontal scale implied. Bed-thickness successions are grossly simplified. Lateral terminations are inferred (not observed). Differential compaction neglected. The diagrams represent proximal-distal or axial-lateral sections.

2. Coal beds and other evidence for emergence are absent. The only published reference to coal beds in the Misoa Formation is Zambrano *et al.* (1971, p. 509), who state that coal appears towards the western shore of Lake Maracaibo; however, in their fence diagram (Lámina II), these coal beds are indicated as belonging to the Mirador Formation.
3. Sandstones are mostly very-fine and fine grained, dominated by decimetre-scale cross-bedding, and containing *Ophiomorpha*, bivalves, gastropods and echinoids (Van Veen, 1972; Maguregui and Tyler, 1991; Ambrose *et al.*, 1995).
4. Sand bodies can have sharp or gradational bases and tops, resulting in variable vertical sequences (coarsening-up, fining-up, or neutral; Van Veen, 1972; Maguregui and Tyler, 1991; Ambrose *et al.*, 1995).

Notwithstanding these similarities, three differences are discernible in the nature of the sand bodies in the subsurface: (a) they can be thicker, commonly 5- to 20-m thick (Van Veen, 1972, Fig. 9), compared to 3- to 10-m at outcrop; (b) they are less bioturbated, resulting in greater preservation of cross-stratification; and (c) they commonly contain mud drapes within the cross-sets ("laminillas de arcilla" of Van Veen, 1972, p. 1087). These differences can be interpreted as reflecting a more proximal position along the tidal sand-transport path, within the fair-weather dune belt (Figs. 7 and 8). This would not only explain the greater thickness, but also the reduced bioturbation, reflecting near-constant motion of the sand substrate (fair-weather dune migration), unfavourable for colonization by animals. The model also explains the mud drapes, which are *"a distinctive, if not entirely diagnostic, feature of tidal deposits"* (Johnson and Baldwin, 1986, p. 260), and are deposited during slack-water pauses in (fair-weather) dune migration. Mud drapes are not to be expected at outcrop, in sand bodies of the climbing-dune belt (Facies 4), because dune migration only occurs there during storms, which lack slack-water interludes.

In addition to sheets, there is evidence for isolated sand ridges, which are the other main type of sand deposit of modern tidal shelves ("sand banks" of Belderson *et al.*, 1982, and Stride *et al.*, 1982). Modern examples are tens of kilometres long, 1- to 3-km wide, 1- to 10-km apart, and 10- to 50-m high (Belderson *et al.*, 1982, Table 3.3; Stride *et al.*, 1982, Fig. 5.16). The presence of sand ridges in the Misoa Formation is suggested by linear "thicks" spaced 1- to 2-km apart on published net-sand isopach maps derived from well logs in the *Lagunillas* field (Fig. 1; Maguregui and Tyler, 1991, Figs 8, 9 and 10; Ambrose *et al.*, 1995, Figs 9b, 21, 23 and 29). These "thicks" do not directly indicate sand-ridge dimensions, because each map represents the *cumulative* thickness of numerous sand bodies in a stratigraphic interval. However, closely-spaced well logs allow individual sand bodies to be correlated, indicating the presence of laterally disconnected, elongated sand bodies 0.5- to 2-km wide and 5- to 10-m thick (Maguregui and Tyler, 1991, Figs 12, 13 and 14; Ambrose *et al.*, 1995, Fig. 24). These sand bodies are interpreted here to be offshore sand ridges; by contrast, Maguregui and Tyler (1991) and Ambrose *et al.* (1995) interpreted them as deltaic distributary channels and delta-front tidal sand ridges. Their small thickness (5-10 m), compared to heights of 10-50 m for modern sand ridges, could reflect degradation by storm waves following abandonment ("moribund sand banks" of Stride *et al.*, 1982).

Distinction between sand *sheets* and sand *ridges* is difficult from cores alone, due to the similarity of the sedimentary structures. Both sheets and ridges are mantled by migrating sand dunes (the "sand waves" of Belderson *et al.*, 1982, and Stride *et al.*, 1982), so the internal sedimentary structure in both cases is cross-bedding, with or without mud drapes and bioturbation. Furthermore, vertical successions are similar: sand ridges can show either fining-up or coarsening-up trends (Dalrymple, 1992), and the same is probably also true of sand sheets. Thus, distinguishing between sand sheets and sand ridges in the Misoa Formation is difficult from cores; the same applies to grain-size profiles inferred from well-logs (*cf.* Zamora, 1977). The distinction therefore requires additional information on: (1) external geometry (sheet or shoestring), obtained from outcrops or detailed well-

