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Sedimentology of Miocene Carbonate Buildups, Central Luconia, Offshore Sarawak

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Abstract: During the Miocene, the Central Luconia Province offshore Sarawak became an area of carbonate production and deposition characterised by the extensive development of buildups. These buildups are of considerable size and some 200 have been seismically mapped.

An extensive drilling programme over the last decade revealed that the carbonates can be subdivided into four basic facies types which reflect specific ecological and bathymetrical conditions. Although some intervals suffered compaction during subsequent burial, the majority of the carbonates have preserved excellent secondary porosity. Fresh water leaching during stages of emergence and dolomitisation were the major diagenetic events leading to the overall good reservoir rock qualities of the Central Luconia carbonate buildups.

INTRODUCTION

The Central Luconia Province forms the largest part of Sarawak Shell Berhad's contract area on the Sarawak Shelf (Fig. 1), which overlies a number of post-orogenic basins. From the Upper Eocene to the Pleistocene, these basins have been successively filled by predominantly clastic sediments deposited during eight regressive cycles (Ho, 1977; Fig. 2).

The Central Luconia Province is atypical in that Miocene carbonates extensively developed mainly during Cycles IV and V. Central Luconia is limited to the north by the present shelf edge while in the south, west and east it is bordered by the geological provinces of the Balingian, the western Sarawak clastic shelf and the Baram Delta respectively (Fig. 1).

Structurally, Central Luconia is located in an intermediate position between areas of subsidence and faulting in the north and zones of pronounced Lower to Mid Tertiary compressional tectonics in the south (e.g. in the Balingian area; cf. Fig. 2). Central Luconia shows a relatively low degree of structural deformation. It underwent moderate faulting during the Oligocene to Lower Miocene and again between the Lower and Middle Miocene. The latter movements induced the formation of a number of 'basins' and 'highs'. Subsequently, the elevated blocks triggered the prolific growth of reefal carbonate buildups.

Up to now, some 200 carbonate structures have been seismically mapped by Sarawak Shell Berhad. A total of 43 buildups were drilled leading to the discovery of 20 gas accumulations (Fig. 3).

The Central Luconia gas reserves are planned to be developed and produced into a liquefaction plant which is being constructed in Bintulu by Malaysia LNG Sendirian Berhad.

THE DEVELOPMENT OF THE BUILDUPS

As in most other Cainozoic buildup systems, carbonate production in Central Luconia was primarily controlled by the growth of corals and coralline algae. This

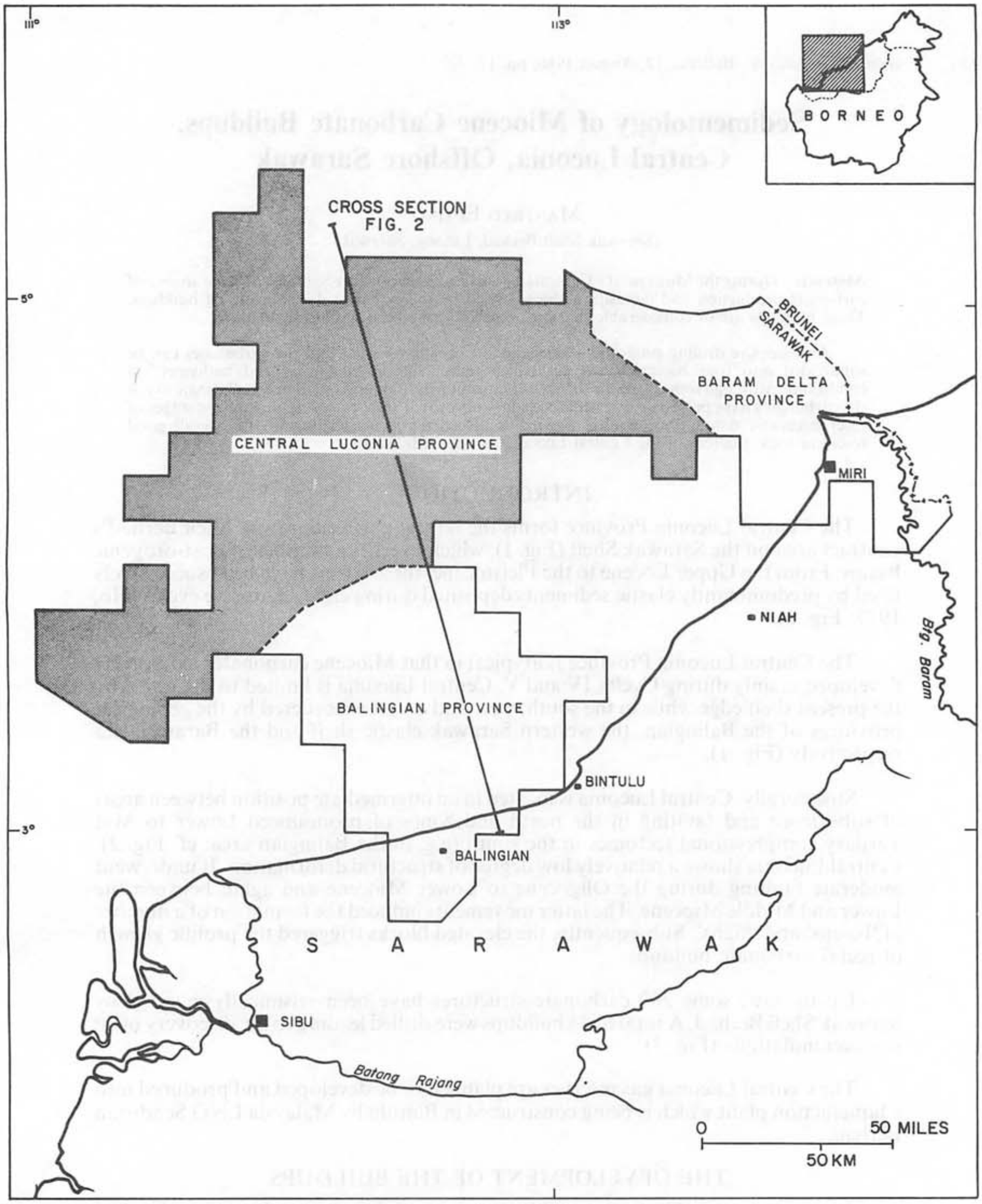


Fig. 1. Situation map. The present contract area of Sarawak Shell Bhd is outlined.

