

Micropaleontological investigations in the modern Mahakam delta, East Kalimantan (Indonesia)

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Abstract: The Mahakam delta is a mixed, fluvial and wave dominated delta located in the eastern part of the island of Borneo (the East Kalimantan province of Indonesia). The distribution of benthic fauna in this delta system is influenced by the combined or antagonistic action of three main parameters: fluvial input of fresh water and sediment, tide, and a strong regional north to south drift current. A model of the present-day faunal distribution has been established taking into account the perturbations induced by the tide and by the regional drift current. This model has been extrapolated into the recent past through the study of shallow cores that permit the reconstruction of late Holocene deltaic regression patterns.

Key Words: Indonesia, Kalimantan, Mahakam Delta, fluvial input, tide, drift current, benthonic Foraminifera, biofacies, distribution pattern

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Résumé : Recherches micropaléontologiques dans le delta actuel de la Mahakam, Est de l'île de Kalimantan (Indonésie).- Le delta de la Mahakam est un delta mixte, influencé par les apports fluviaux et la marée, localisé sur la partie est de l'île de Bornéo (province indonésienne de Kalimantan Est). La répartition de la microfaune benthique est contrôlée par l'action parfois combinée, parfois antagoniste de trois principaux facteurs, l'apport fluvial d'eau douce et de sédiments, de la marée et de l'action d'un fort courant balayant du Nord vers le Sud le détroit de Makassar qui sépare l'île de Bornéo de l'archipel des Célèbes. Un modèle de distribution de la microfaune actuelle a été établi prenant en compte les perturbations induites par l'action de la marée et du courant de dérive. Ce modèle de distribution a pu être extrapolé au passé par le biais de l'étude de carottages superficiels illustrant la régression holocène.

Mots-Clefs : Indonésie, Kalimantan, delta de la Mahakam, apports fluviaux, marée, courant de dérive, Foraminifères benthiques, biofacies, modèle de distribution

Version française abrégée - Extended French Abstract: Recherches micropaléontologiques dans le delta actuel de la Mahakam, Est de l'île de Kalimantan (Indonésie).- Le delta de la Mahakam est un delta mixte, influencé par les apports fluviaux et la marée, localisé en Indonésie (sur l'île de Kalimantan et débouchant sur le détroit de Makassar) sous un climat équatorial humide. Le courant balayant le détroit de Makassar (de direction nord-sud) a pour effet de perturber les dépôts sableux qui se concentrent dans les parties centrale et sud du delta. La fraction péliitique est répartie sur un large périmètre et se retrouve très loin vers le Sud.

La répartition de la microfaune benthique à l'intérieur de ce système deltaïque va être influencée par l'action conjuguée ou antagoniste de ces trois facteurs (apport fluvial, marée et courant de dérive).

Les apports fluviaux dominants au Centre et au Sud se traduisent par la présence d'un "delta front" très développé où les cortèges faunistiques sont relativement bien discriminés avec:

- "mud flats" (slikke) associés à la partie tidale du delta
 - groupe *Trochammina*
 - *Ammotium salsum* (CUSHMAN & BRÖNNIMANN) 1948 (rare)
 - *Arenoparrella mexicana* (KORNFELD) 1931
 - *Miliammina fusca* (BRADY) 1870 (rare)
- "tidal flats" à la limite interne du "delta front"
 - groupe *Trochammina*
 - *Ammobaculites agglutinans* (ORBIGNY) 1846
 - *Eggerelloides scabrum* (WILLIAMSON) 1858
 - *Ammonia beccarii* (LINNÉ) 1758 (forme à six loges)
- "delta front" interne et barres d'embouchures
 - *Ammonia beccarii* (LINNÉ) 1758 (forme à neuf loges)
 - groupe *Elphidium* (faciès argileux)
- "delta front" externe
 - *Asterorotalia trispinosa* (THALMANN) 1933
- prodelta supérieur
 - *Operculina gaymardi* ORBIGNY 1832
 - *Pseudorotalia conoides* (ORBIGNY) 1826
 - *Ammonia annectens* (PARKER & JONES) 1865

L'influence de la marée se traduit d'une manière assez spectaculaire par la "remontée" de microfaunes de la partie externe du "delta front" (*Asterorotalia*) voire du prodelta (*Operculina*, *Pseudorotalia*) à l'intérieur des chenaux localisés dans la partie interne du "delta front". Cette observation est fondamentale pour l'exploitation des données fossiles où des dépôts sableux

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chenalisants contenant une microfaune calcaire sont souvent abusivement interprétés comme des dépôts de plate-forme interne.

L'influence du courant de dérive s'exerce essentiellement sur la partie nord du delta où il renforce considérablement l'action perturbatrice de la marée. On assiste à une véritable migration de microfossiles dont l'origine est parfois lointaine (*Calcarina spengleri* (GMELIN) 1791, *Calcarina venusta* (BRADY) 1884, *Elphidium ibericum* (SCHRODT) 1932), provenant des faciès sub-corralligènes situés au Nord et pénétrant très profondément à l'intérieur du "delta front" jusqu'à atteindre les limites de la partie tidale du delta, le cas ultime s'observant au niveau amont des chenaux de "delta front" dans lesquels le contraste est saisissant entre le fond (*Asterorotalia*, *Pseudorotalia*, *Operculina*, *Calcarina*) et les "tidal flats" bordiers (*Trochammina*, *Ammobaculites*, *Eggerelloides*). Si les facteurs mécaniques sont indéniables (tests roulés, brisés fréquents dans la partie nord du delta), il n'est pas exclu qu'une partie de cette microfaune ait trouvée dans le fond des chenaux, dont l'eau est plus salée, un milieu refuge.

Une série de petites carottes prélevées dans la partie sud-est, très fortement progradante, a permis d'étudier le comportement de la microfaune face à l'arrivée massive de sable. Une cartographie assez précise de la distribution faunistique associée à la mise en place d'une barre sableuse a pu être établie. Grâce au contenu des carottes, c'est l'évolution chronologique des associations qui a pu être déterminée. Il ressort de cette étude que les progradations sont extrêmement rapides et très étendues (la barre sableuse représente une surface de cinq kilomètres sur cinq kilomètres pour une épaisseur de quelques mètres).

La variété des biofaciès rencontrés nous oblige à dessiner un modèle de répartition relativement complexe à la hauteur de la diversité des facteurs physico-chimiques influant sur la distribution des tests. Il constitue un outil important pour l'interprétation des séries néogènes sous-jacentes au delta actuel. Ce modèle permet tout à la fois, de mieux apprécier les variations de faciès à petite échelle (à l'échelle de quelques kilomètres) et de mieux mesurer, à la lueur de la complexité des phénomènes observés, les limites de nos propres interprétations.

Introduction

Located in the eastern central portion of the island of Borneo in the Indonesian province of Kalimantan, the Mahakam river drains the Kutei basin and debouches into the Makassar strait. The climate is humid and tropical with an average rainfall of over 260 cm (100") a month. Consequently, deposits in the broad, many-mouthed delta of the Mahakam include all types of terrigenous detritus. Its site of deposition is greatly influenced by the strong north-south currents of the Makassar strait and by wave action so the sand-sized fraction is concentrated in the central and southern portions of the delta, thus permitting the classification of the delta as mixed fluvial/tidal. The pelitic fraction is spread over a large area and is transported far to the south.

The distribution of the benthonic microfauna in the deltaic system is controlled by three factors: fluvial input, tidal action and drift currents which may act in parallel or in opposition.

Purpose of the study

For the micropaleontologist the reconstruction of paleoenvironments is a constant preoccupation, particularly for those engaged in exploration for hydrocarbons. A number of contributions have been published on this topic, among them several regarding existing distribution patterns. An understanding of modern environments is paramount and is the key to an understanding of ancient systems. This approach is particularly valid for reconstructing environments of the last ten million years (when taxa were similar to those of existing faunas). This study investigates the

distribution of foraminiferal assemblages in the Mahakam delta (Fig. 1), particularly those in the active depositional center, and to analyze some of the environmental parameters which may influence microfaunal distribution. It should be of considerable value for the interpretation of ancient delta deposits in Kutei.

The Kutei basin has been an oil producer for a long time (since the end of the 19th century). The reservoirs are mainly deltaic sandstones of Early to Late Miocene age. The presence of a modern delta superimposed on its Neogene oil-producing equivalents constituted an ideal opportunity for a comparison of modern and ancient delta systems.

This opportunity was first exploited in 1974 by sedimentologists (TOTAL internal reports: ALLEN G.P., CASSOUDEBAT & THOUVENIN, 1979). During their field trips, a great number of surface samples were collected (350). In 1992, another field trip, devoted specifically to the mouth bar complex, resulted in the collection of a hundred more surface and core samples.

General features of delta systems

Studies by COLEMAN & WRIGHT (1975) and GALLOWAY (1975) have shown that deltas can be categorized into several types. Differences in morphology and internal geometry are generated by the relative importance of various physical parameters, such as water flow, sediment input, wind, currents, waves and tidal processes. The classification adopted here centers around poles corresponding to the three main classes:

- 1) tide-dominated deltas,
- 2) wave-dominated deltas (Rhône),
- 3) river-dominated deltas (Mississippi).

The Mahakam delta is a mixed, tide- and river-dominated delta in a humid equatorial

climate.



Figure 1: Location map of the studied area.

Previous micropaleontological work

Literature devoted to the micropaleontology of deltas as such is scarce. In comparison, coastal or estuarine environments are better known (HAMAN, 1981; JENNINGS & NELSON, 1992; JONASSON & PATTERSON, 1992). However some deltaic systems have been studied and provide data relevant to the present study.

- River-dominated (Mississippi delta):
LANKFORD (1959) was the first to introduce a zonation based on microfauna distribution. He distinguished six formal assemblages, namely marsh, interdistributary bay, fluvial marine, deltaic marine, sand, and open shelf. ANDERSON (1968) completed this early work.

- Wave-dominated (Rhône delta):
The main contribution was published by KRUIT (1955). This study shows a clear dominance of *Ammonia beccarii*, associated with *Nonion depressulum* (WALKER & JACOB) 1798. These two species are present in the outer part of the deltaic complex (present-day beaches, abandoned coastal ridges, coastal lagoons). Agglutinated Foraminifera (*Trochammina*, *Haplophragmoides*) are restricted to the inner part of the deltaic system: swamps.

Most recently the previous works have been completed by VANGEROW (1974).

- Kutei basin:
During the past twenty years, several studies have been published on modern

micropaleontological distributions in the Mahakam delta (OESTERLE, 1974; HOIBIAN, 1984) and neighboring areas (COUSTILLAS, 1983; BOICHARD *et alii*, 1985; GRANIER, VILLAIN & BOICHARD, 1997).

In his pioneer work, OESTERLE (TOTAL internal report, 1974) distinguished four biofacies associated respectively with the deltaic plain, inner delta front, outer delta front and prodelta slope. These subdivisions were later used by HOIBIAN (1984).

The present study supplements earlier work by including a sedimentological approach and proposing a micropaleontological model for deltaic clastic deposits that are potential reservoirs for oil.