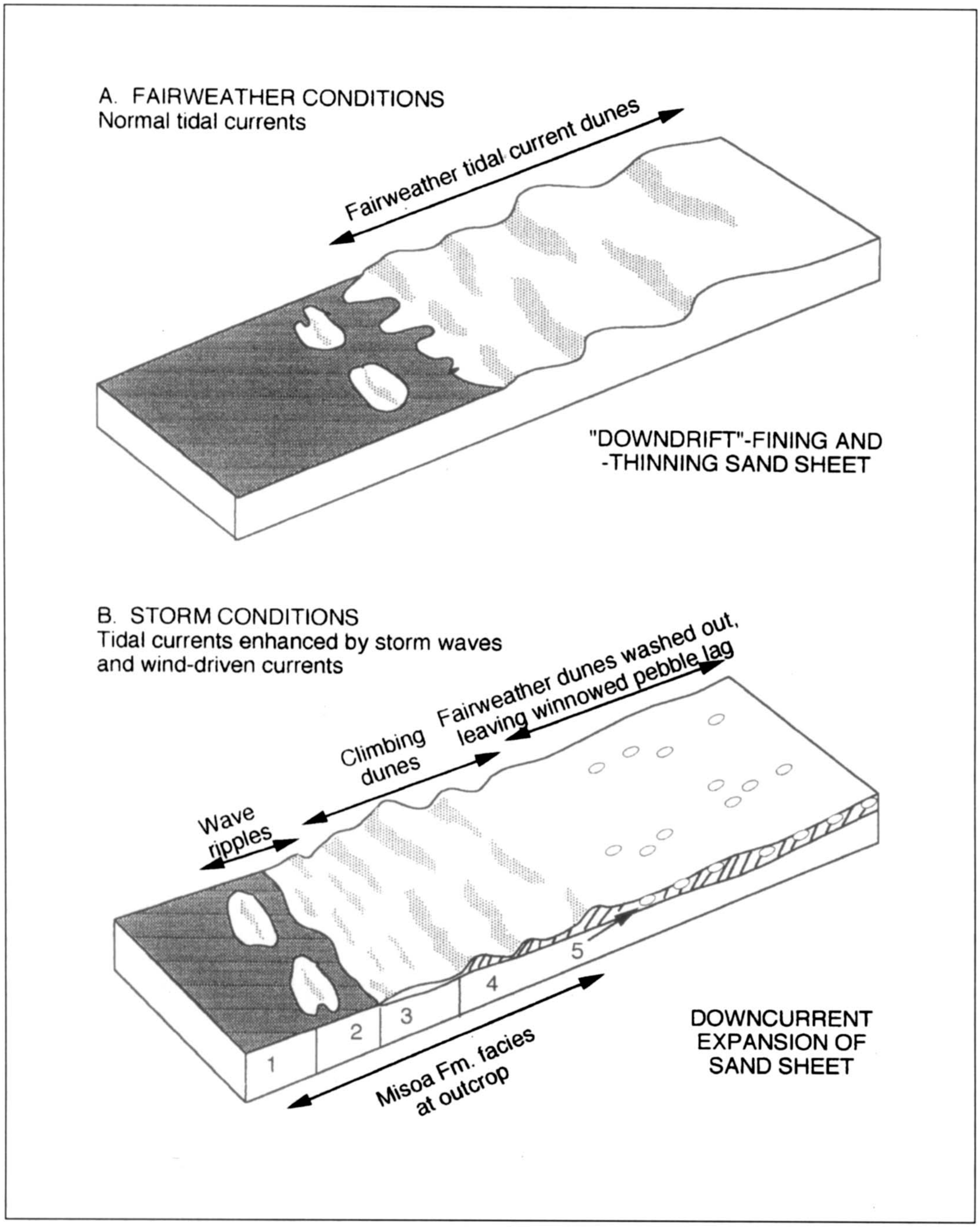

Fig. 7. Model of Misoa Formation tidal-shelf sand sheets. (A) Fair-weather conditions; peak tidal-current velocities decrease distally. (B) Storm conditions. After the storm, the fair-weather dunes are rebuilt and the climbing-dune belt reverts to fair-weather mud sedimentation. Due to the increasing relative influence of storms distally, cross-bedding is of fair-weather origin in the proximal sand sheet and storm-produced in the distal sheet (Fig. 8). Not to scale. Block is of the order of tens to hundreds of kilometres long. After Anderton (1976) and Johnson and Baldwin (1986).

log correlations; or (2) internal architecture, such as the arrangement of palaeocurrents and "master-bedding" surfaces, obtainable only in good surface exposures (Stride *et al.*, 1982).

The variability of vertical successions in the subsurface (coarsening-up, fining-up, or neutral) is interpreted to reflect advance or retreat of sand sheets and ridges, due to: (1) relative sea-level changes; or (2) variations in sediment supply controlled by tectonics, climate or an autocyclic mechanism.

The apparent absence of sand ridges at outcrop, as indicated by the exclusively sheet-like geometry of Facies 4, suggests that ridges were developed only in relatively proximal areas of the shelf, represented by present-day subsurface regions. This, in turn, could indicate that ridges formed preferentially during relative rises in sea level, causing the sediment to be confined relatively close to shore, whereas sand sheets possibly represent highstands and/or relative falls in sea level.

COMPARISON WITH PREVIOUS INTERPRETATIONS

Having demonstrated that a tidal-shelf model adequately describes much of the Misoa Formation, both in the subsurface and at outcrop, a summary of previous interpretations of the depositional environment is instructive.