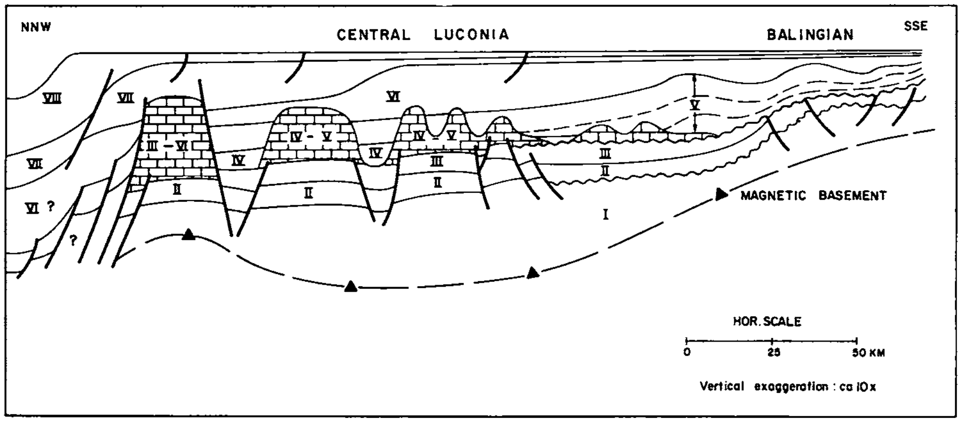


Fig. 2. Schematic NNW-SSE section showing carbonate development and cycle relationship.

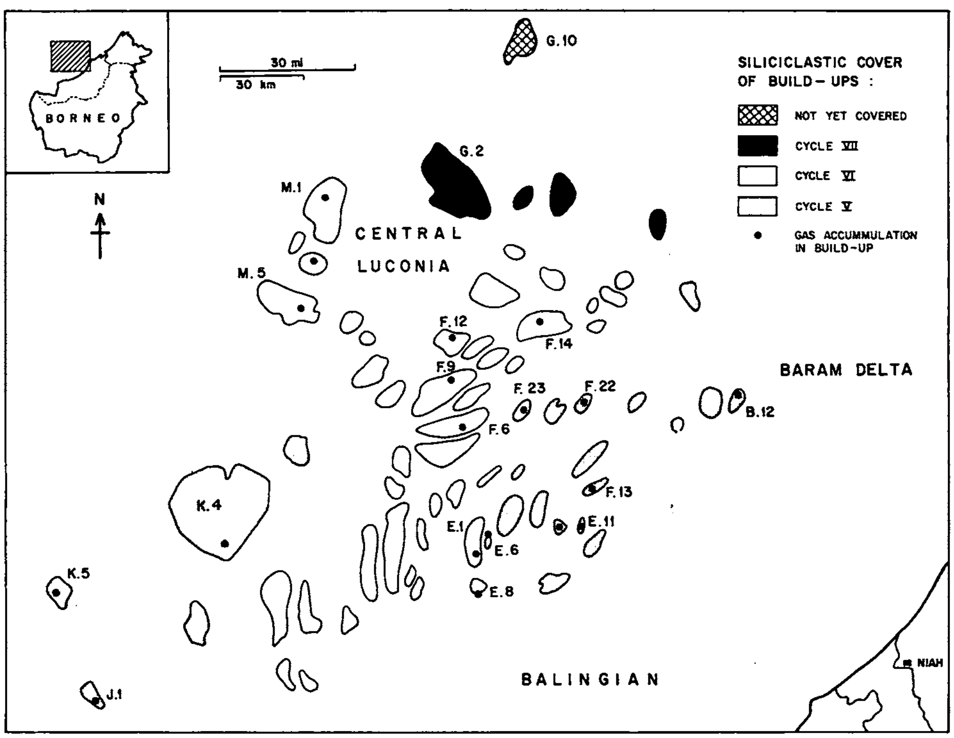


Fig. 3. Areal distribution of major carbonate buildups in Central Luconia. The buildups are covered by siliciclastic sediments of progressively younger cycles towards the north.

community of organisms forms a wave-resistant framework generally occupying a well defined zone often termed 'reef flat' (Fig. 7). This reef flat, although highly variable in shape, separates a fore-reef zone with accumulation of seaward moving debris, from the back-reef and lagoonal zones, which mainly consist of protected environments.

The geometry and internal organisation of the Central Luconia carbonates are similar to those encountered in any other shallow-water carbonate body in that they are determined by the net result of two major processes: the rate of (predominantly skeletal) carbonate production and the rate of sea level changes (or subsidence of the sea bottom). Basically, four cases can be distinguished (Fig. 4):

Rate of carbonate production is of the same magnitude as rising sea level.

As long as growth of the rock-forming organisms keeps pace with the rising sea level, generation of reef debris will be maintained and carbonate sedimentation in the lagoon will continue in a shallow marine environment. Under these circumstances the carbonate complex actively grows upwards. This is the 'classic' buildup situation characterised by a steep organic reef flank (Fig. 4A).

Rate of carbonate production exceeds rise in sea level

In this case a build-out system develops. The reef flat and the fore-reef slope migrate seawards and the lagoon becomes enlarged (Fig. 4B). In this situation the protected part of the carbonate complex may undergo a further differentiation into distinct physiographic zones characterised by different sedimentary environments (e.g. intertidal and supratidal flats).