Presentation and sedimentological features

The Mahakam delta is located in Indonesia (Fig. 1) on the eastern coast of Kalimantan Island (between 0°21' and 1°10' south latitude, and 117°40' east longitude). The coastline of this part of Kalimantan is oriented NNE-SSW, and borders the Makassar strait. This delta, like all modern deltas, is a recent feature, having developed in the last phase of the Holocene transgression, over a 5,000 to 7,000 year period during which delta progradation gave rise to a system comprising approximately 1,300 km² of subaerial delta plain, 1,000 km² of delta front and 2,700 km² of prodelta accumulations (ALLEN G.P., CASSOUDEBAT & THOUVENIN, 1979).

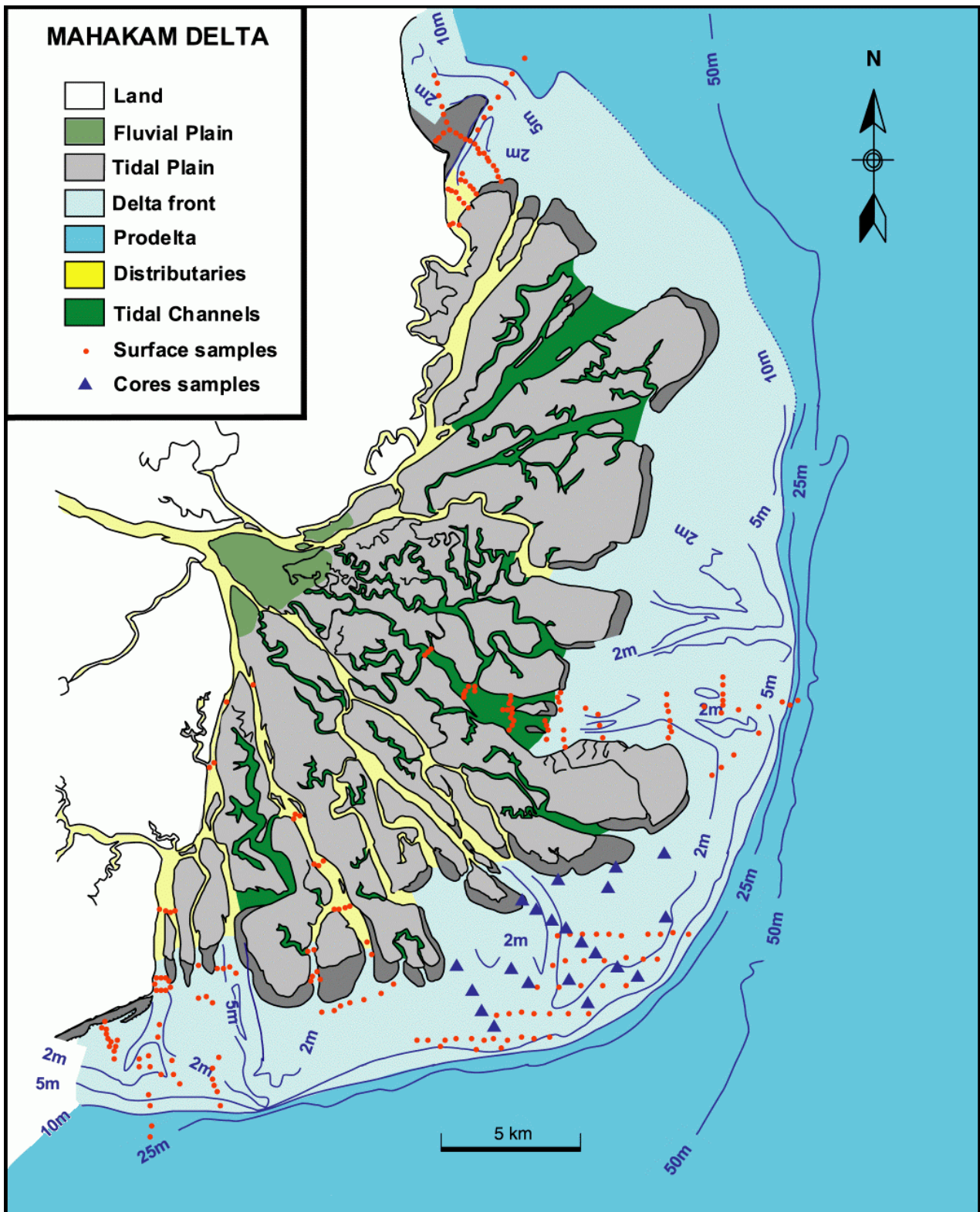


Figure 2: Mahakam delta sedimentological features and sampling locations.

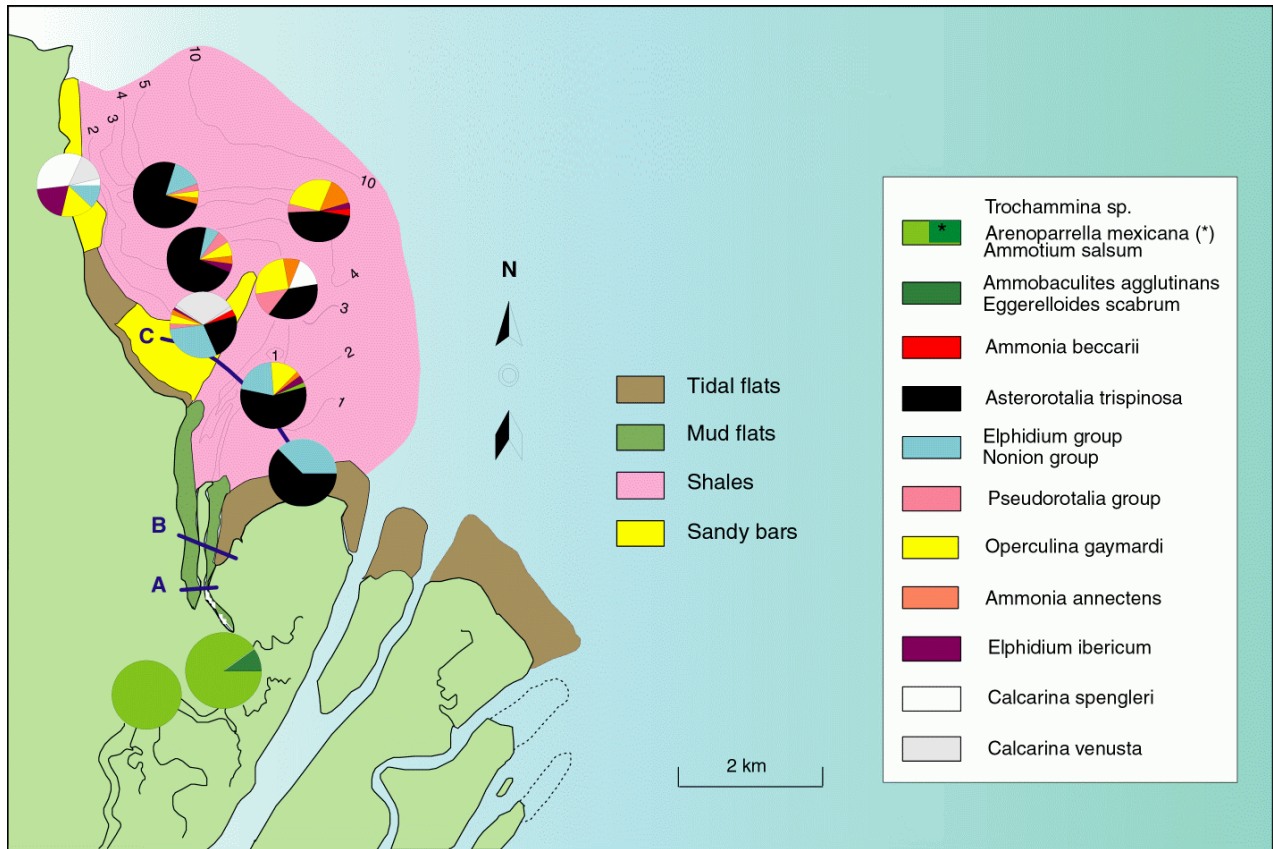


Figure 3: North Mahakam delta: microfaunal distribution shows the foraminifera assemblages of three profiles (A, B, C) including channel sections. Note the dominance of *Asterorotalia* in the muddy delta front facies and the presence of transported calcareous taxa (*Calcarina*) in the sands of beaches and bars.

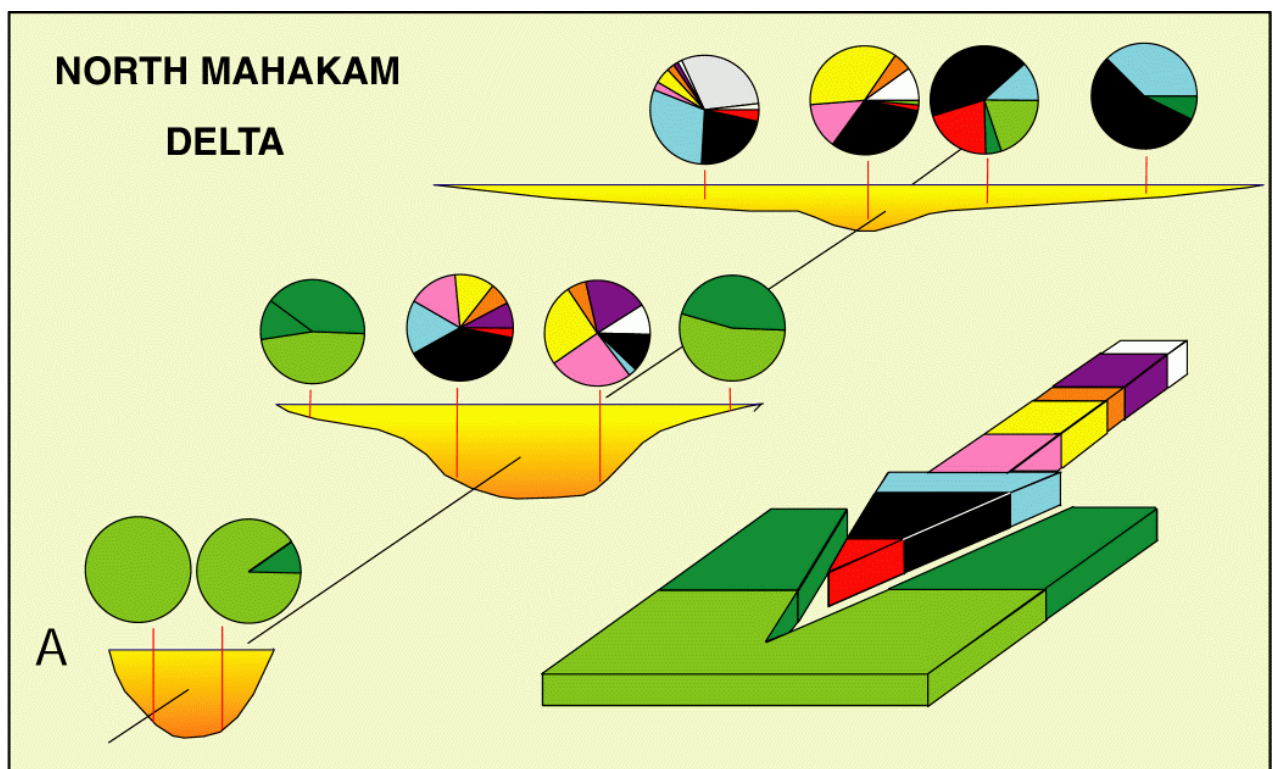


Figure 4: North Mahakam delta: lateral distribution of the assemblages across tidal delta and delta front channels. The main feature is the penetration of calcareous taxa (colored arrow) in the bottom channels (drift current, tide). For colors coding, see Fig. 3.