Subsurface

As mentioned above, the Misoa Formation beneath Lake Maracaibo is conventionally regarded as deltaic, following Van Veen (1972), who visualized a delta comparable in size to the modern Mississippi, fed from the SW by a fluvial system preserved as the Mirador Formation. Previously, Zambrano *et al.* (1971) hinted at a more marine interpretation, described vaguely as "marino-parálico" (p. 506), with the Misoa Formation deposited in a "Platform Province", seaward of a "Deltaic Province" corresponding to the Mirador Formation (their Fig. 9). Additionally, these authors stated that a large part of the Misoa Formation in south-central Lake Maracaibo is marine (p. 509).

Modifying the traditional deltaic model somewhat, Maguregui and Tyler (1991) proposed that the Misoa "B-2" interval at the *Lagunillas* field was deposited on the outer part of a tide-dominated delta (intertidal lower delta plain and subtidal delta front). The same model was extended to the entire "C" interval of this field by Ambrose *et al.* (1995). However, the model is inadequate for two reasons: (1) the Misoa Formation here, as elsewhere, lacks desiccation cracks characteristic of the intertidal delta plain (e.g. Dalrymple, 1992, Fig. 29); and (2) it is inconceivable that marshes (hence, coal beds) of the upper delta plain did not prograde over the supposed lower delta plain and delta front during the deposition of such a thick interval (1,500 m Misoa "C" at *Lagunillas*; Ambrose *et al.*, 1995, Fig. 3).

Finally, two drawings by Parnaud *et al.* (1995, Figs. 16 and 17) imply shelf deposition for the entire Misoa Formation, but no accompanying explanation or references were given.

Outcrop

Brondijk (1967a, p. 10) interpreted the Misoa Formation of the type area as *"predominantly a shallow marine deposit, with mostly sheetlike sand and shale bodies and very little channeling or lensing. Such fauna as is present suggests shallow marine conditions with frequent brackish influences"*. In contrast, Van Veen (1972, p. 1079) proposed the following delta-oriented interpretation for the same area (author's translation): *"It is possible that the sandstones were deposited in front of or beside a delta, as a complex of islands in the form of littoral barriers.....or as a widespread delta-front sheet sand, or as fluvio-marine bar-finger sands"*. A deltaic setting was also inferred by

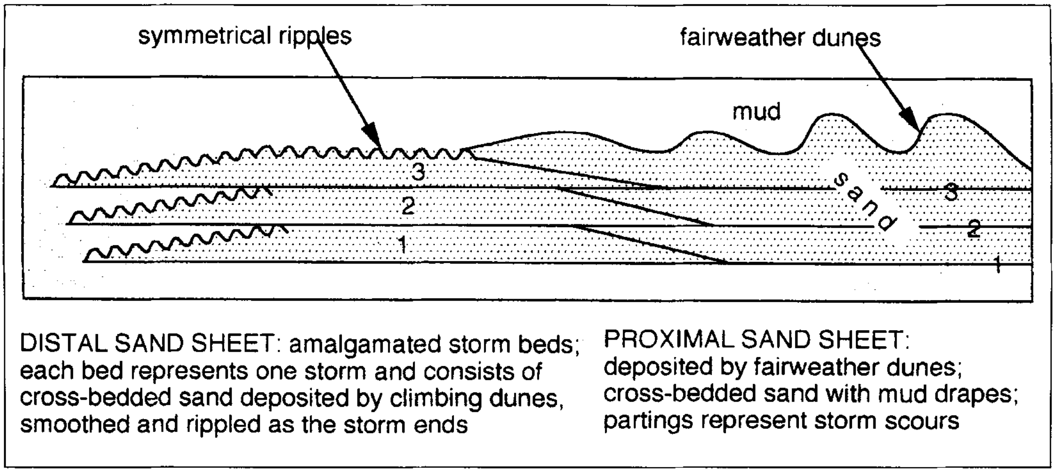

Fig. 8. Inferred cross-sectional geometry and internal architecture of Misoa Formation sand sheets. A parallel-sided distal sheet, characteristic of the present-day outcrops, is thought to pass into a dune-covered proximal sheet in the subsurface. Not to scale. Length is of the order of tens to hundreds of kilometres. Thickness is typically 3 to 10 m distally and 5 to 20 m proximally. For clarity, only three successive storm-produced erosion surfaces are shown in the proximal sheet, numbered 1 to 3, which can be flat or broadly channelled. Corresponding storm beds 1 to 3 were deposited in the distal sheet. Following each storm, fair-weather dunes were rebuilt in the proximal zone, while mud was deposited over the distal zone. The entire sheet was draped in mud following abandonment.

Lagazzi *et al.* (1993), who proposed the following range of environments for outcrops in the Serranía de Trujillo: floodplain, strandplain, tidal channel, distributary channel, distributary mouth bar, and prodelta marine.

DISCUSSION

Compatibility of Misoa Formation thickness with shelf model

The great thickness of the Misoa Formation (up to 3 km beneath Lake Maracaibo) is not unusual among shelf successions, suggesting that basins can maintain a steady state or equilibrium shelf profile for extended periods, with storm waves or tides sweeping excess sediment into deeper water, thus creating a long-term balance between sediment accumulation and subsidence (Seilacher, 1982; Covey, 1986). According to Covey (1986), foreland basins attain steady state only after the early deep-water "flysch trough" has been filled; excess sediment is then swept longitudinally out of the basin into the adjacent (remnant) ocean. However, this model is at odds with the evidence, discussed below, for a contemporaneous flysch trough north of the "Misoa Shelf". Other examples of thick tidal-shelf deposits are the Jura Quartzite (> 5 km; Anderton, 1976), the Lower Sandfjord Formation (1.5 km; Levell, 1980) and the Gog Group (> 500 m; Hein, 1987).