Rate of carbonate production cannot keep pace with rising sea level (but rise is not fast enough to drown the carbonate complex below the photic zone).

In this situation a build-in system will develop. The actively growing reef flat will move inwards to topographically elevated (e.g. previously supratidal or emergent) areas (Fig. 4C1). In the absence of the latter, the carbonate complex will become submerged and a shallow marine bank will be established (Fig. 4C2). Although a coral/algal community may persist in a subdued form, a different and diverse fauna and flora is likely to colonise the bank.

Rate of carbonate production is greatly reduced due to fall in sea level

In this case the reef flat is most likely to become inactive. Growth of coral/algal communities will be halted or restricted to marginal rims. Some erosion may occur, giving rise to sand cays and shingle and boulder tracts on the reef flats. Simultaneously the lagoon may also become infilled by intertidal and supratidal sediments which, depending on whether the climate was humid or arid, will be lignitic or evaporitic respectively. A modern example of an almost inactive reef complex is Low Isles Reef of the Great Barrier Reef Australia (Fig. 5, MAXWELL, 1968).

A considerable fall in sea level causes a carbonate complex to become partly or completely emergent. In such conditions the carbonate sediments are most likely to be affected by surface-related diagenetic processes such as fresh water leaching, early cementation and dolomitisation.

In the Miocene buildups of Central Luconia all four situations mentioned above occurred in a specific pattern in space and time (Fig. 6).

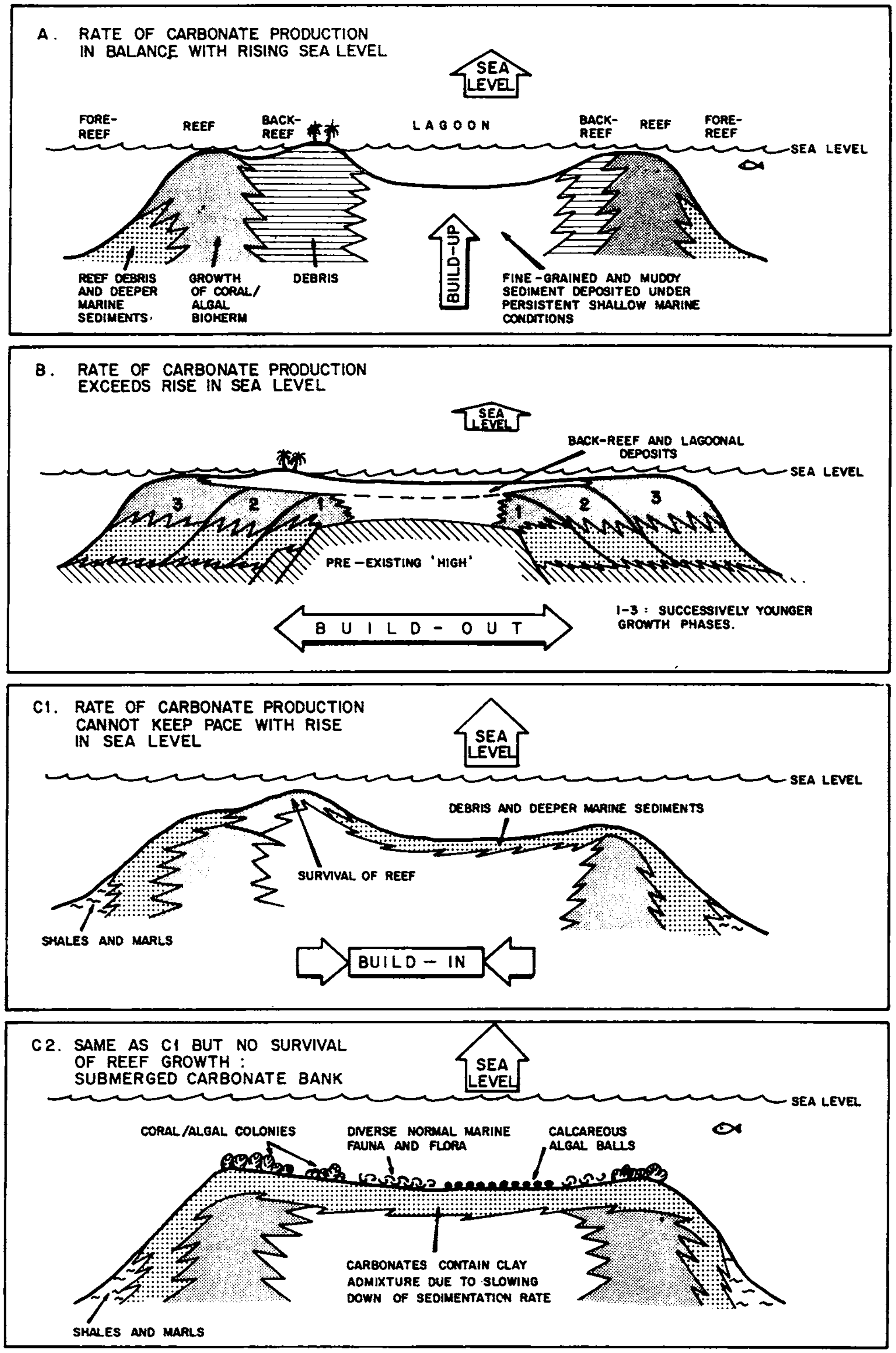


Fig. 4. Main development stages of carbonate buildup systems.

