The Effects of Eustatic Sea Level Change in the Development of Carbonate Reservoir: An Overview

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1. Introduction

There are some major factors that control the variations in stratal patterns and lithofacies distributions within carbonate rocks. They include tectonic subsidence, eustatic change of sea-level, sediments volume, and climate (Sarg, 1988; Moore, 1989; Tucker, 1992, etc.). However, the major control over carbonate sedimentation is the eustatic change of sea-level (Vail & Todd, 1981).

The cyclic changes in global sea level produce reciprocal sedimentations that alternately open

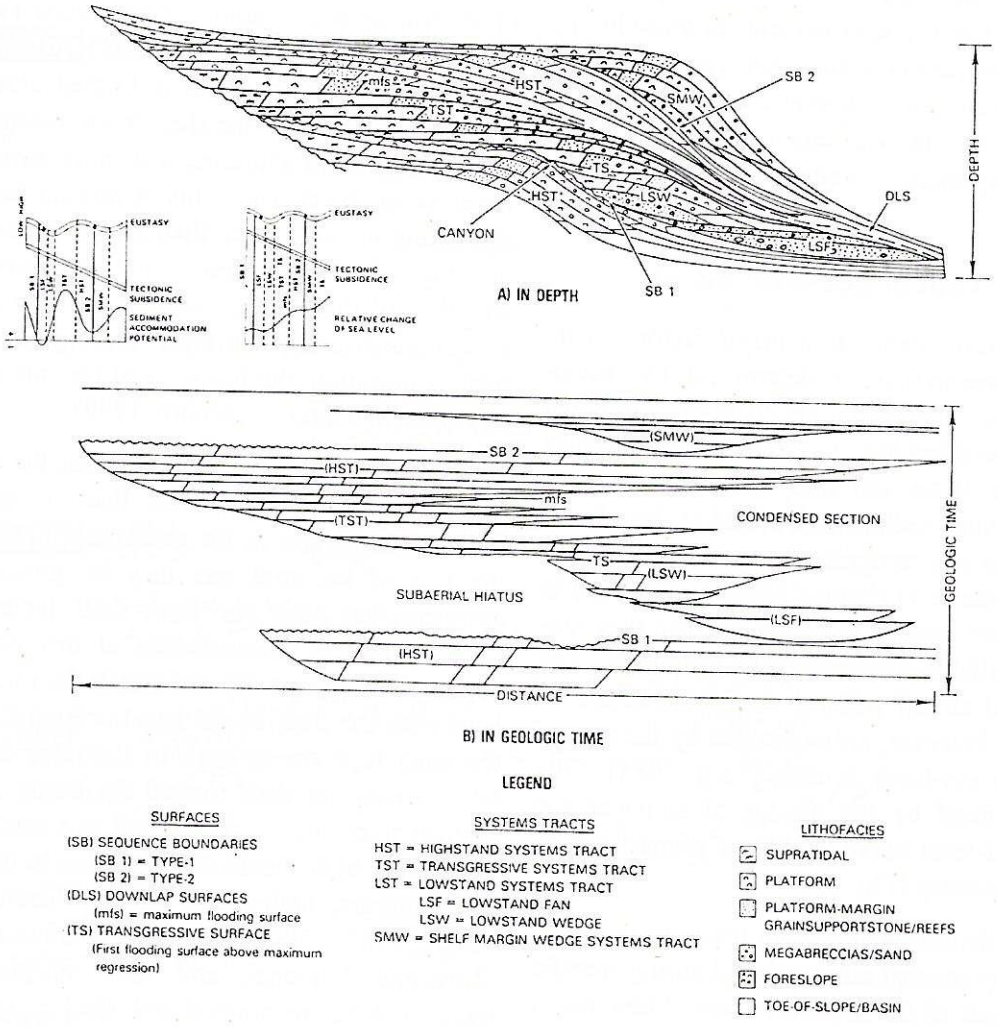


Fig. 1 Summary schematic diagram of carbonate lithofacies distribution in a sequence framework. Stratal patterns are controlled by the rate of relative change of sea level expressed as the change in slope of the eustatic curve. Systems tracts are deposited during specific time intervals of the sea-level curve. A relatively steep platform margin is predicted to have extensive slope front erosion during formation of a type 1 sequence boundary. Debris sheets and allodapic sands are deposited at the toe of slope (lowstand fan- LSF) and in submarine channels. A lowstand wedge (LSW) bank and transgressive-system tracts (TST) onlap the slope and palaeoplatform. The LSW and shelf margin wedge (SMW) are predicted to be more extensive and better developed on low-angle ramps or banks, where there will be abundant area for shallow-water carbonate production. A major transgressive surface (TS) separates the LSW from the TST. Following the time of maximum flooding, the highstand systems tract aggrades and progrades basinward. Te maximum flooding surface (mfs) separates the highstand from the transgressive-system tract (Sarg, 1988).

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and shut off transport of terrigenous clastics across the shelf into the basin. These clastics are highly involved in carbonate deposits development. During high stand of sea level, carbonates are the dominant lithologies that accumulates on the shelf, shelf margin, and in the basin. During succedingly lower stands of sea level, terrigenous clastics progrades across the shelf, and initial clastic sedimentation occurres as they by-passes the slope and accumulates in the basin (Silver, 1983).

Sea-level changes not only controls the carbonate sedimentation, but also controls the thickness and the internal structures of the carbonate rocks. Various depositional environments produce by the sea level changes cause the heterogeneity of carbonae reservoir. The sea level changes are highly related to the carbonate reservoir creation, therefore it is important to understand their relationship.