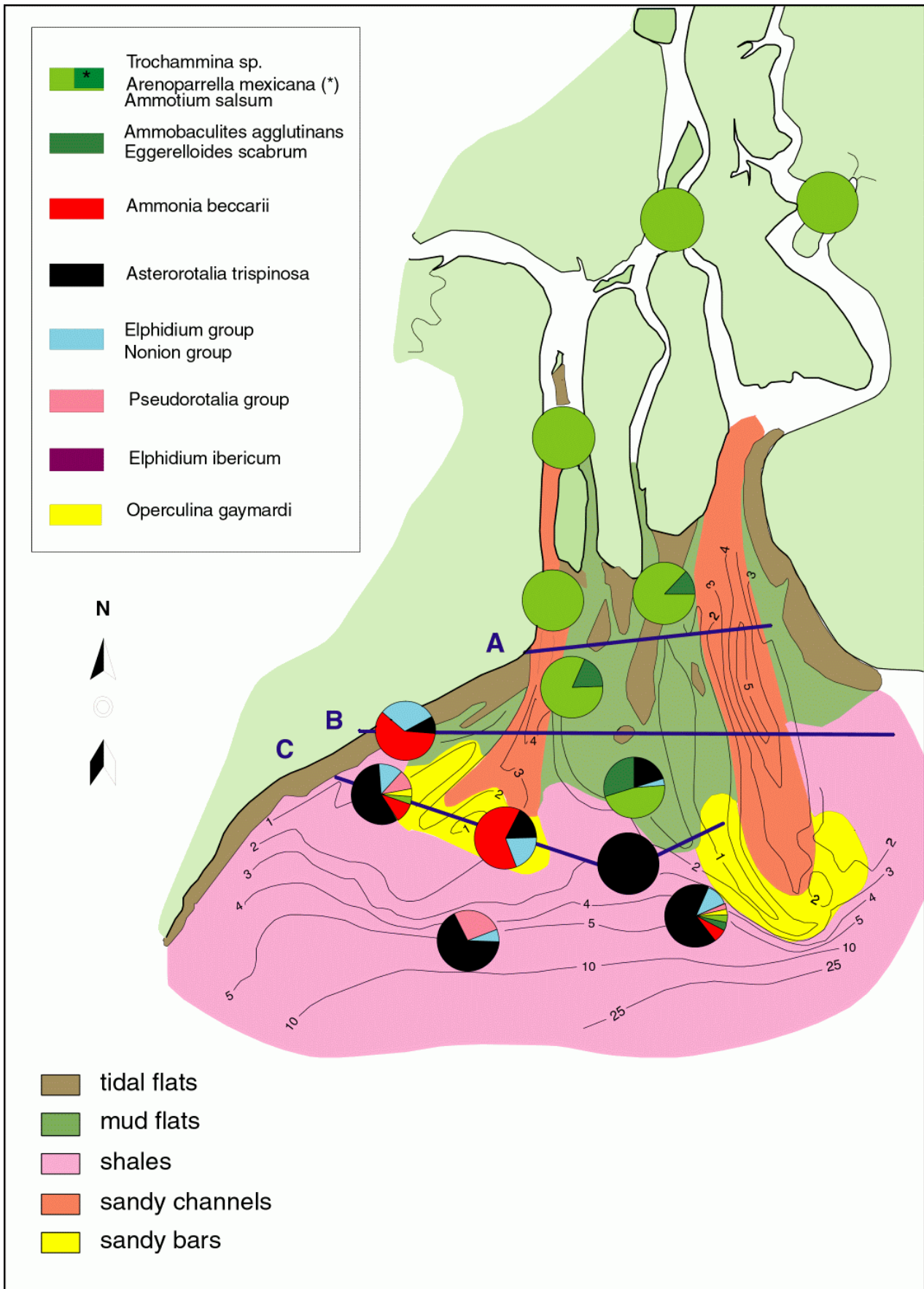


Figure 5: South Mahakam delta: microfaunal distribution. In this area, the mud and tidal flats are very well developed. The main result is the wide development of arenaceous biofacies. *Asterorotalia* and small *Elphidium* predominate in the muddy delta front facies, the sandy beaches and bars contain populations of *Ammonia*.

The general morphology of the delta can be divided into three radially concentric systems (Fig. 2): the delta plain, delta front, and prodelta (ALLEN G.P., CASSOUDEBAT & THOUVENIN, 1979).

Delta plain

The delta plain forms the subaerial part of the delta. It can be subdivided into a fluvial delta plain, and a tidal delta plain. The fluvial delta plain is characterized by highly compacted

and well drained ground, covered with hardwood trees. Its width is between 10 and 20 km. The tidal delta plain is characterized by its low elevation that consequently is subject to daily inundations. The plant cover is Nipah palms and mangroves. The tidal deltaic plain is incised by both distributaries and tidal channels. Its width ranges between 20 and 30 km (ALLEN G.P., CASSOUDEBAT & THOUVENIN, 1979).

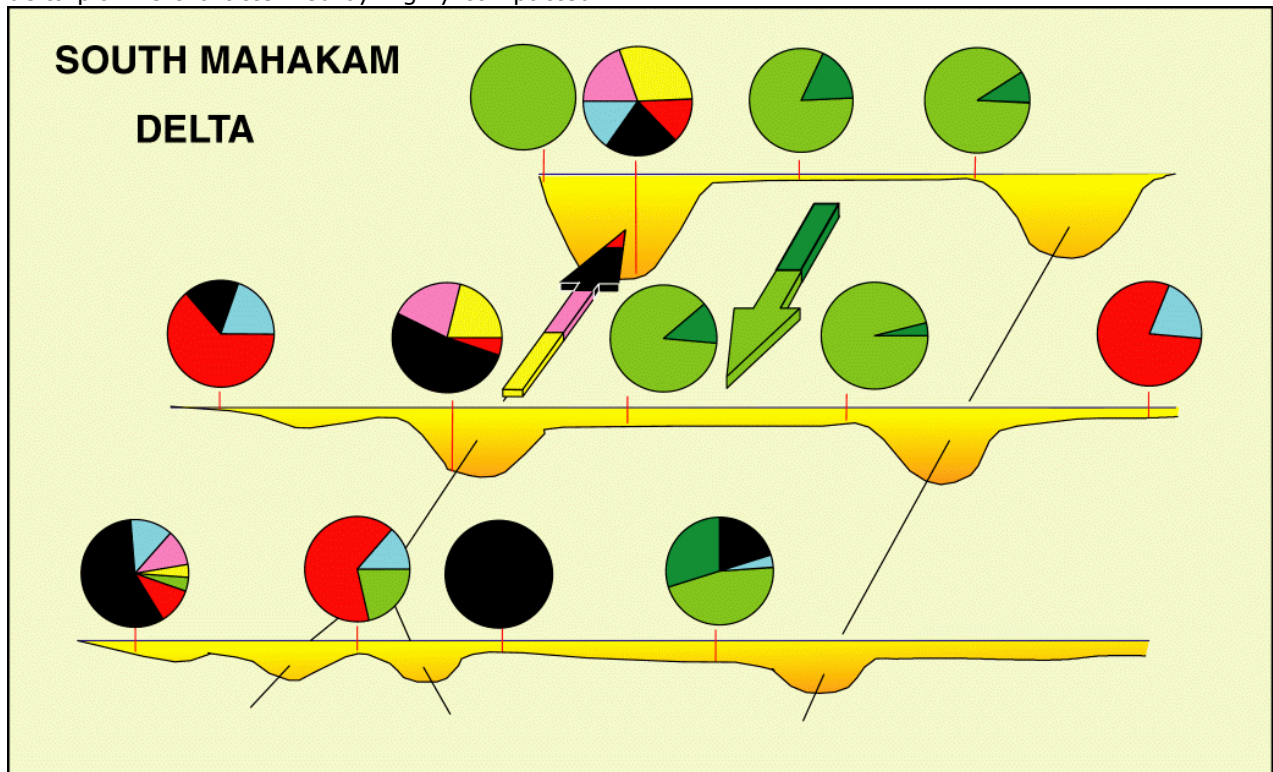


Figure 6: South Mahakam delta: lateral distribution of the microfauna across delta front channels. Note the extent of arenaceous taxa (green arrow) associated with the mudflats advance and in contrast the deep penetration of calcareous taxa like *Operculina* never seen in the delta front itself (colored arrow). For colors coding, see Fig. 5.

Delta front

The delta front is an intertidal to shallow subtidal platform. Its width ranges between 8 and 10 km. The topography consists of linear undulations perpendicular to the coast forming bars and shoals. The delta front too is incised by distributary channels. They extend seaward to its outer limit, terminating in a mouth bar. The inner portion is made up of extensive tidal flats.

Prodelta

The prodelta is a smooth seaward slope, the inner part set off by an abrupt break in the slope at the 5 m isobath. The outer limit is between the 60 and 70 m isobaths. The width of the prodelta shows a sharp asymmetry, an effect of the drift current. Off the southern distributary system it is 30 km wide, but 5 to 15

km wide in the central and northern portions (see below).

Dynamic factors acting on foraminiferal distribution (fluvial influx, tide and drift current)

The repartition of benthonic microfauna seems to be controlled by two parameters:

- River input: No precise studies were made of the quantity of water inflow; however analyses of rainfall data associated with drainage basin evaluation suggest that the discharge is probably on the order of 1,000-3,000 m³ per second. This flow, added to the low general salinity of Indonesian seas (32 g per 1,000), favors the development of agglutinated Foraminifera.