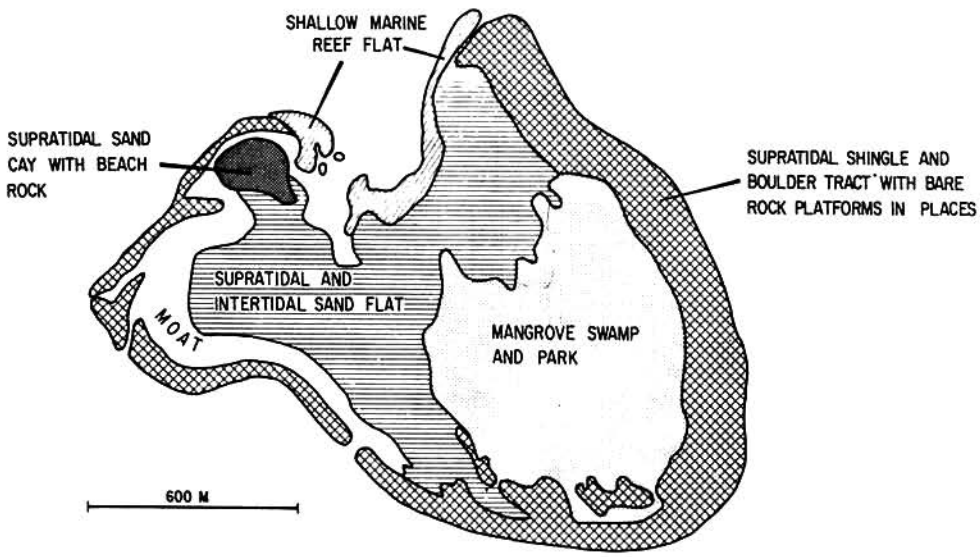


Fig. 5. A modern example of an almost inactive reef complex: Low Isles Reef, E. Australia (after MAXWELL, 1968).

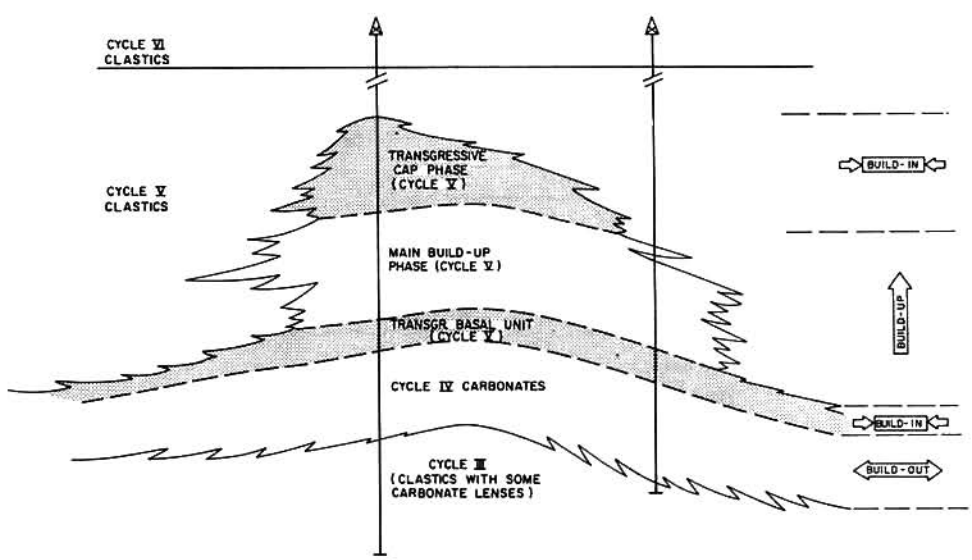


Fig. 6. Typical growth pattern of a Central Luconia carbonate buildup.

Once their growth had started on uplifted highs during Cycle IV, the rate of carbonate production exceeded subsidence. This resulted in a wide lateral expansion of carbonate deposition corresponding to a build-out system. The full range of different carbonate facies is still unknown because only the relatively central areas of these carbonates have been drilled so far. The sediments consist of fine-grained and muddy back-reef and lagoonal carbonates with local intercalations of tidal deposits (e.g. mangrove swamp layers).

Subsequently, Central Luconia experienced a regional transgression which is best developed in the south-eastern area. As a consequence a build-in system developed eventually resulting in the diasappearance of the coral/algal reef flat. It is replaced by a thick transgressive unit (Lowermost Cycle V) consisting of argillaceous open marine carbonates (Fig. 6).

The major part of Cycle V is characterised by an equilibrium between carbonate production and rise in sea level. This stage has been termed Main Buildup Phase.

In most cases the upper Cycle V section is formed by an overall build-in sequence which is interrupted by minor buildup stages (Transgressive Cap Phase). The bulk of the carbonate complexes became inactive during Cycle V prior to be covered by clastic sediments derived from prograding delta systems. In the southeast and the southwest, the areas closest to the deltas, the cover is of Cycle V age (Fig. 6). In the central part and towards the north the clastic cap rock is of Cycle VI age or younger. The northernmost buildup, G. 10, located on the edge of the Sarawak Shelf, is still actively growing today (Fig. 3).

ENVIRONMENTS OF DEPOSITION

In Central Luconia, the recognition of various environments of deposition has led to a fourfold subdivision (Fig. 7 & Table 1) which appears to be most suitable for practical work such as mapping of reservoir zones. It has to be borne in mind,

TABLE I. SUBDIVISION INTO ENVIRONMENTS OF DEPOSITION IN CENTRAL LUCONIA CARBONATES AND LIST OF INDICATIVE FOSSILS

REEF SETTING (environment related to wave resistant reef flat.)	SUBMERGED BANK SETTING (no reef flat)	TYPICAL FAUNAL AND FLORAL ELEMENTS
PROTECTED		Branching and massive corals imperforate Foraminifera : Sorites, Miliolina, Alveolinella, Marginopora, Austrotrillina . Branching calcareous algae Burrowing organisms.
REEFOID		Massive corals encrusting calcareous algae, bivalves, Amphistegina.
SHALLOW OPEN MARINE OFFREEF	SHALLOW OPEN MARINE BANK	Massive and platy corals, larger Foraminifera : Lepidocyclina, Miogypsina, Miogypsinoides, Amphistegina, Heterostegina, Operculina encrusting calcareous algae algal balls (rhodolites, especially on banks)
DEEPER OPEN MARINE OFFREEF	DEEPER OPEN MARINE BANK	Platy corals, encrusting calcareous algae, Cycloclypeus, Eulepidina, Spiroclypeus, Lepidocyclina, Operculina, Miogypsina, Miogypsinoides, Amphistegina, Bryozoa Planktonic Foraminifera.