Incised valleys at the base of the Misoa Formation?

The unconformity at the base of the Misoa Formation overlies shelf deposits (Guasare Formation; Zambrano *et al.*, 1971), suggesting that it was formed by the subaerial exposure of a shelf (Type 1 sequence boundary of Van Wagoner *et al.*, 1988). Such unconformities are characterized by incised valleys filled with fluvial and estuarine deposits (Van Wagoner *et al.*, 1990). Incised valleys can thus be predicted to occur at the base of the Misoa Formation, offering a potential hydrocarbon "play". In the "interfluves" between incised valleys, the unconformity is likely to be overlain directly by shelf deposits, except for a possible thin (dm) transgressive lag (Van Wagoner *et al.*, 1990).

Incised valleys have also been postulated within the Misoa Formation, based on intervals with a "blocky" log character (Marais-Gilchrist and Higgs, 1993) and seismic anomalies (Pestman *et al.*, 1994). Alternatively, some of these anomalies could represent isolated tidal sand ridges, encased in shale, offering an equally interesting exploration target.

Palaeogeography

Conventional palaeogeographic maps show the Misoa Formation merging SW-wards into the fluvial Mirador Formation, the transition supposedly taking place beneath SW Lake Maracaibo (e.g. Zambrano *et al.*, 1971, Fig. 9; González de Juana *et al.*, 1980, Figs VI-6 and VI-8). However, this configuration is contradicted by seismic profiles, which show SW-ward onlapping at the base of the Misoa Formation (Perdomo and Bot, 1986; Marais-Gilchrist and Higgs, 1993), demonstrating that a non-depositional high separated the "Misoa Basin" from a separate "Mirador Basin". This high was invoked as early as 1948 by Schaub (p. 223), as a *"threshold, separating..... two provinces"*, to explain the contrasting stratigraphy on either side. According to Brondijk (1967b, p. 39), the high *"separated sedimentation completely along its southeastern part (the Avispa Massif) and partly at its (plunging?) northwestern end (the Palmar Uplift)"*. The high was shown on cross-sections and a map by Van Veen (1972, Figs 1, 8 and 15), but he expressed uncertainty as to whether it was syn- or post-depositional.

Thus, Lower and Middle Eocene palaeogeographic maps need to be modified to include a non-depositional Palmar-Avispa High (*cf.* Mathieu, 1989). Instead of the Mirador Formation merging with the Misoa Formation across present-day Lake Maracaibo, as on conventional maps, the two formations possibly merged around the NW end of the high (Fig. 9). Here, braided streams (Mirador Formation) are inferred to have met a tidal sea (Misoa Formation), defining a braidplain delta (Orton, 1988). Under Lake Maracaibo, the shelf deposits of the Misoa Formation are inferred to pass SW-ward into a narrow fringe of coastal-plain deposits diachronously onlapping the Palmar-Avispa High (Fig. 9).

The Palmar-Avispa High could arguably be regarded as a reactivation and prolongation of the Mérida Arch, a Mesozoic basement high which crosses the present-day Mérida Andes, and which was progressively onlapped by Lower Cretacous deposits (Zambrano *et al.*, 1971; Lugo, 1994). The Mérida Arch was indeed reactivated in the Early Eocene according to Zambrano *et al.* (1971), but as a high whose influence did not reach as far NW as Lake Maracaibo (contrast their Fig. 9 with Fig. 9 of this paper).

The sediment-transport direction on the "Misoa Shelf" is poorly constrained, due to the difficulty of measuring palaeocurrents in the field, as already mentioned, and in cores. This problem is partly resolved by considering the regional distribution of proximal (core descriptions) and distal (outcrop) control points. However, the few core descriptions are clustered and remote from the outcrops (Fig. 1), so the sediment-transport direction can only be loosely constrained, to between NE-ward (i.e. offshore, Fig. 9) and SE-ward (alongshore). A further complication is that the transport direction could have varied temporally; for example, sand sheets may be characterized by alongshore transport, and ridges by offshore transport.

The orientation of the net-sand "thicks", interpreted as tidal sand ridges, provides a possible clue to the transport direction, because modern North Sea ridges are typically orientated obliquely, with their long axes angled at 7 to 15° to the transport direction (Kenyon *et al.*, 1981). The "thicks" are oriented NE-SW in the Misoa "C" interval (Ambrose *et al.*, 1995) and ENE-WSW in the "B-2" interval (Maguregui and Tyler, 1991). These orientations, taking obliquity into account, suggest that sediment transport in the ridge systems was offshore rather than alongshore (Fig. 9).