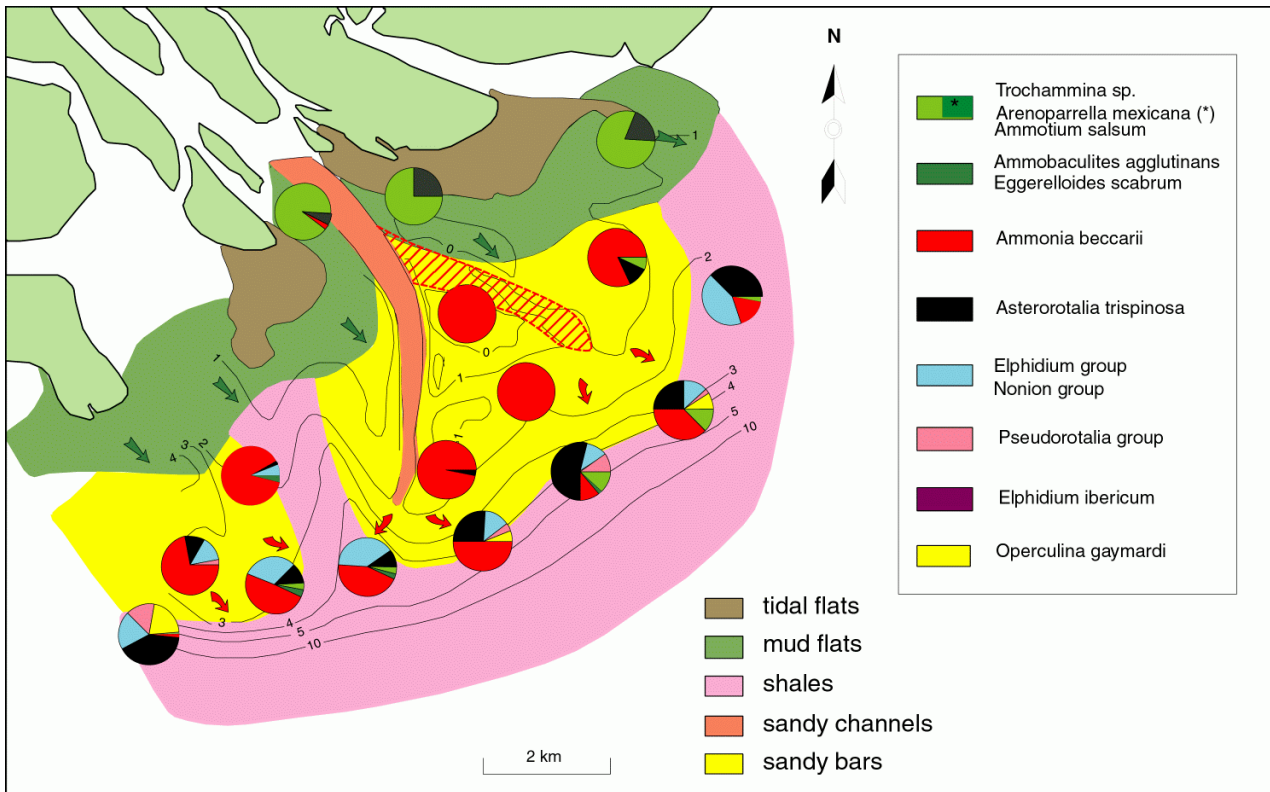


Figure 7: South East Mahakam delta: microfaunal distribution. The dominance of *Ammonia beccarii* is associated with the relative importance of sand bodies (mouth bars) in this area (red arrows indicate the sandy progradation, the green arrow shows the advance of mud flats overlying the sands (in red dashes, an old distributary channel)).

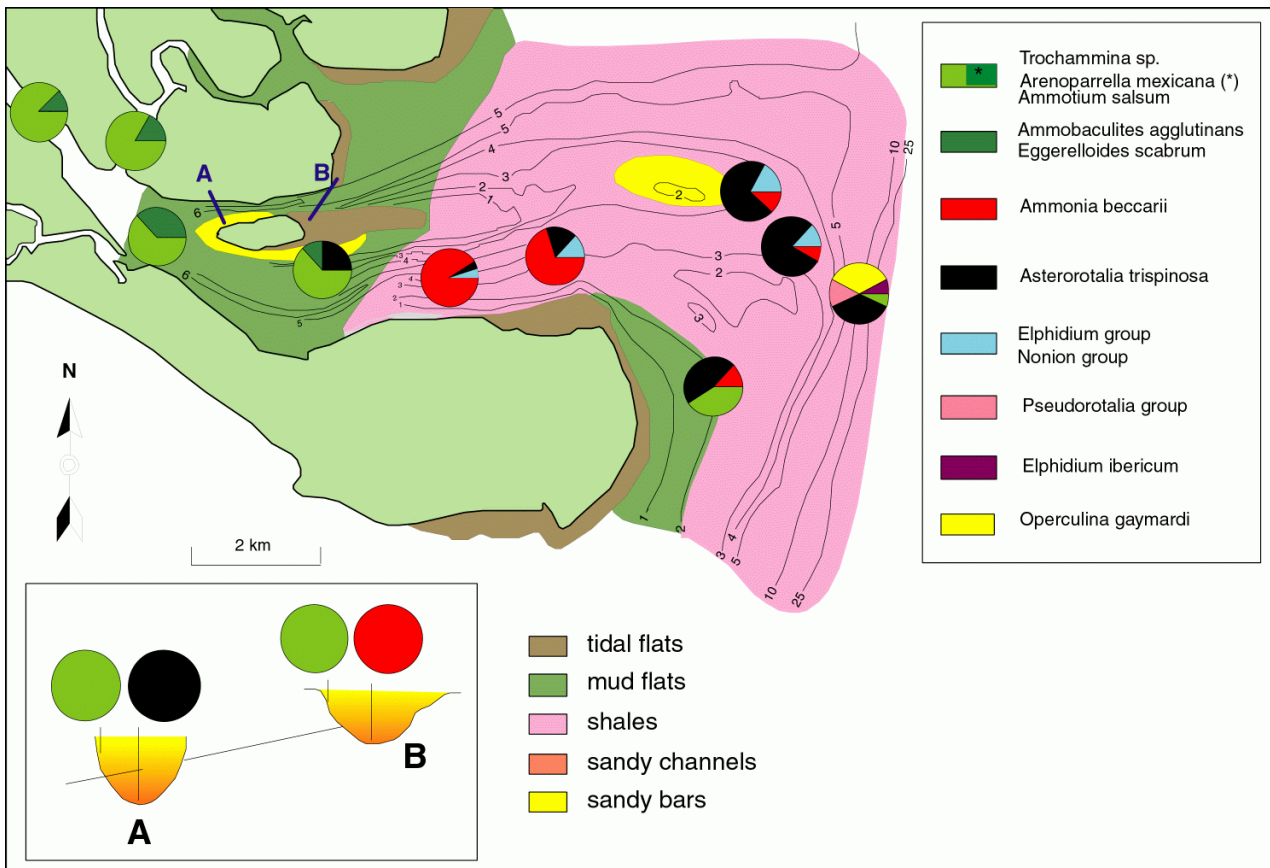


Figure 8: East Mahakam delta: microfaunal distribution (interdistributary area). As in the previously studied areas, note the presence (A and B profiles) of calcareous taxa in the channel bottoms.

- Drift current: In the Makassar strait, the direction of surface water circulation is North-South with a maximum speed in February of 0.5 m per second. This current is sufficiently strong to transport suspended shales clay-sized particles away from the delta. In association with tidal currents it serves also to influence the distribution pattern of benthonic Foraminifera, especially in the north. OESTERLE (TOTAL internal report, 1974) suggested that distributary flow displaced

the agglutinated microfauna of the deltaic plain into a marine environment. Unfortunately, the two samples he mentioned as evidence of this do not agree with our samples from the same localities. In general, we have no definite evidence for this type of transportation.

- Tide: Within the channels tidal flow may cause migration landward of the calcareous fauna of the outer delta front. This point is discussed below.

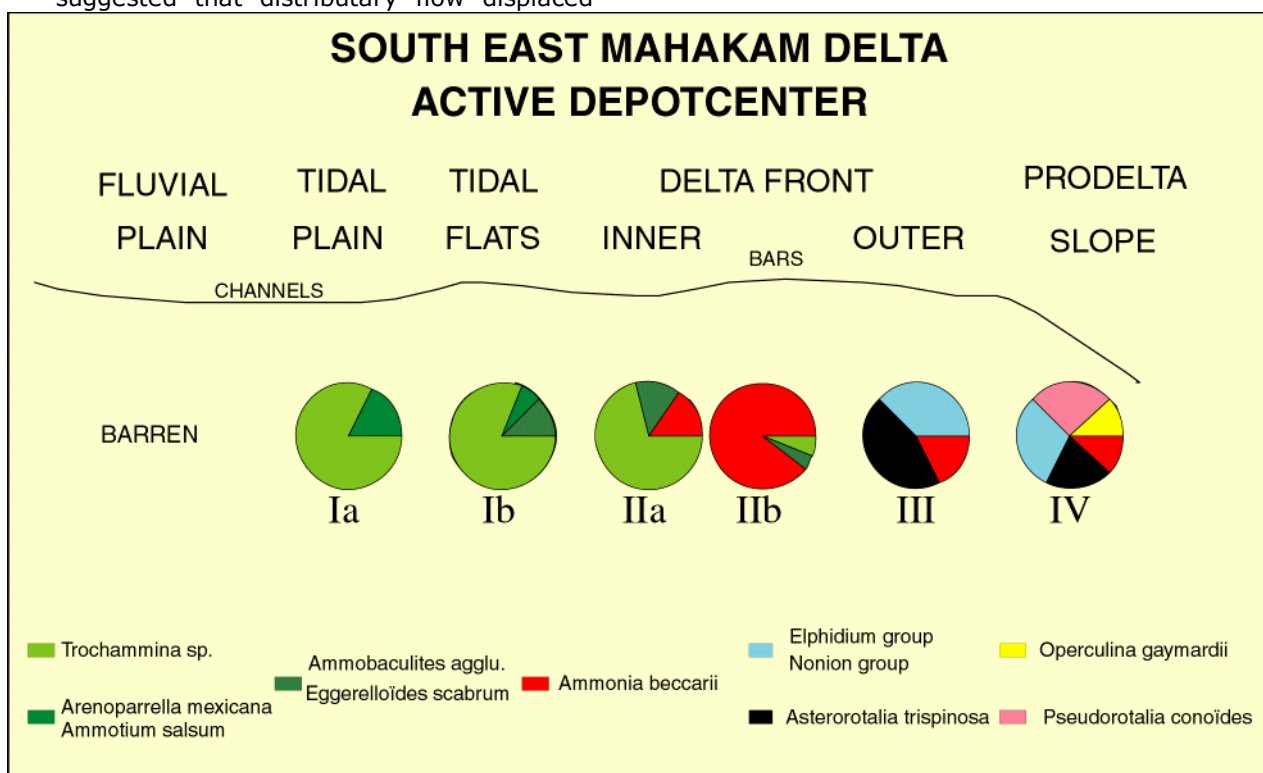


Figure 9: South East Mahakam: delta biofacies distribution. This sketch shows the general distribution of the main Foraminiferal taxa in relation to the topographical and sedimentological pattern.

General biofacies distribution

In this study, we have selected for investigation taxa well represented in both surface and core samples (such as *Trochammina*, *Ammonia*, *Asterorotalia*, *Pseudorotalia*), neglecting the lower frequencies (such as Miliolids). We have considered unimportant the determination to specific levels of several genera, for example: "Elphidium group" includes all small species (*Elphidium advenum* (CUSHMAN) 1922 (Pl. 1, fig. 11), *E. crispum* (LINNÉ) 1767 (Pl. 1, fig. 9), "Pseudorotalia group" includes mainly *Pseudorotalia conoides* associated with a few *Pseudorotalia schroeteriana* (PARKER & JONES) 1862, "Nonion group" includes *Nonion boueanum* (ORBIGNY) 1846, *Nonion scaphum* (FITCHEL & MOLL) 1798, *Nonion* sp.

The following relationships between microfauna and facies were established:

A - North Mahakam (surface sampling, combination of drift current and tide)

The main characteristic of this area is the complex interaction between several factors:

1 - The confrontation between coastal facies (with reefal influences) and deltaic deposits,

2 - The synergy between dynamic tide and drift current effects (the importance of the longshore current was reported previously by OESTERLE, 1974).