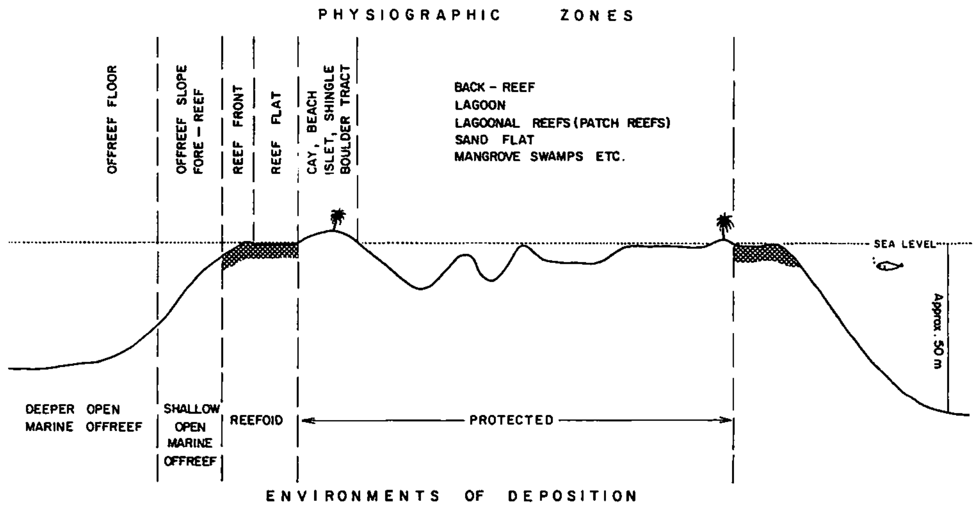


Fig. 7. Areal distribution of environments of deposition and physiographic zones in a Central Luconia buildup.

however, that each environmental unit may comprise several physiographic zones (Fig. 7). Furthermore, the recognition of the various environments is often made difficult by a strong diagenetic overprint on the carbonates (see below).

1) The **protected** environment includes a variety of zones which all occur behind the reef flat. Their extension is primarily controlled by the size of the buildup. In big complexes, the surface covered by protected environments may amount to 80–90 % of the total buildup area. Since the protected area may include such heterogeneous units as supratidal flats, mangroves swamps and lagoons, the sediments deposited exhibit a wide range in texture and grain size. The most common sediment types are carbonate mudstones and wackestones which have been formed in sheltered lagoonal parts. Sediments which have been deposited under restricted marine conditions are characterised by the abundant occurrence of imperforate benthonic Foraminifera. In some cases however, lagoonal deposits may be coarse because the lagoon was connected to the open sea by channels, and strong currents have winnowed away all the fines.

2) The **reefoid** environment is characterised by the occurrence of coral colonies in association with encrusting and branching calcareous algae, encrusting and free-living benthonic Foraminifera, bivalves, gastropods, echinoids etc. The corals form the basis of the community by providing a hard framework within which the remaining organisms can either attach themselves or shelter.

It is a well known fact that the reefoid zone, being the most important element of a buildup complex, may cover only a narrow belt. This may be further reduced by organic and mechanical destruction (e.g. during storms). Moreover, the reef belt may be completely modified by biological and early diagenetic processes such as boring, encrustation, micritisation, internal sedimentation and cementation ('dynamic reef formation' sensu SCHROEDER & ZANKL, 1974). These are the main reasons why a 'genuine' reefoid environment is not only seldom encountered in Central Luconia, but is also rare in other Cainozoic buildup systems (FRIEDMAN, 1979).

3) The **shallow open marine** environment exists either on the seaward slope of the reef flat or on a submerged bank after active reef growth has come to a halt (Fig. 4C1). In a *'offreef'* setting reef-derived debris are mixed with highly diversified, normal marine fauna and encrusting calcareous algae. Shallow marine *bank* sediments lack the reef debris, and, locally, they exhibit abundant calcareous algal balls (rhodolites). In the case of increased subsidence they may cover the entire carbonate complex. The reduction in sedimentation rate is reflected in the relatively high content of clay minerals (up to 10%).

4) The **deeper open marine** environment exists further down slope and seawards of the reef flat ('deeper offreef'; Fig. 7) or on a deeply submerged but still carbonate-producing bank (Fig. 4C2). In practice, there is hardly any distinction between the two settings because both of them lack coarse reef debris. The bulk of the sediment consists of carbonate mud, platy corals, encrusting calcareous algae and a diversified fauna of benthonic and planktonic Foraminifera. Most of the carbonates are highly argillaceous (up to 20% clay minerals).

DIAGENETIC PROCESSES

As in modern reef sediments the bulk of the carbonate sediments of the Luconia buildups was composed of metastable aragonite and Mg-calcite. The changes into stable calcite and dolomite, as encountered today, occurred at an early stage in the diagenetic history under surface-related physico-chemical conditions. This early stabilisation was of utmost importance for the development of secondary porosity. Diagenetic processess which affected the buildups during the burial stage were less abundant and occurred primarily within the argillaceous intervals.

Investigation of textures and geochemistry of the core material suggests the following sequence of diagenetic events (Fig. 8):

1) **Early cementation**

Shortly after deposition the bulk of the sediment was affected by micritisation and early submarine cementation processes such as formation of drusy cement rims, overgrowth cementation on echinid fragments and microcrystalline cement.