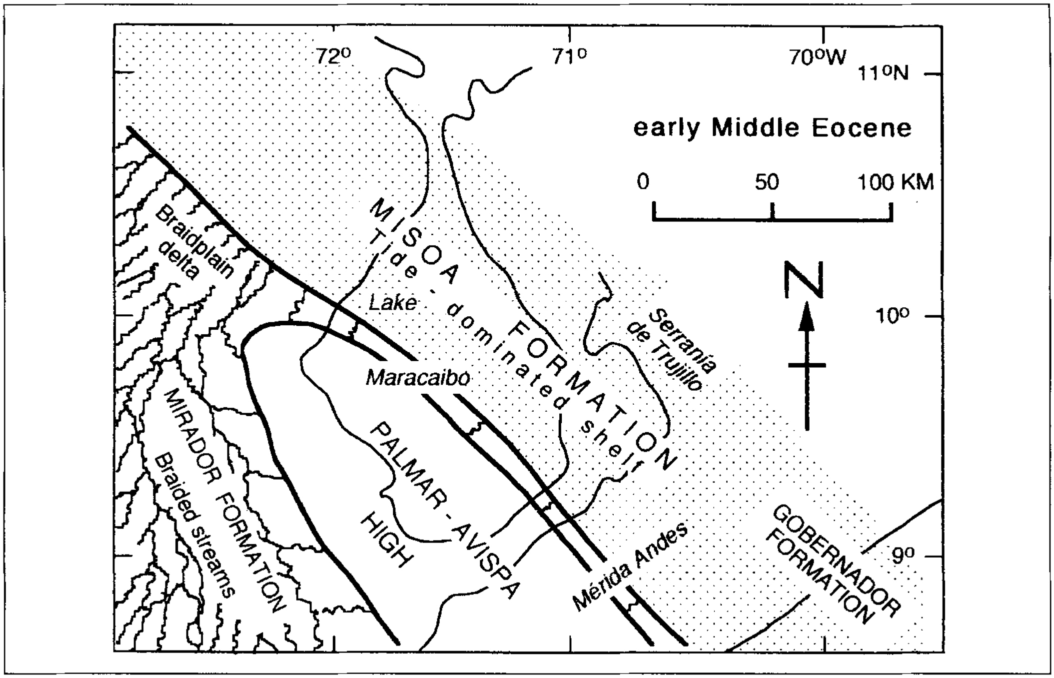

Fig. 9. Proposed palaeogeography of the Maracaibo Basin during early Middle Eocene time. Italics indicate modern geographic features, shown for reference. Palmar-Avispa High concept after Brondijk (1967b).

The seaway of which the "Misoa Shelf" formed one flank (Fig. 9) was probably either partially enclosed or "blind", based on the evidence for strong tidal currents (Johnson and Baldwin, 1986). A "blind" gulf, opening eastward, could have been created by oblique collision between the (NE-trending) Caribbean volcanic arc and northern South America in Palaeocene-Eocene time (Pindell and Barrett, 1990; Pindell, 1993, Fig. 6K). In this gulf, a deep-water trough may have lain north of the "Misoa Shelf", in front of the advancing arc-accretionary complex. Probable remnants of the trough-fill include turbidites and olistostromes of the Lara Complex (Matatere Formation), partially coeval with the Misoa Formation, which were thrust southward onto the Misoa Formation at the end of the Middle Eocene (Stephan, 1985).

Sand-body geometry and reservoir implications

Misoa Formation sand bodies are inferred to be of two main types, analagous to those of the modern NW European Shelf: namely sand *sheets* and sand *ridges*. At outcrop, a sheet geometry is indicated by the flat bases and tops of sand bodies (Facies 4; Brondijk, 1967a), which are interpreted as the distal, storm-deposited fringes of sand sheets. These sheets are interpreted to extend (proximally) into the subsurface, where they thicken and pass into the fair-weather-dune zone; here, the sheets possibly have undulating upper surfaces, if dune topography was preserved following sand-sheet abandonment (Fig. 8). Such dunes could have wavelengths and amplitudes in the order of 150-500 m and 3-15 m, respectively, based on modern examples (the "sand waves" of Belderson *et al.*, 1982, Stride *et al.*, 1982, and Johnson and Baldwin, 1986). The dunes could be asymmetrical or nearly symmetrical (Belderson *et al.*, 1982, Fig. 3.5), depending on the degree of asymmetry of the tidal cycle (Allen, 1980).

In terms of areal extent, the Misoa Formation sand sheets are envisaged to vary from tens to hundreds of kilometres wide and long, similar to modern counterparts on the NW European Shelf, which commonly reach 20,000 sq.km in area (Stride *et al.*, 1982), large enough to span the entire study area (Fig. 1). In contrast, sand ridges are predicted to be much smaller: perhaps tens of kilometres long by 1- to 3-km wide. Despite their smaller size, sand ridges are attractive exploration targets, because they are laterally separated and therefore likely to be sealed within shales, forming stratigraphic traps.

Reservoir compartmentalisation is considered to be characteristic of Misoa Formation oilfields, and has been attributed to a combination of faulting and shoestring sand geometry (Ambrose *et al.*, 1995). However, in addition to shoestring sands, many sand bodies in the Misoa Formation are inferred here to have a sheet geometry, possibly pinching and swelling laterally due to dune topography. Consequently, the interconnectedness of reservoirs may be greater than is commonly believed.