1 - Coastal component

The sandy beaches contain a specific assemblage dominated by *Calcarina spengleri* (Pl. 2, fig. 6) and *Calcarina venusta* (Pl. 2, fig. 4) associated with *Elphidium ibericum* and *Operculina gaymardi*. The origin of microfossils belonging to the genus *Calcarina* is traced to the nearby northern patch reefs.

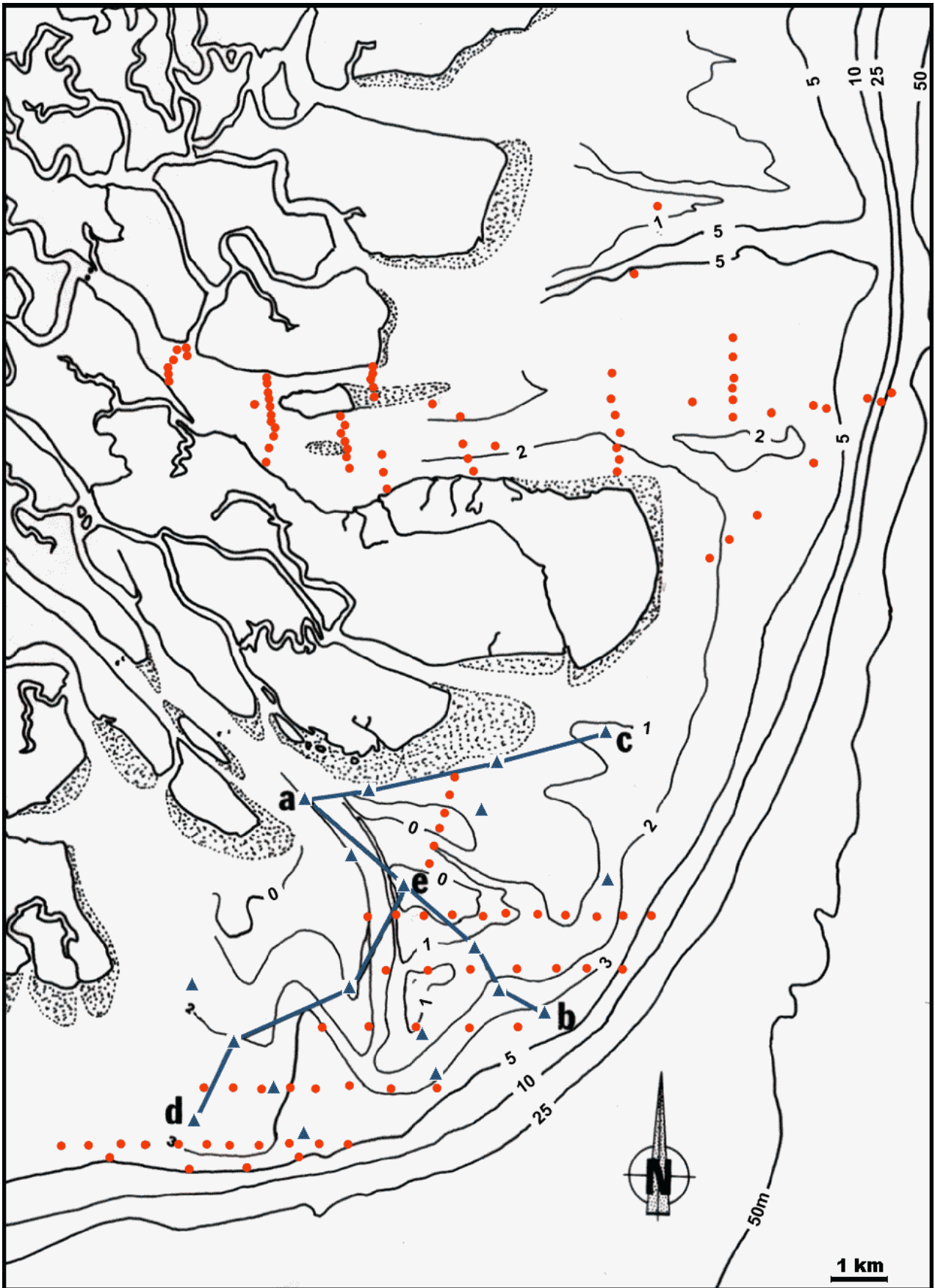


Figure 10: Location of cores (A) and associated surface samples taken in the Tunu mouth bar.

In contrast, the fauna of the muddy inner shelf is very different with a clear predominance of *Asterorotalia trispinosa* (deltaic influx).

The sandy bar located at the northern limit of the deltaic system presents a mixed association with *Calcarina venusta*, *Asterorotalia trispinosa* and the *Elphidium* group, thus comprising another biofacies.

2 - Deltaic component

The tidal deltaic plain in this area is composed of muddy distributary channels and associated organic mud. The samples contain only agglutinated species (*Trochammina* group, *Arenoparrella mexicana*) (Fig. 3-A, 4-A).

The mud (tidal) flats located on either side of the distributary channel (Fig. 3-B, 4-B) contain a more diversified assemblage of agglutinated Foraminifera (*Trochammina* group plus *Trochammina globigeriniformis* (PARKER & JONES) 1865, *Ammobaculites agglutinans*, *Eggerelloides scabrum*). Channel bottoms contain a calcareous microfauna comprising various taxa: *Asterorotalia trispinosa*, *Operculina gaymardi*, *Pseudorotalia* group, *Elphidium ibericum*".

The tidal flats contain an association composed of only two taxa (*Asterorotalia trispinosa* and the *Elphidium* group).

The fauna of the muddy delta front varies in composition depending on the location of the sample. The dominant taxon is *Asterorotalia trispinosa*. The samples located very close to the channel contain agglutinated taxa and *Ammonia beccarii*. The samples located within the channel contain a more varied calcareous microfauna: *Asterorotalia trispinosa*, *Pseudorotalia* group, *Operculina gaymardi*, *Ammonia annectens*, *Elphidium ibericum*", *Calcarina spengleri* (center of Fig. 3).

B) - South and East Mahakam

Southern part (surface sampling)

Because of the important fluvial influx the southern part of the delta is an active depositional center. The primary consequence is the existence of widespread mud (tidal) flats and the presence of a relatively wide delta front.

In the mud flats associated with channels the tidal deltaic plain contains only agglutinated species: the *Trochammina* group, *Ammotium salsum* (Fig. 5).

The tidal flats contain a more diversified agglutinated microfauna: the *Trochammina* group, *Ammobaculites agglutinans*, *Eggerelloides scabrum*. In the outer part of these tidal flats we note the presence of *Asterorotalia trispinosa*.

In the inner delta front the bottom of the channels (Fig. 6 A, B, C) contains a relatively

more diversified calcareous microfauna: *Ammonia beccarii*, *Asterorotalia trispinosa*, *Pseudorotalia* group, *Operculina gaymardi*.

In the sandy mouth bars *Ammonia beccarii* predominates.

In the delta front muds *Asterorotalia trispinosa* is ascendant.

The delta front - prodelta boundary too is dominated by *Asterorotalia trispinosa* associated with the *Pseudorotalia* group, *Elphidium ibericum*", and *Operculina gaymardi*.

Beach deposits contain an association dominated by *Ammonia beccarii* which here is associated with *Asterorotalia trispinosa* and the *Elphidium* group.

Eastern part (distributary channels)

A large mouth bar occupies most of this area (Fig. 7). This bar was cored in order to get a better understanding of progradational processes (see below).

The tidal flats contain only an agglutinated assemblage: *Trochammina* group, *Ammobaculites agglutinans*, *Eggerelloides scabrum* associated with rare *Ammonia beccarii* (6 chambers).

The inner sandy delta front is colonized by *Ammonia beccarii* (9 chambers).

The outer delta front presents a more diversified association with the appearance of *Asterorotalia trispinosa* and the *Elphidium* group.

Eastern part (interdistributary channels)

The tidal deltaic plain is composed of muddy channels. The microfauna is represented by agglutinated Foraminifera: the *Trochammina* group and numerous *Arenoparrella mexicana*.

The tidal flats are always dominated by agglutinated species: the *Trochammina* group, *Ammobaculites agglutinans*, *Eggerelloides scabrum*. As in other areas the channel bottoms contain a calcareous microfauna: *Asterorotalia trispinosa*, *Ammonia beccarii* (Fig. 8-A, 8-B).

The muddy inner delta front is dominated by *Ammonia beccarii*, with *Asterorotalia trispinosa*, the *Elphidium* group and the *Nonion* group increasing in number progressively seaward.

The outer muddy delta front is dominated by *Asterorotalia trispinosa*.

The boundary between the delta front and the prodelta is characterized by the presence of the *Pseudorotalia* group and *Operculina gaymardi*.

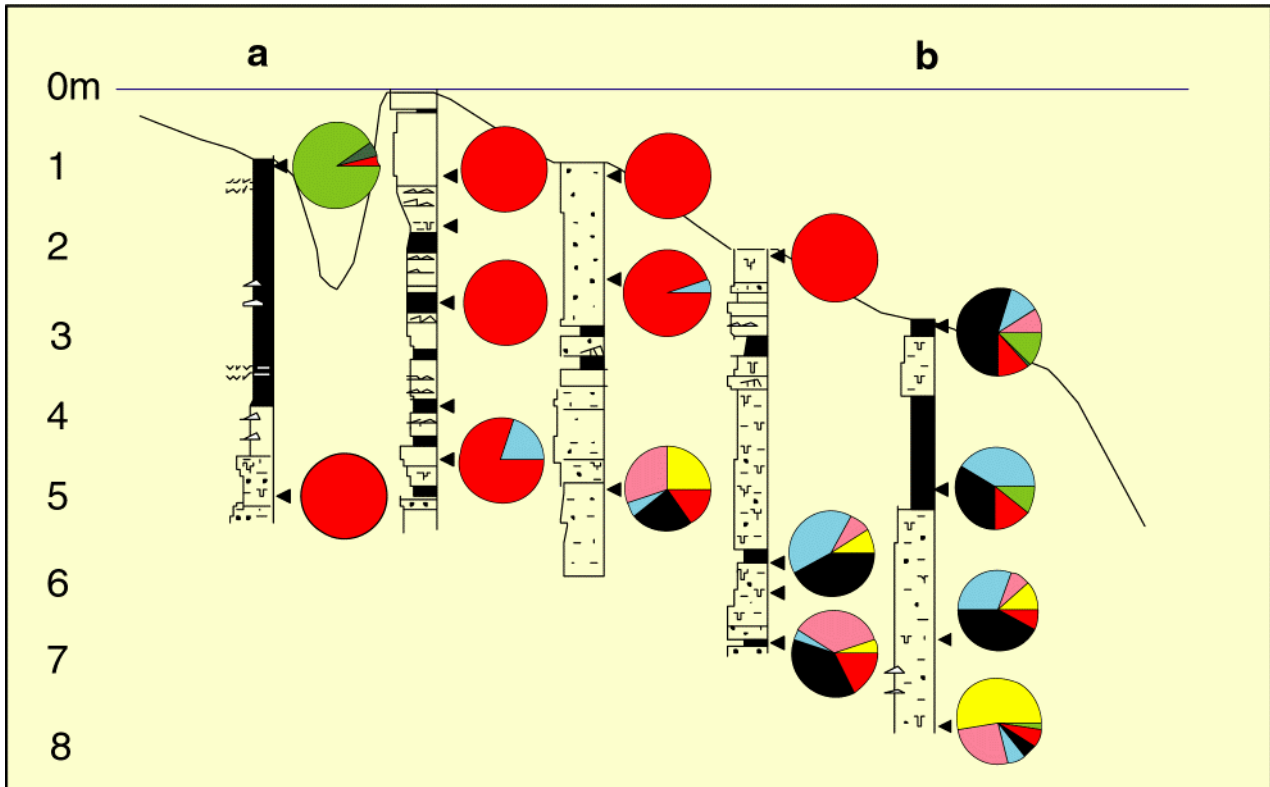


Figure 11: Tunu mouth bar, profile 1. This "dip" profile illustrates the progradational process (for colors coding, see Fig. 9).