2) **Dolomitisation**

This process predominantly affected large parts of the protected and reefoid environments within the buildups. It occurred during build-out (e.g. Cycle IV) and buildup phases, but never during a build-in or a bank situation. Complete dolomitisation often transformed lagoonal mudstones and wackestones into sucrosic dolomites. In most grain-supported sediments, however, dolomitisation was less complete. There, only the muddy matrix was turned into dolomite. In addition, many particles initially composed of Mg-calcite, such as coralline red algae, were transformed into a very fine texture-preserving dolomite fabric.

The textural and geochemical data suggest that dolomitisation occurred intermittently during buildup growth. Dolomite crystals replaced the sediment already rich in Mg-calcite. The additional Mg^{2+} ions required were supplied by fluids which penetrated the sediment via the surface. From geochemical data, such as stable isotope measurements, it cannot be decided whether dolomitisation is the result of refluxing brines with a high Mg/Ca ratio (ADAMS & RHODES, 1960) or of a freshwater/marine water mixing zone ('Dorag' model: RADIOZAMANI, 1973).

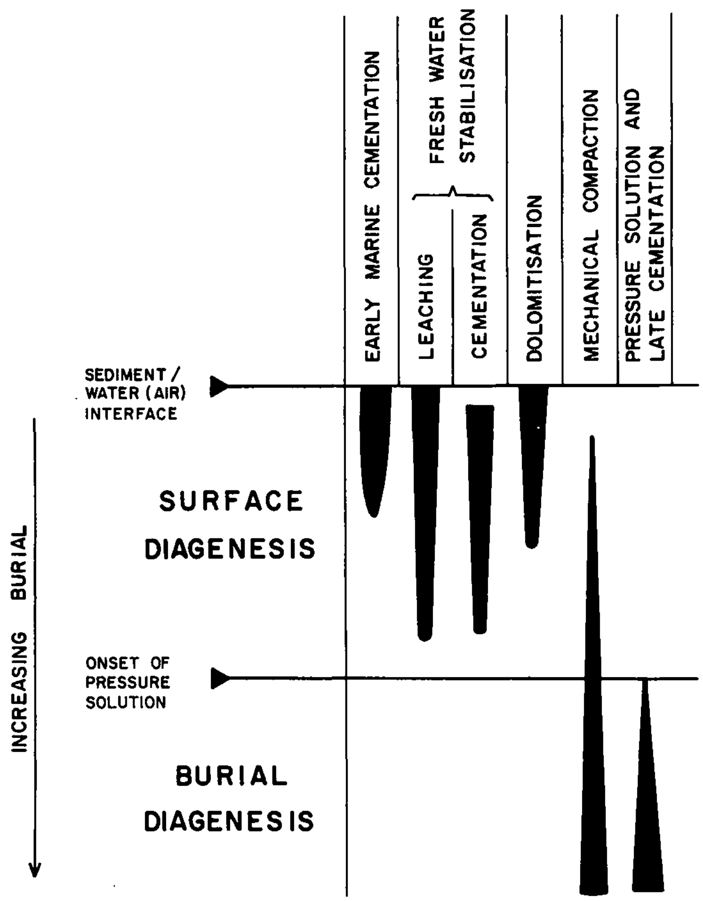


Fig. 8. Diagrammatic representation of major diagenetic events in Central Luconia buildups.

3) Fresh water stabilisation

During periods of emergence fresh water produced by rainfall entered the carbonates to form lenses floating on top of the denser sea water ('GHYBEN-HERZBERG lens'). This caused a fresh water stabilisation of the carbonates comprising dissolution of particles of metastable mineralogy and precipitation of stable calcite into primary and secondary pore space.

In many cases skeletal grains have been leached away to form moulds. In mud-supported sediments dissolution occurred at the surface of the mud-sized crystals leading to a chalkified texture. Simultaneously, stable calcite crystals precipitated into primary and, to a lesser degree, secondary pore space.

Compared with dolomitisation, fresh water stabilisation affected larger portions of most buildups in both vertical and lateral directions. However, its imprint varies greatly amongst the buildups (see below).

4) **Compaction**

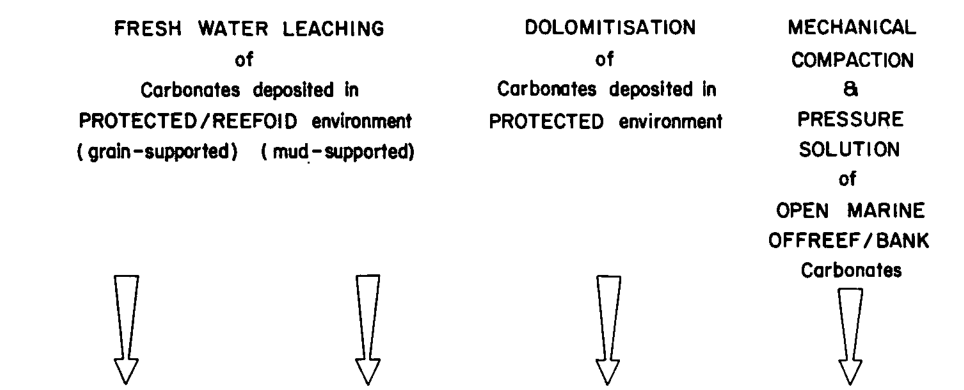
Burial diagnesis comprises primarily mechanical compaction and pressure solution. Both processes are thought to have started at an early stage in burial history, and they have caused a reduction in bulk volume in all carbonate sediments irrespective of the environment of deposition. However, they were most pronounced in the argillaceous limestones deposited under open marine conditions. In these sediments the compressive stresses caused horsetail fabrics and stylolites along which accumulated seams of insoluble residue such as clay minerals and organic matter. As porosity-creating processes such as dolomitisation and fresh water leaching had little or no access to these sediments they were eventually turned into tight limestones.