Limited fauna of the Misoa Formation

The overall paucity of fossils in the Misoa Formation could be interpreted as indicating less-than-marine salinities. However, although fossil abundance is indeed limited, the *diversity* (number of taxa) is substantial, including foraminifera (mainly benthonics: Brondijk, 1967a; Van Veen, 1972), bivalves, gastropods and echinoids. In addition, the sporadic limestones in the lower part of the Misoa Formation contain red algae, bivalves, gastropods and large calcareous foraminifera (Brondijk, 1967a). This diversity, coupled with the *Skolithos* ichnofacies, suggests that the bottom-water salinity was normal, in which case alternative explanations are needed for the low faunal abundance and for the near-absence of planktonic foraminifera (Brondijk, 1967a; Fuenmayor, cited in Bolli *et al.*, 1994).

One cause of reduced fossil abundance is diagenetic leaching of carbonate shells, as indicated by the fact that all the molluscs and echinoids found in this study occur as moulds. Absence of fossils in subtidal sandstones was also attributed to leaching by Johnson and Levell (1995). Additional evidence for carbonate dissolution is seen in thin sections (Ghosh *et al.*, 1985).

Certain benthonic organisms could have been suppressed by high suspended-sediment concentrations, supplied to the Misoa Formation shelf by the delta mentioned above. The same delta is likely to have produced a freshwater surface plume, fed by prolific (tropical) river inflow, which could contribute to the scarcity of planktonic foraminifera.

CONCLUSIONS

Outcrop studies, complemented by a survey of published descriptions of confidential cores, indicate that the majority of the Misoa Formation can be interpreted to have been deposited on a marine shelf, along storm-enhanced, tidal-shelf sand sheets and in tidal sand ridges, in contrast to the traditional deltaic model. The new depositional model is vital for the reliable prediction of reservoir geometry and, thus, for the better placement of exploration and development wells, leading to more economical recovery of hydrocarbons. Whereas previous models of the Misoa Formation invoke mainly shoestring sand bodies, interpreted most recently as distributary channels and delta-front tidal sand ridges (Ambrose *et al.*, 1995), sand bodies are predicted here to have two main geometries: (1) sheets up to about 20-m thick, extending tens to hundreds of kilometres laterally, and possibly pinching and swelling laterally due to dune topography; and (2) isolated ridges tens of kilometres long, up to 3-km wide, and perhaps as much as 50-m thick, by analogy with modern examples. Thicker reservoir bodies can, of course, be formed by amalgamation of sheets and/or ridges.

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REFERENCES

ALLEN, J.R.L., 1980. Sand waves: a model of origin and internal structure. *Sediment. Geol.*, **26**, 281-328.

AMBROSE, W.A., FERRER, E.R., DUTTON, S.P., WANG, F.P., PADRON, A., CARRASQUEL, W., YEH, J.S. and TYLER, N., 1995. Production optimization of tide-dominated deltaic reservoirs of the lower Misoa Formation (Lower Eocene), LL-652 Area, *Lagunillas* Field, Lake Maracaibo, Venezuela. University of Texas at Austin, Bureau of Economic Geology, *Report of Investigations,* **226**, 46 pp.

ANDERTON, R., 1976. Tidal shelf sedimentation: an example from the Scottish Dalradian. *Sedimentology*, **23**, 429-458.

BELDERSON, R.H., JOHNSON, M.A. and KENYON, N.H., 1982. Bedforms. In: Stride, A.H. (Ed.). Offshore Tidal Sands. Chapman and Hall, London, 27-57.

BOLLI, H.M., BECKMANN, J.P. and SAUNDERS, J.B., 1994. Benthic Foraminiferal Biostratigraphy of the South Caribbean Region. Cambridge University Press.

BRONDIJK, J.F., 1967a. The Misoa and Trujillo Formations. *Asociación Venezolana de Geología, Minería y Petróleo, Boletín Informativo,* **10**(1), 3-19.

BRONDIJK, J.F., 1967b. "Eocene" formations in the southwestern part of the Maracaibo Basin. *Asociación Venezolana de Geología, Minería y Petróleo, Boletín Informativo,* **10**(2), 35-50.

COVEY, M., 1986. The evolution of foreland basins to steady state: evidence from the western Taiwan foreland basin. In: Allen, P.A. and Homewood, P. (Eds.). Foreland Basins. *Int. Ass. Sediment., Spec. Publ.,* **8**, 77-90.

DALRYMPLE, R.W., 1992. Tidal depositional systems. In: Walker, R.G. and James, N.P. (Eds.). Facies Models: Response to Sea Level Change. Geological Association of Canada, St. John's, 195-218.

DOTT, R.H., Jr. and BOURGEOIS, J., 1982. Hummocky stratification: significance of its variable bedding sequences. *Geol. Soc. America Bull.,* **93**, 663-680.

ELLIOTT, T., 1986. Deltas. In: Reading, H.G. (Ed.). Sedimentary Environments and Facies, 2nd edn. Blackwell Scientific Publications, Oxford, 113-154.

GHOSH, S.K., MAGUREGUI, J., GARCIA, L.E. and AGUADO, B., 1985. Diagénesis y calidad de las areniscas de la Formación Misoa (Eoceno Inferior) al norte de la Cuenca de Maracaibo. *Sociedad Venezolana de Geólogos, VI Congreso Geológico Venezolano, Memoria,* **II**, 749-774.