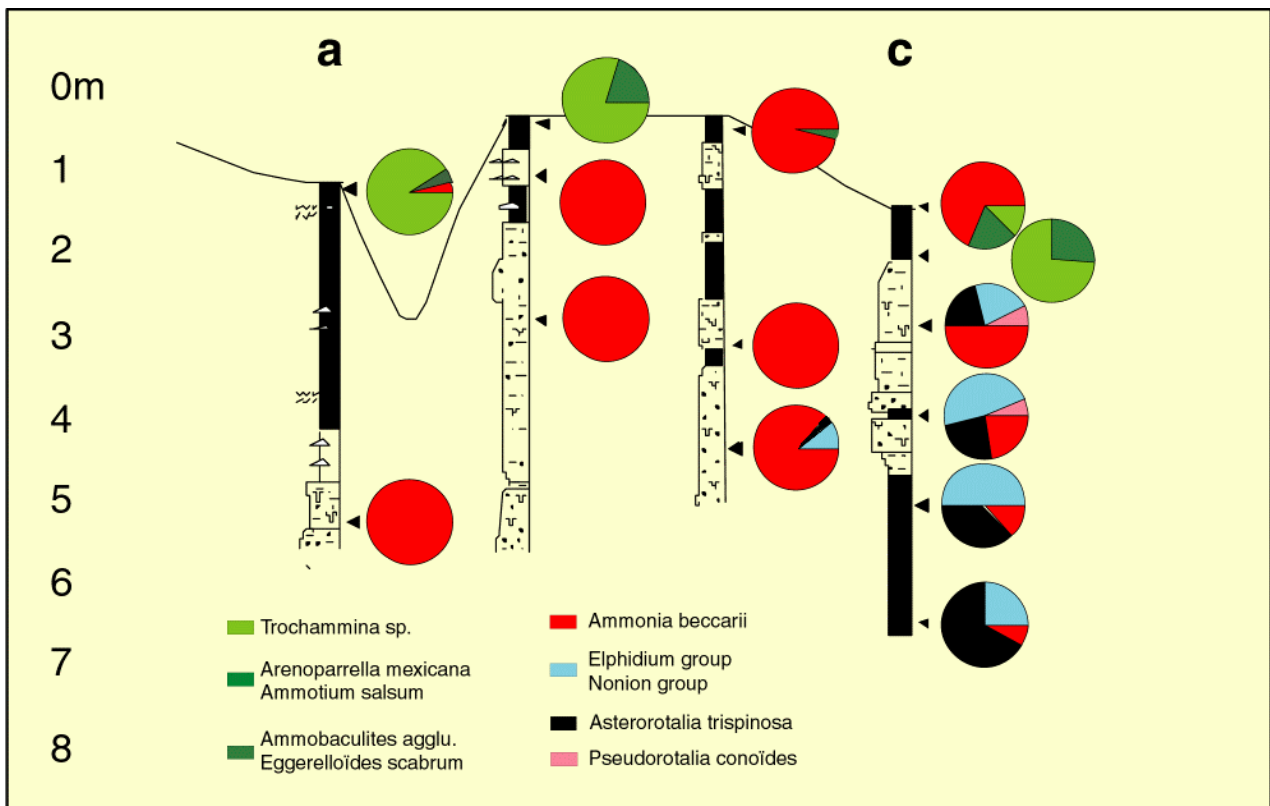


Figure 12: Tunu mouth bar, profile 2. "Strike" profile located along the tidal flats (see Fig. 10). We note the difference in microfaunal composition between the surface mudflats (arenaceous, *Ammonia*) and delta front shales (*Asterorotalia*, *Elphidium*, *Nonion*). As do the surface samples, the core sands contain numerous *Ammonia beccarii*.

C) - General model of distribution

In the southern and eastern parts of the Mahakam delta, the distribution of the several taxa seems to follow the same pattern (Fig. 9).

Biofacies Ia (Tidal Plain: mudflats, channels, 0-6 m water depth)

The tidal deltaic plain contains only agglutinated Foraminifera represented by:

- *Trochammina* group (abundant): Pl. 1, fig. 3
- *Arenoparrella mexicana*: Pl. 1, fig. 2
- *Ammotium salsum* (rare): Pl. 1, fig. 4
- *Miliammina fusca* (BRADY) 1870 (rare): Pl. 1, fig. 1

Biofacies Ib (Tidal Plain: tidal flats, 0-2 m water depth)

The tidal flats located on either side of the delta front channels present a more diversified group of arenaceous Foraminifera including:

- *Trochammina* group
- *Ammobaculites agglutinans*: Pl. 1, fig. 6
- *Eggerelloides scabrum*: Pl. 1, fig. 5
- *Ammonia beccarii* (rare 6 chambers specimens)

In the northern parts of the Mahakam delta, *Trochammina globigeriniformis* (Pl. 1, fig. 7) is present.

Biofacies IIa (delta front, 0-2 m water depth)

The first significant calcareous benthonic foraminiferan to appear in the inner delta front is *Ammonia beccarii* (9 chambered specimens). The complete association is composed of the following species:

- *Trochammina* group
- *Ammobaculites agglutinans*
- *Eggerelloides scabrum*
- *Ammonia beccarii* (9 chambers): Pl. 1, fig. 8

Biofacies IIb (delta front, 0-1 m water depth)

In sandy bars deposited in the delta front, the number of *Ammonia beccarii* increases. Frequently the samples contain only numerous *Ammonia* specimens.

Biofacies III (delta front, 1-5 m water depth)

The outer part of the delta front presents a more diversified association with the appearance of *Asterorotalia trispinosa* (Pl. 1, fig. 13), the *Elphidium* group (Pl. 1, fig. 10), and the *Nonion* group (Pl. 1, fig. 12).

Biofacies IV (prodelta, water depth > 5 m)

Samples taken along the prodelta slope were characterized by a greater diversity of species:

- *Ammonia beccarii*
- *Asterorotalia trispinosa*
- *Elphidium* group
- *Pseudorotalia conoides*: Pl. 2, fig. 1
- *Ammonia annectens*: Pl. 2, fig. 2
- *Operculina gaymardi*

The general pattern of distribution observed in the southern and eastern parts of the delta does not fully apply in the northern parts due to the specific characteristics discussed above. This illustrates the need for caution and restraint when trying to apply directly and rigidly a modern model to ancient sediments.

Stratigraphy and evolution of the late Holocene regression

Core location

Eighteen cores were taken in the eastern distributary part of the delta in order to investigate the most recent regression phase. Three representative profiles were studied. The retained area is an active sandy mouth bar deposit (Fig. 10). The general aspect of the sandy bar corresponds to a triangular body 5 to 6 km wide. This body is bounded to the SW by another sandy bar and to the NE by the muddy facies of the delta front. The front of the bar is adjacent to the edge of the prodelta. The first profile corresponds to a longitudinal section of the bar. The other two profiles correspond to transverse sections.

Description and biofacies

1) First profile

Four cores are located on this NW-SE profile in a continuation of the main distributary channel (Fig. 11).

The surface samples show the general trend from a mudflat facies (*Trochammina* sp., *Ammobaculites agglutinans*, *Eggerelloides scabrum*) to upper prodelta shales (*Asterorotalia trispinosa*, *Ammonia beccarii*, *Pseudorotalia conoides*, etc.).

The change in microfaunal distribution is relatively clear. In core (a), the mudflat facies of the upper part overlies a silty facies containing populations of *Ammonia beccarii*. In the following cores the sandy bar overlies a sandy, silty bioturbated facies containing a more diversified microfauna: *Pseudorotalia conoides*, *Operculina gaymardi*, *Asterorotalia trispinosa*, etc. In the last core (b), the *A. trispinosa* shales are superimposed on a silty facies dominated by *O. gaymardi* and *P. conoides*.

2) Second profile

This profile of four cores is parallel to the present-day mud flat (Fig. 12). Surface samples along the profile indicate a mudflat facies. Foraminiferal assemblages are dominated by arenaceous forms associated to varying degrees

with *Ammonia beccarii*. The sandy and silty facies present below are mostly dominated by *A. beccarii*. However, the most distal core (c) presents a slightly different distribution. The relatively high frequency of *Asterorotalia trispinosa* and small *Elphidium* in this core, especially in the muddy facies, is noteworthy.

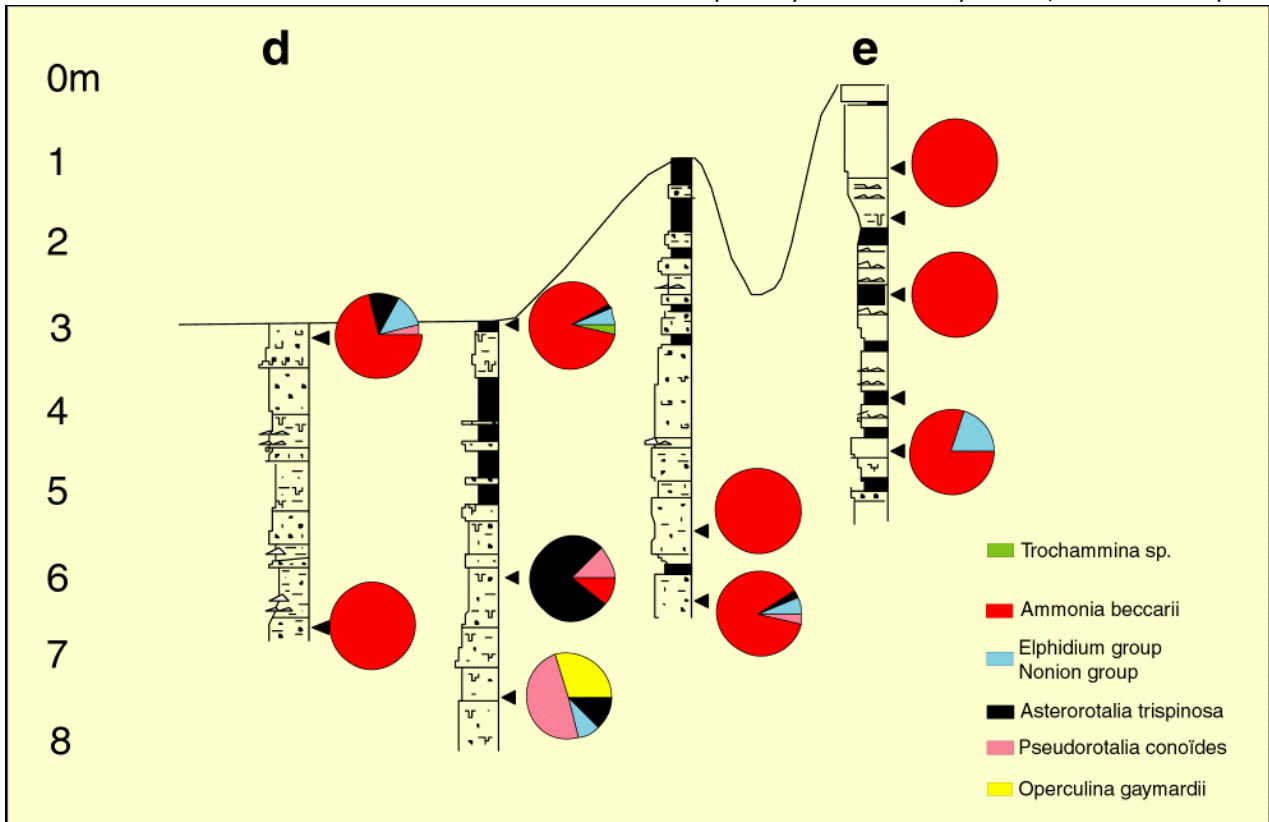


Figure 13: Tunu mouth bar, profile 3. This profile represents the sandy mouth bar; *Ammonia* predominates in the samples. However, in the deepest level of the core, the presence of a more diversified biofacies suggests a more distal influence (for colors coding, see Fig. 12).