CARBONATE ROCK TYPES

During the past five years, studies in ancient carbonates have shown that the different rock types, as they appear today, are the result of a characteristic sequence of diagenetic events on a specific facies unit. This is also true of the Central Luconia buildups which basically can be subdivided into four rock types with porosities ranging from 2–40% (Figs. 9, 10) namely:

1) mouldic limestone
2) chalkified limestone
3) sucrosic dolomite
4) tight (argillaceous) limestone

It appears that the processes affected the various depositional units selectively (Fig. 9). The sediments deposited in reefoid and protected environments were preferentially transformed by dolomitisation and fresh water leaching. This is no surprise considering the fact that both porosity-creating processes occurred under very shallow marine or even subaerial conditions.



MOULDIC LIMESTONE	CHALKIFIED LIMESTONE	SUCROSIC DOLOMITE	TIGHT (ARGILLACEOUS) LIMESTONE
Ø = 20 – 40% K = 10 – 400 mD	Ø = 10 – 20% K = 5 – 50 mD	Ø = 15 – 30% K = 10 – 500 mD	Ø = 2 – 8% K ≤ 1 – 5 mD

Fig. 9. General subdivision into carbonate rock types occurring in Central Luconia buildups. Note different ranges in porosity (ϕ) and permeability (K, in millidarcys).

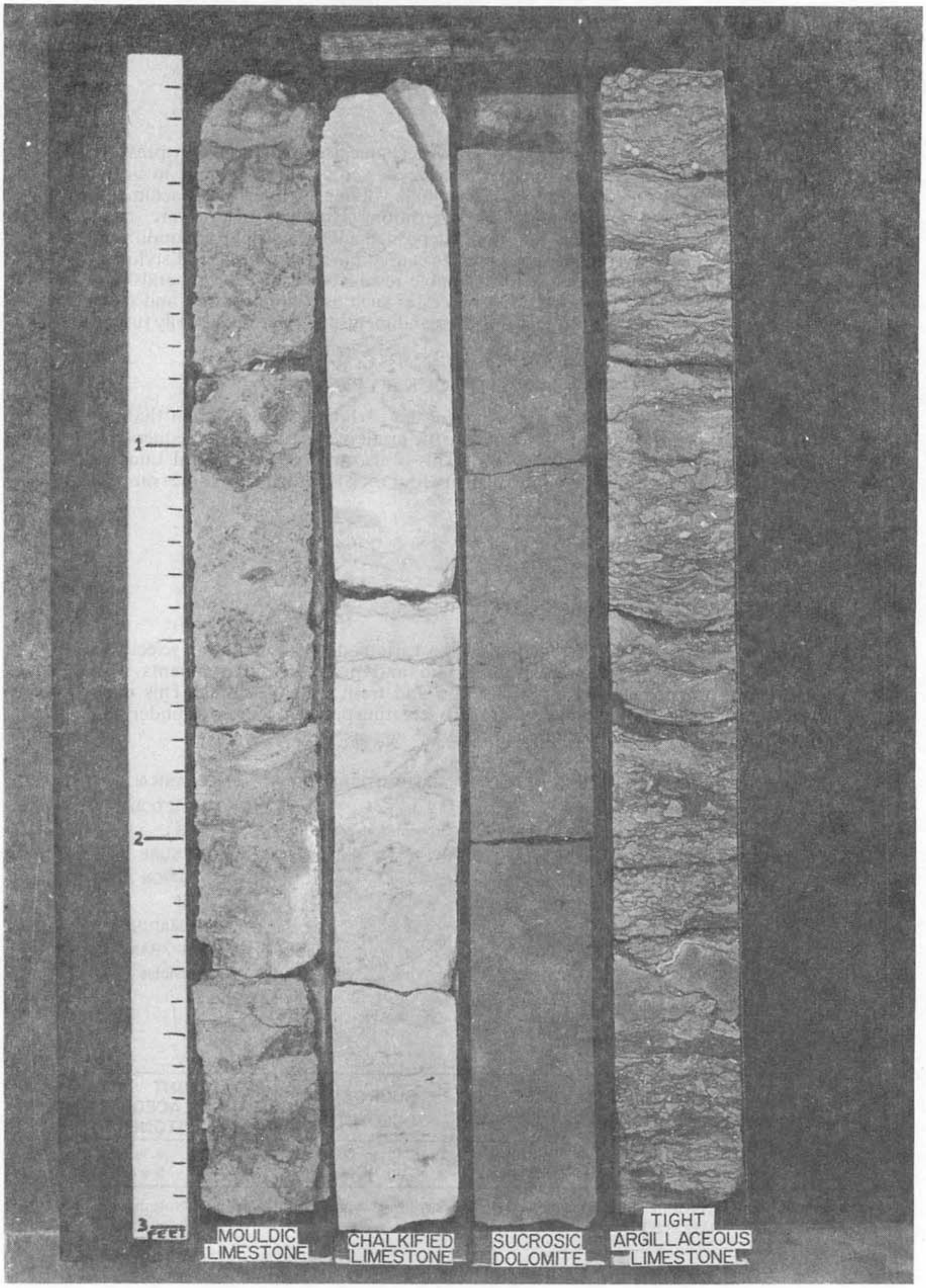


Fig. 10. Selected core intervals of the four main carbonate rock types occurring in Central Luconia buildups.