GONZALEZ DE JUANA, C., ITURRALDE DE AROZENA, J.M. and PICARD, X., 1980. Geología de Venezuela y de sus Cuencas Petrolíferas. Ediciones Foninves, Caracas. 1031 pp.

HEIN, F.J., 1987. Tidal/littoral offshore shelf deposits - lower Cambrian Gog Group, southern Rocky Mountains, Canada. *Sediment. Geol.,* **52**, 155-182.

HIGGS, R., 1995. Depositional environment and sequence stratigraphy of the Misoa Formation, Eocene, Maracaibo Basin. IX Congreso Latinoamericano de Geología, Caracas, Venezuela, 5-8 November, Volumen de Resumenes (*abstract*).

JAMES, K.H., 1990. The Venezuelan hydrocarbon habitat. In: Brooks, J. (Ed.). Classic Petroleum Provinces. *Geol. Soc. London, Spec. Publ.*, **50**, 9-35.

JOHNSON, H.D. and BALDWIN, C.T., 1986. Shallow siliciclastic seas. In: Reading, H.G. (Ed.). Sedimentary Environments and Facies, 2nd edn. Blackwell Scientific Publications, Oxford, 229-282.

JOHNSON, H.D. and LEVELL, B.K., 1995. Sedimentology of a transgressive, estuarine sand complex: the Lower Cretaceous Woburn Sands (Lower Greensand), southern England. In: Plint, A.G. (Ed.). Sedimentary Facies Analysis. *Spec. Publ. Int. Ass. Sediment.*, **22**, 17-46.

JOHNSON, M.A., KENYON, N.H., BELDERSON, R.H. and STRIDE, A.H., 1982. Sand transport. In: Stride, A.H. (Ed.). Offshore Tidal Sands. Chapman and Hall, London, 58-94.

KENYON, N.H., BELDERSON, R.H., STRIDE, A.H. and JOHNSON, M.A., 1981. Offshore tidal sand banks as indicators of net sand transport and as potential deposits. In: Nio, S.-D., Shüttenhelm, R.T.E. and Van Weering, Tj. C.E. (Eds). Holcene Marine Sedimentation in the North Sea Basin. *Spec. Publ. Int. Ass. Sediment.*, **5**, 257-268.

LAGAZZI, R., CHACARTEGUI, F. and SAMPSON, E., 1993. An integrated view of the Eocene Misoa Formation, Maracaibo Basin, Venezuela. AAPG - Sociedad Venezolana de Geólogos conference, Caracas, *Field Trip Guidebook*, **2**, 67 pp.

LEVELL, B.K., 1980. A late Precambrian tidal shelf deposit, the Lower Sandfjord Formation, Finnmark, North Norway. *Sedimentology*, **27**, 539-557.

LUGO, J., 1994. The Mérida Arch: tectonic control on deposition from late Mesozoic to early Cenozoic in western Venezuela. *Sociedad Venezolana de Geólogos, V Simposio Bolivariano de Exploración Petrolera en las Cuencas Subandinas, Memorias*, 291-310.

MAGUREGUI, J. and TYLER, N., 1991. Evolution of Middle Eocene tide-dominated deltaic sandstones, *Lagunillas* field, Maracaibo basin, western Venezuela. In: Miall, A.D. and Tyler, N. (Eds.). The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery. *SEPM, Concepts in Sedimentology and Paleontology*, **3**, 233-244.

MARAIS-GILCHRIST, G. and HIGGS, R., 1993. Sequence stratigraphy of the Misoa Formation (Eocene), Lake Maracaibo, Venezuela *(abstract)*. *AAPG Bull.*, **77**, 332.

MATHIEU, X., 1989. La Serranía de Trujillo-Ziruma aux confins du bassin de Maracaibo, de la Sierra du Falcon et de la Chaine Caribe (Venezuela). Unpublished Ph.D. thesis, Université de Bretagne Occidentale, France.

MULLER, J., DE DI GIACOMO, E. and VAN ERVE, A.W., 1987. A palynological zonation for the Cretaceous, Tertiary, and Quaternary of northern South America. *American Association of Stratigraphic Palynologists, Contributions Series*, **19**, 7-76.

ORTON, G.J., 1988. A spectrum of Middle Ordovician fan deltas and braidplain deltas, North Wales: a consequence of varying fluvial clastic input. In: Nemec, W. and Steel, R.J. (Eds.). Fan Deltas: Sedimentology and Tectonic Settings. Blackie, Glasgow, 23-49.

PARNAUD, F., GOU, Y., PASCUAL, J.-C., CAPELLO, M.A., TRUSKOWSKI, I. and PASSALACQUA, H., 1995. Stratigraphic synthesis of western Venezuela. In: Tankard, A.J., Suarez, R. and Welsink, H.J. (Eds.). Petroleum Basins of South America. *AAPG Mem.*, **62**, 681-698.

PEMBERTON, S.G., MACEACHERN, J.A. and FREY, R.W., 1992. Trace fossil facies models: environmental and allostratigraphic significance. In: Walker, R.G. and James, N.P. (Eds.). Facies Models: Response to Sea Level Change. Geological Association of Canada, St. John's, 47-72.