3) Third profile

This profile, including four cores, is oriented SW-NE and is located on two of the present-day sandy mouth bars (Fig. 13). Sediments are mostly sands and silty shales. *Ammonia beccarii* is by far the most abundant microfossil.

Conclusions

The micropaleontological study of the cores confirms the general trend inferred from analysis of the surface samples. It supports a strong relationship between the occurrence of *Ammonia beccarii* and an influx of sand and a high level of correlation between muddy facies and the occurrence of small species of *Elphidium* (associated with *Asterorotalia trispinosa*).

An important result is the appreciation of the rate of sedimentation. As the average depth of the cores is five meters, we may estimate the

advance of the sand body as having been between three and four kilometers during the time that three or four meters of sediment accumulated. Bearing in mind that 30 to 40 kilometers of new land has formed in 10,000 years, we can estimate that the time required for the full development of the sandy bar was less than 1,000 years, its sediments deposited at a rate of 3 to 4 millimeters per year.

Exploration models

It is most important to the petroleum geologist to be able to interpret the relationship between fossil distribution, sedimentological processes and the resulting lithology. Identical lithologies may contain discrete microfaunal associations; a unique association may be found in several lithologies.

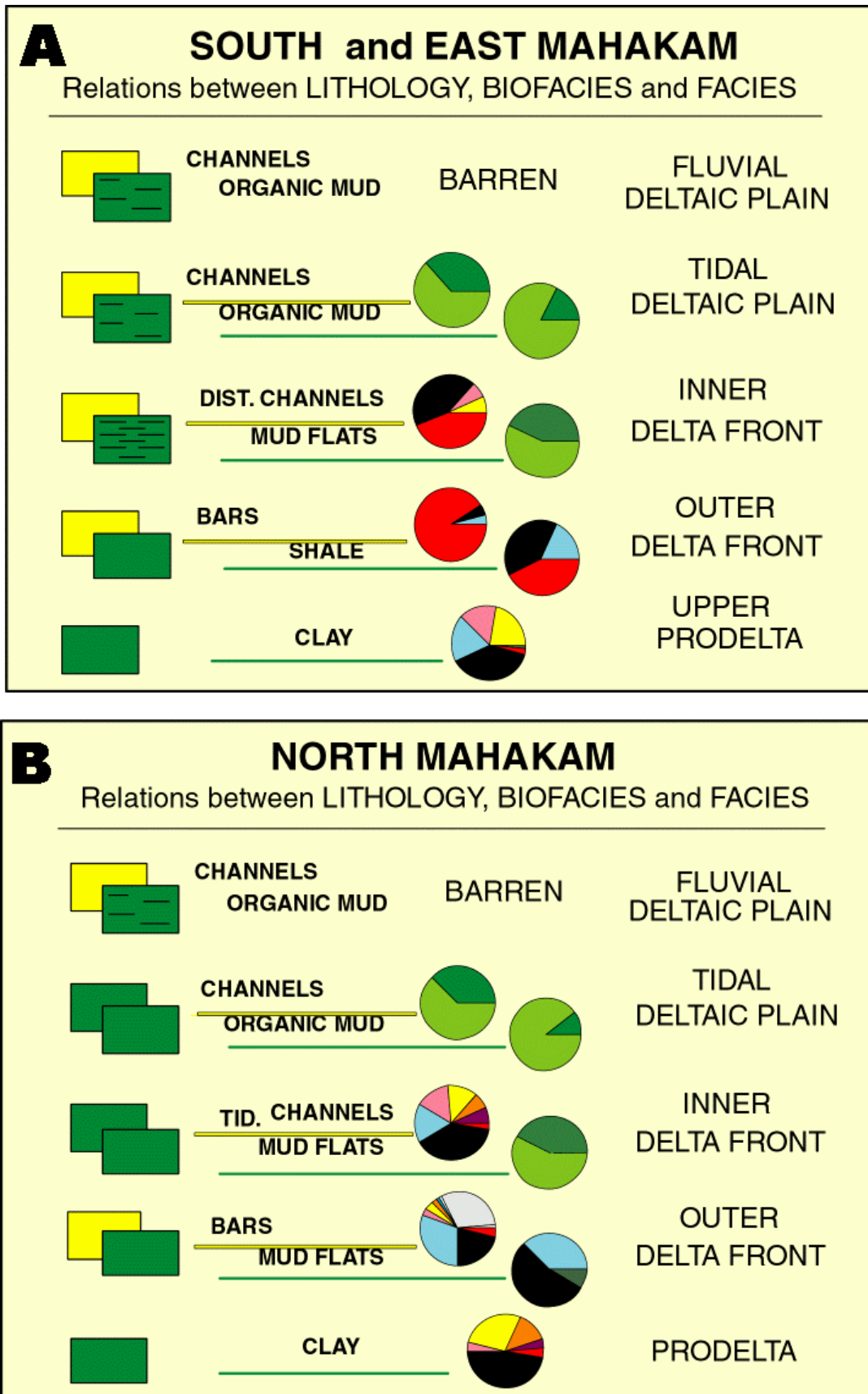


Figure 14: Relations between lithology, biofacies and lithological facies. Depending on their location in the delta, identical lithologies have different associations (especially marked between the North and the other areas). For colors coding, see Fig. 12.

Biofacies and lithology

In the Mahakam delta, the two main lithologies are sands and compacted mud ("shale"). Their microfaunal content depends on their locations relative to the deltaic influx (Fig. 14). We have seen earlier the importance of allochthonous factors (tide and current) on the areal distribution of faunas especially in the northern part of the delta.

- Pyritic organic muds more or less rich in wood remains

This type of sediment is found only in the delta itself.

- The muds associated with the fluvial deltaic plain (fresh water only) are always barren.

- The muds associated with the tidal delta plain (salty influx) contain a typical arenaceous association (1a) with the *Trochammina* group, *Arenoparrella mexicana*, *Ammotium salsum*, *Miliammina fusca*.

- The muds associated with tidal flats contain a variable association depending on their geographical location.

In the southern and eastern part, of the delta the association present in the organic mudflats is composed of the *Trochammina* group, *Ammobaculites agglutinans*, *Eggerelloides scabrum*, *Ammonia beccarii* (6 chambers).

In the northern part of the delta faunal content varies with locality:

- In muds located in close proximity to the channels: *Trochammina* group, *Ammobaculites agglutinans*, *Eggerelloides scabrum*, *Ammonia beccarii* (6 chambers) plus *Trochammina globigeriniformis*.
- In flats at a distance from the channels: small *Elphidium*, *Asterorotalia trispinosa*.
- In the muddy infills of delta front channels: *A. trispinosa*, *Pseudorotalia* group, *Operculina gaymardi*, *Ammonia annectens*, *Elphidium "ibericum"*.

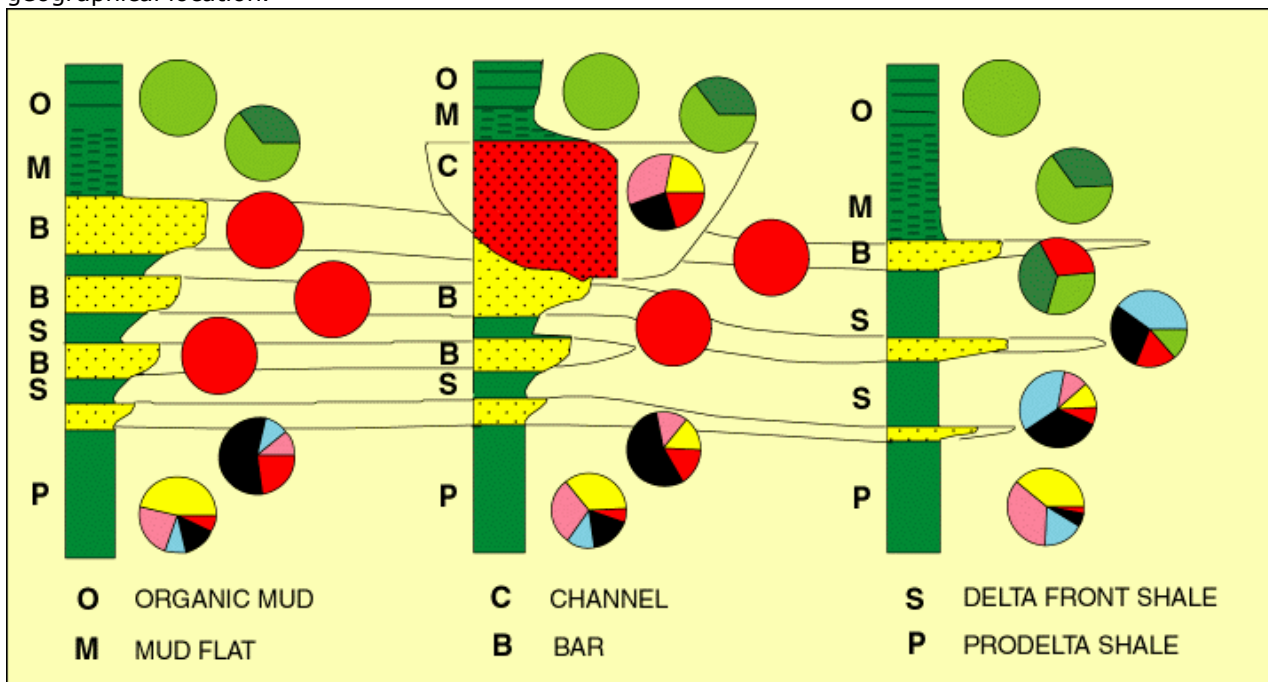


Figure 15: Biofacies distribution in the regressive deposits of the Mahakam delta. Most useful is information regarding the association of sandy sediments and various calcareous taxa (including large benthonics like *Operculina*). In many previous studies this association was interpreted as indicating inner shelf sand deposits. In fact this association indicates delta front channels (for colors coding, see Fig. 12).