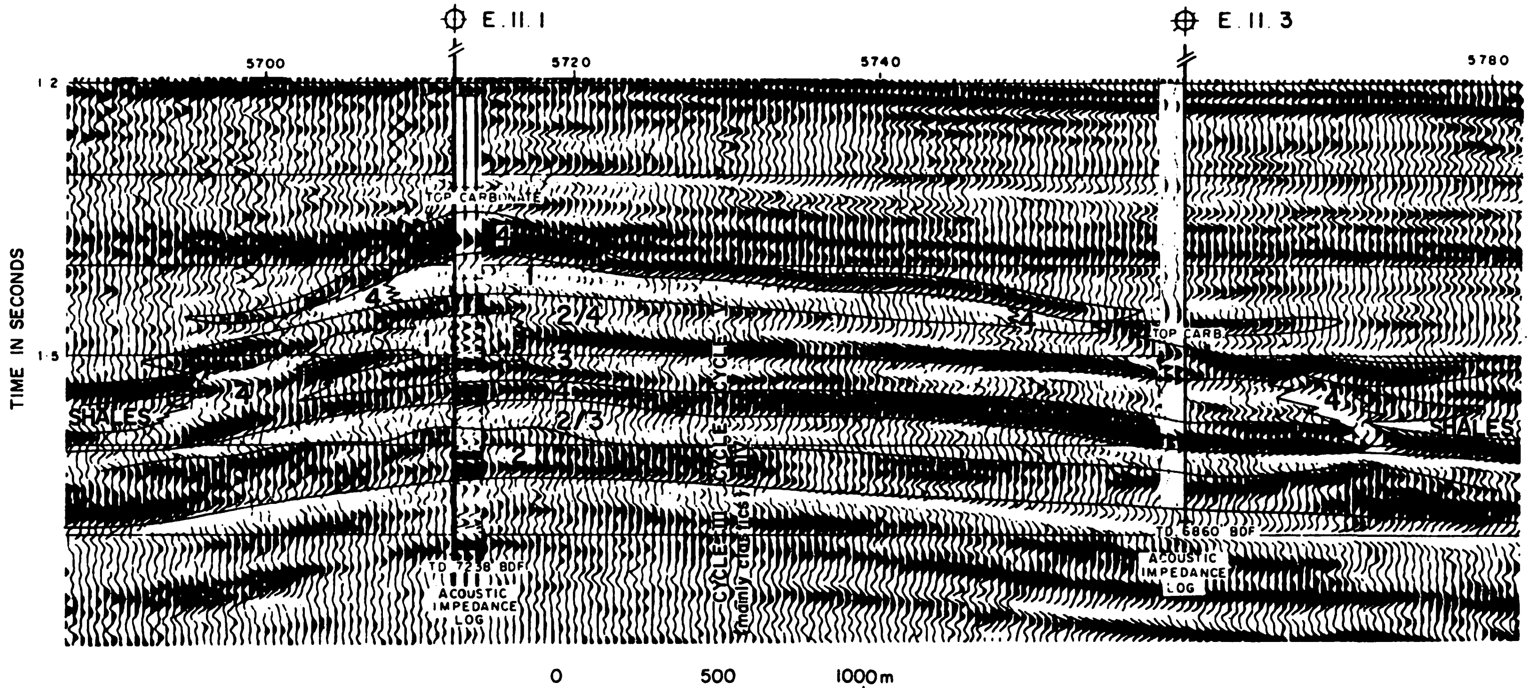


Fig. 11. Distribution of carbonate rock types in E. 11 buildup as interpreted on a migrated impedance section. Note that layering corresponds to alternation of porous and tight intervals. 1 = mouldic limestone; 2 = chalkified limestone; 3 = sucrosic dolomite, 4 = tight (argillaceous) limestone.

The open marine offreef/bank sediments were primarily deposited in deeper normal marine waters and subsequently subjected to porosity-destroying compactional processes. This, of course, would not exclude a priori that these deposits might have come into contact with porosity-creating diagenetic processes at a later stage. In fact, they often underlie porous limestones and dolomites of protected/reefoid origin. However, their reservoir quality was rarely improved, and it is assumed that mechanical compaction had already started at an early stage turning them into low-permeability barriers to subsequent flow of fresh water and dolomitising brines.

As a result, there is a very marked alternation of porous and tight rock types. This frequently leads to a distinct layered appearance of the buildups in seismic sections (Fig. 11).

CONCLUDING REMARKS

In virtually all the buildups drilled so far a similar pattern of environments of deposition, diagenetic processes and resulting rock types has been encountered. However, the effect of the different diagenetic processes varies considerably on a regional scale. In the central area of Central Luconia the buildups were apparently emergent over a considerable period at the end of their growth prior to being covered by Cycle VI clastics. This resulted in fresh water leaching which had such an overriding impact that even the compacted open marine sediments were turned into moderately porous reservoir rocks. In the southeast of Central Luconia, where buildups had already been covered during Cycle V, only short periods of emergence occurred intermittently, and the bulk of good reservoir rock is formed by sucrosic dolomite.

It will be clear from these examples that most of the buildups have to be analysed on their own merits. Realistic reservoir models showing the distribution of the various carbonate rock types must utilise the concept of total rock history which comprises both depositional pattern and diagenetic overprint.

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REFERENCES

ADAMS, J.E. and RHODES, M.L., 1960. Dolomitization by seepage refluction. *Amer. Assoc. Petr. Geol. Bull.*, 44, 1912–1920.

BADIOZAMANI, K., 1973. The Dorag dolomitization model. Application to the Middle Ordovician of Wisconsin. *J. Sed. Petrology*, 43, 965–985.

FRIEDMAN, G., 1977. Recognition of post-Paleozoic reefs: an experience in frustration. *Can. Soc. Petr. Geol. Reservoir*, 4/10, 1–2.

HO KIAM FUI, 1978. Stratigraphic framework for oil exploration is Sarawak. *Geol. Soc. Malaysia Bull.*, 10, 1–13.

MAXWELL, W.G.H., 1968. *Atlas of the Great Barrier Reef.* Elsevier, Amsterdam, 258 pp.

SCHROEDER, J.H. and ZANKL, H., 1974. Dynamic reef formation: a sedimentological concept based on studies of Recent Bermuda and Bahama reefs. *Proc. Second. Int. Coral Reef Symp.*, 2, 413–428.