PERDOMO, J.L. and BOT, P., 1986. Estratigrafía sísmica en el Eoceno de la Cuenca de Maracaibo. *Sociedad Venezolana de Ingenieros Geofísicos, III Congreso Venezolano de Geofísica, Memoria*, 473-483

PESTMAN, P.J., BARTOK, P., GHOSH, S.K. and MELENDEZ, L., 1994. Influencia tectónica y de fluctuaciones del mar en sistemas fluviales, con ejemplos del Eoceno en la Cuenca de Maracaibo, Venezuela. *Sociedad Venezolana de Geólogos, V Simposio Bolivariano de Exploración Petrolera en las Cuencas Subandinas, Memoria*, 65-84.

PINDELL, J.L., 1993. Regional synopsis of Gulf of Mexico and Caribbean evolution. Gulf Coast Section SEPM Foundation, *Proc.* 13th Annual Res. Conf., 251-274.

__________ and BARRETT, S.F., 1990. Geological evolution of the Caribbean region; a plate-tectonic perspective. In: Dengo, G. and Case, J.E. (Eds.). The Caribbean Region. Geological Society of America, The Geology of North America, **H**, 405-432.

PLINT, A.G. 1991. High-frequency relative sea level oscillations in Upper Cretaceous shelf clastics of the Alberta foreland basin: possible evidence for a glacio-eustatic control? In: MacDonald, D.I.M. (Ed.). Sedimentation, Tectonics and Eustasy. *Spec. Publ. Int. Assoc. Sediment.*, **12**, 409-428.

PUCHE, E., CHACARTEGUI, F., AZPIRITXAGA, I., BRANDT, R., ALVAREZ, G., FERRER, F. and SUAREZ, O., 1989. Estudio multidisciplinario del yacimiento B-6, Formación Misoa del Eoceno, Ceuta SE, Lago de Maracaibo. *Sociedad Venezolana de Geólogos, VII Congreso Geológico, Venezolano, Memoria,* **IV**, 1717-1743.

SCHAUB, H.P., 1948. Outline of sedimentation in Maracaibo Basin, Venezuela. *AAPG Bull.*, **32**, 215-227.

SEILACHER, A., 1982. General remarks about event deposits. In: Einsele, A. and Seilacher, A. (Eds.). Cyclic and Event Stratification. Springer-Verlag, Berlin, 161-174.

STEPHAN, J.F., 1985. Andes et chaîne caraïbe sur la transversale de Barquisimeto (Venezuela) évolution géodynamique. In: Mascle, A. (Ed.). Géodynamique des Caraïbes, Symposium. Editions Technip, Paris, 505-529.

STRIDE, A.H., BELDERSON, R.H., KENYON, N.H. and JOHNSON, M.A., 1982. Offshore tidal deposits: sand sheet and sand bank facies. In: Stride, A.H. (Ed.). Offshore Tidal Sands. Chapman and Hall, London, 95-125.

TALUKDAR, S.C. and MARCANO, F., 1994. Petroleum systems of the Maracaibo Basin, Venezuela. In: Magoon, L.B. and Dow, W.G. (Eds.). The Petroleum System - from Source to Trap. *AAPG Mem.*, **60**, 463-481.

VAN ANDEL, T.H., 1958. Origin and classification of Cretaceous, Paleocene and Eocene sandstones of western Venezuela. *AAPG Bull.*, **42**, 734-763.

VAN VEEN, F.R., 1972. Ambientes sedimentarios de las formaciones Mirador y Misoa del Eoceno inferior y medio en la Cuenca del Lago de Maracaibo. *Venezuela Ministerio de Minas e Hidrocarburos, IV Congreso Geológico Venezolano, Caracas, 1969, Memoria, Boletín de Geología, Publicación Especial,* **5**(II), 1073-1104.

VAN WAGONER, J.C., POSAMENTIER, H.W., MITCHUM, R.M., VAIL, P.R., SARG, J.F., LOUTIT, T.S. and HARDENBOL, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K. *et al.* (Eds.). Sea-level changes: an integrated approach. *SEPM, Spec. Publ.*, **42**, 39-45.

VAN WAGONER, J.C., MITCHUM, R.M., CAMPION, K.M. and RAHMANIAN, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies. *AAPG, Methods in Exploration Series,* **7**, 55 pp.

WALTON, W.M., 1967. The informal units of the subsurface Eocene. *Asociación Venezolana de Geología, Minería y Petróleo, Boletín Informativo,* **10**(1), 21-30.

ZAMBRANO, E., VASQUEZ, E., DUVAL, B., LATREILLE, M. and COFFINIERES, B., 1971. Síntesis paleogeográfica y petrolera del occidente de Venezuela. *Venezuela Ministerio de Minas e Hidrocarburos, IV Congreso Geológico Venezolano, Caracas, 1969, Memoria, Boletín de Geología, Publicación Especial,* **5**(I), 483-552.

ZAMORA, L.G., 1977. Uso de perfiles en la identificación de ambientes sedimentarios del Eoceno del Lago de Maracaibo. *Venezuela Ministerio de Energía y Minas-Sociedad Venezolana de Geólogos, V Congreso Geológico Venezolano, Memoria,* **IV**, 1359-1380.