- Sands

Sandy facies are found in the delta itself (distributary channels) and on the delta front (channels and bars).

- The microfaunal content of delta sands is similar to that of the associated muds: barren in the fluvial plain, arenaceous Foraminifera in the tidal plain.

- The distributary channels located in the

southern and eastern part of the delta are filled with bioclastic sands containing *Ammonia beccarii*, *Operculina gaymardi*, *Asterorotalia trispinosa*, and the *Pseudorotalia* group.

- Sandy bars in the southern and eastern part, of the delta are dominated, by *Ammonia beccarii*. In the northern part, their content is more diversified with small *Elphidium*, *Asterorotalia trispinosa*, *Calcarina spengleri*, etc.

- Shales, clays

These sediments are associated with the delta front and upper prodelta. The dominant species is *Asterorotalia trispinosa* everywhere in the delta.

- In the delta front this species is associated with *Ammonia beccarii* (in the vicinity of the sandy bars) and small *Elphidium*.

- In the outer part of the delta front and in the upper prodelta the association is more diversified with *Asterorotalia trispinosa*, the *Pseudorotalia* group, *Operculina gaymardi*, small *Elphidium*, etc.

Biofacies and sedimentology

From all these observations it is possible to propose a general model of distribution, particularly for the southern and eastern parts of the delta; the northern part is more specific in nature. This model is now widely used for the interpretation of Upper Neogene deltaic sediments in the Mahakam basin (Fig. 15).

This model presents a tridimensional distribution of micropaleontological associations thus providing an accurate means of determining the nature and location of sand reservoirs and the shaly facies associated with them.

General conclusions

The distribution of the benthonic microfauna in the deltaic system is controlled by three factors: fluvial input, tidal action and drift currents which may act in parallel or in opposition.

Fluvial input, dominant in the center and south, is indicated by the presence of a widely developed delta front, in which faunal suites are relatively well segregated:

- mud flats associated with the tidal portion of the delta
 - *Trochammina* group
 - *Ammotium salsum* (CUSHMAN & BRÖNNIMANN) 1948 (rare)
 - *Arenoparrella mexicana* (KORNFELD) 1931
 - *Miliammina fusca* (BRADY) 1870 (rare)
- tidal flats located at the inner edge of the delta front
 - *Trochammina* group
 - *Ammobaculites agglutinans* (ORBIGNY) 1846
 - *Eggerelloides scabrum* (WILLIAMSON) 1858
 - *Ammonia beccarii* (LINNÉ) 1758 (six chambers forms)
- inner delta front and mouth bars
 - *Ammonia beccarii* (LINNÉ) 1758 (nine chambers forms)
 - *Elphidium* group (argillaceous facies)

- outer delta front
 - *Asterorotalia trispinosa* (THALMANN) 1933
- upper prodelta
 - *Operculina gaymardi* ORBIGNY 1832
 - *Pseudorotalia conoides* (ORBIGNY) 1826
 - *Ammonia annectens* (PARKER & JONES) 1865

The influence of the tide is shown rather spectacularly by the migration up-river of microfaunas from the outer part of the delta front (*Asterorotalia*), and even from the prodelta (*Operculina*, *Pseudorotalia*) along channels located in the inner part of the delta front. This observation is fundamental for the accurate interpretation and use of fossil data, for sand deposits with a calcareous microfauna are often misinterpreted as inner platform deposits.

Drift currents are most effective in the northern part of the delta where they reinforce markedly disturbances produced by tides. Together they allowed a veritable migration of microfossils deep into the delta front, some from a considerable distance (*Calcarina spengleri* (GMELIN) 1791, *Calcarina venusta* (BRADY) 1884, *Elphidium ibericum* (SCHRODT) 1932), their habitat a sub-reefal facies to the north. These forms occur far shoreward in delta front deposits. The extreme is shown by the innermost reaches of delta front channels where the contrast is striking between the channel fauna (*Asterorotalia*, *Pseudorotalia*, *Operculina*, *Calcarina*) and that of the bordering tidal flats (*Trochammina*, *Ammobaculites*, *Eggerelloides*). Although some of the fossils in the channels have undoubtedly been subjected to abrasion (tests rolled, often broken in the northern part of the delta) it is possible that a part of this microfauna found a refuge in the bottom of the channels where the water was saltier.

A series of shallow cores, taken in the southeastern, strongly prograding part of the delta, allowed us to study the reaction of the microfauna to a massive influx of sand during the most recent part of the holocene regression. They made possible a reasonably precise map of the effects of the formation of a (massive) sandy bar on the distribution of the fauna. A study of the cores allowed the determination of changes in faunal associations over time. They showed that progradations are both extremely rapid and widespread (the sandy bar covers 25 square kilometers and is several meters thick).

The great diversity in the facies encountered forced us to design a relatively complex model of faunal distribution in conformity with the wide diversity in physical and chemical factors that controlled foraminiferal habitats. This model is an important tool for interpreting the Neogene series underlying the present-day delta. Not only does it allow a better evaluation of small-scale variations in facies (on the order of a few

kilometers) but also, because of the complexity of the phenomena observed, reminds us of the limitations of our interpretations.

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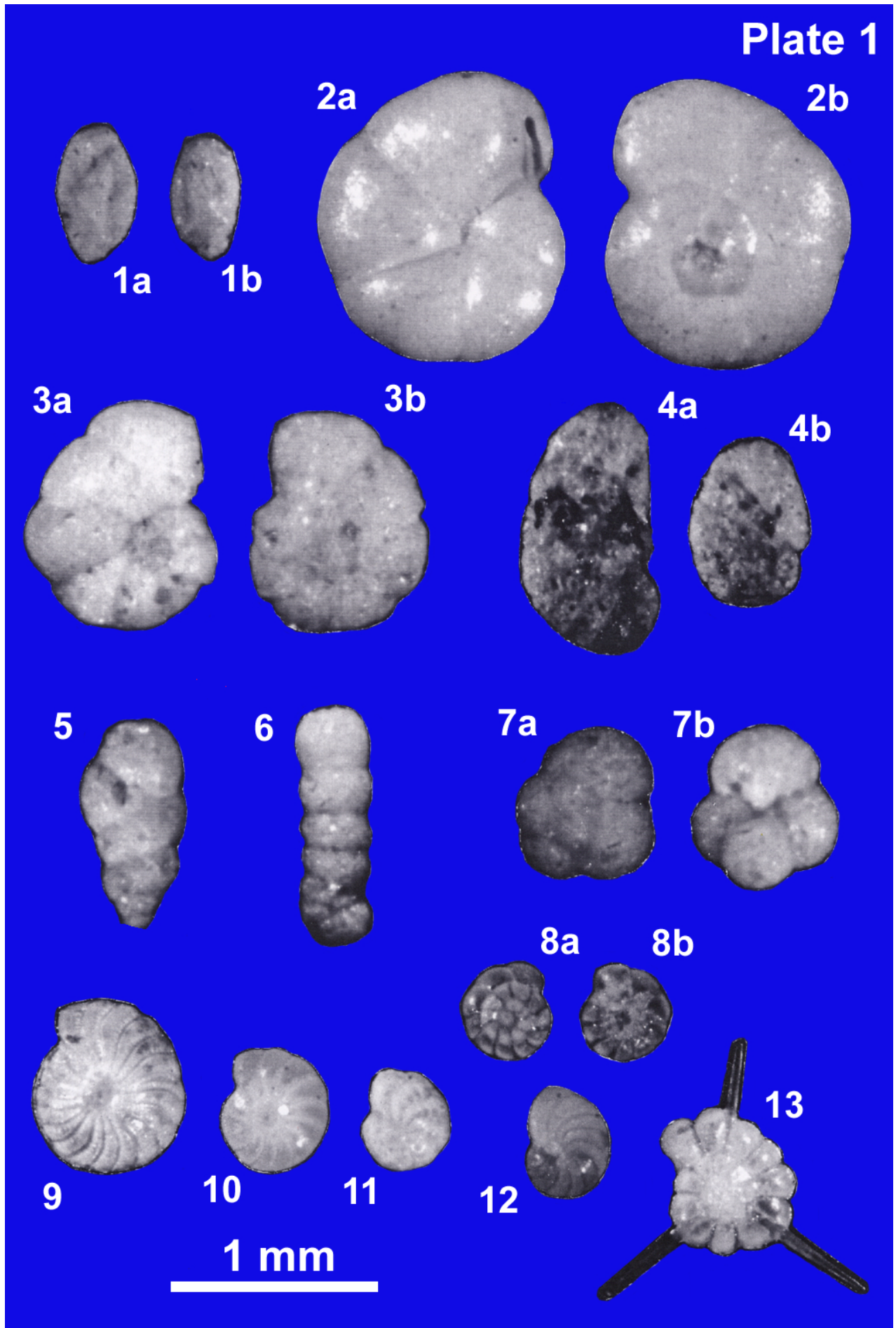


PLATE 1

- Fig. 1a, 1b: *Miliammina fusca* (BRADY) 1870
- Fig. 2: *Arenoparrella mexicana* (KORNFELD) 1931
Fig. 2a: umbilical view
Fig. 2b: spiral view
- Fig. 3: *Trochammina* sp.
Fig. 3a: umbilical view
Fig. 3b: spiral view
- Fig. 4a, 4b: *Ammotium salsum* (CUSHMAN & BRÖNNIMANN) 1948
- Fig. 5: *Eggerelloides scabrum* (WILLIAMSON) 1858
- Fig. 6: *Ammobaculites agglutinans* (ORBIGNY) 1846
- Fig. 7: *Trochammina globigeriniformis* (PARKER & JONES) 1865
Fig. 7a: spiral view
Fig. 7b: umbilical view
- Fig. 8: *Ammonia beccarii* (LINNÉ) 1758 (9 chambers)
Fig. 8a: spiral view
Fig. 8b: umbilical view
- Fig. 9: *Elphidium crispum* (LINNÉ) 1767
- Fig. 10: *Elphidium* sp.
- Fig. 11: *Elphidium advenum* (CUSHMAN) 1922
- Fig. 12: *Nonion* sp.
- Fig. 13: *Asterorotalia trispinosa* (THALMANN) 1933

PLATE 2

- Fig. 1: *Pseudorotalia conoides* (ORBIGNY) 1826
Fig. 1a: umbilical view
Fig. 1b: profile view
Fig. 1c: spiral view
- Fig. 2: *Ammonia annectens* (PARKER & JONES) 1865
Fig. 2a: umbilical view
Fig. 2b: profile view
Fig. 2c: spiral view
- Fig. 3: *Operculina complanata* (DEFRANCE) 1822
- Fig. 4: *Calcarina venusta* (BRADY) 1884
Fig. 4a: spiral view
Fig. 4b: umbilical view
- Fig. 5: *Elphidium* aff. *craticulatum* (FITCHEL & MOLL) 1798
- Fig. 6: *Calcarina spengleri* (GMELIN) 1791