2. Concept of Sea-level Stands

Global sea-level stand, as a major factor in carbonate sedimentation, is determined by ocean-basin volumes and glacial ice volumes. These two volume parameters are controlled by geotectonics and climate. Rises and falls in sea-level greatly affect carbonate sedimentation, and cycles of sea-level change are recognized on orders of magnitudes. The sea-level changes are very important in sequence stratigraphy concepts because they create the available spaces for the sediments. The depositional stratal patterns and distributions of lithofacies, however, are controlled by the rate of the relative sea-level changes (Sarg, 1988). This expresses itself by the change of slope of the relative sea-level curve, which is primarily controlled by eustasy (Fig. 1)

Particular depositional system tracts in sequence stratigraphy concept are developed during specific time intervals of the sea-level curve. These tracts are defined on the basis of types of bounding surfaces, stratal geometry, and position within the sequence. Thick carbonate sequences are deposited principally in the highstand systems tract, and also in the transgressive systems tract (Sarg, 1988).

3. Transgressive System Tract

When the sea level rise, progradation will occur. Typically, the shelf margin becomes steeper and narrower with time. In this condition onlap patterns will be replaced by toplap patterns. When the sea-level drop, lowstand fan and lowstand wedge will develop seaward. Two types of sequence boundaries develop (types 1 and 2), depending on whether sea-level falls below the shelf break, giving lowstand fans and wedges, or not, when a shelf-margin wedge may form.

Hunt & Tucker (1991) and Hunt (1992) distinguished the two types of geometric stacking patterns that can develop during a transgressive system. The different geometries reflect the ratio of rate of relative sea-level rise to sedimentation rate. When rates of relative sea-level rise are greater than sedimentation, type 1 geometries are developed. During this condition a carbonate ramp is generally established (Wilson, 1975). A transgressive, high-energy shoreline is formed along the innermost margins of the shelf in an instant time. The transgressive shoreline will move across the ramp as sea level rises without leaving behind a significant deposit, other than a thin, high-energy lag (Fig. 2A). Under these conditions, there is no well defined shelf margin, and facies tracts tend to be bathymetrically controlled. During periods of high evaporation, the basin could become density stratified, and euxinic (Moore, 1989).

Type 2 geometries are formed when the rate of relative sea-level rise is less than or equal to sedimentation rates at the shelf margin, although the rate of sea-level rise may be greater than sedimentation rates for inner-shelf facies (Fig. 2B). Carbonate sedimentation at this condition begins to catch up with and match the rate of sea level rise, the shelf builds into the euphotic zone, the inner high energy zone of the ramp is translated across the shelf toward the basin, and the ramp evolves into a rimmed shelf as a result of the higher rate of sediment accumulation in the distal basin margin, high-energy zone (Wilson, 1975; Moore, 1987, 1989). If sea level continues to rise, shorezone, lagoonal, and shelf margin facies tracts will be maintained and stacked vertically through time with no apparent onlap or offlap. This configuration is ideal for the development of barrier-type reef complexes, with patch and pinnacle reefs in the lagoon. Shelf margin relief is potentially the greatest, the basin is generally starved, so there is a high potential for margin-to-basin transport by gravity processes.

4. Highstand System Tract

Highstand sedimentation begins when sedimenta-

tion rates exceed those of relative-sea-level rise for both outer-shelf and inner-shelf facies (Fig. 2C). In this stage, the relative accumulation rates between margin, lagoon, and shore-zone all equal or exceed subsidence, and the lagoon aggrades into the zone of high energy, resulting in the deposition of high energy facies from the shelf margin to the shorezone (Moore, 1989). The emergent platform is commonly the site of extensive meteoric vadose and phreatic diagenesis.

Highstand systems tracts are generally characterized by a relatively thick aggradational-to-progradational geometry. They form widespread platforms, ramps, or prograded banks and have offshore equivalents in isolated platforms. The early highstand is characterized by relatively greater increases in accommodation and by water conditions not necessarily conducive to high-carbonate productivity. Later, as global sea level begins to fall, the rate of increase of accommodation is reduced on the shelf (Fig. 2D). Shelf waters become better circulated and more stable, resulting in higher carbonate productivity. Mounded aggradation to oblique progradation at the platform or bank margin characterizes the late highstand systems tract.

Highstand carbonate systems tracts appear to undergo two fundamentally different depositional histories. These histories are characterized by significant differences in micrite content and / or submarine cement at the platform or bank margin, which can be related to the rates of accumulation. These two depositional styles are termed 'keep up' and 'catch-up' carbonate systems.

A 'keep-up' carbonate system tract displays a relatively rapid rate of accumulation and is able to keep up with relative rises in sea level. At the platform margin, the 'keep-up' carbonates consist of grain-rich, mud-poor parasequences with small amounts of early submarine cement (Sarg, 1988). This system is probably good as a reservoir because of its bulk rock volume and the relatively small amount of mud within the parasequences.

The catch-up carbonate system, which displays a relatively slow rate of accumulation, is characterized at the platform margin by extensive, early submarine cementation, and it may contain abundant mud-rich parasequences. (Sarg, 1988). Although its bulk rock volume is good for a reservoir, the mud-rich parasequences may cause fluid barriers during the hydrocarbon recovery.

5. Lowstand System Tract

Sea level falls are much more rapid than sea level rises (Vail et al., 1977). Rarely can carbonate production keep pace which, in turn, results in stranded progradational depositional patterns at succeeding lower sea level stands within the basin (Silver, 1983). During the relative sea level fall, the shelf becomes emergent, undergoes karstification, and a new, very narrow shelf is established on the slope of the previous shelf margin (Fig. 2D; Moore, 1989). In this lowstand system tract, little carbonate sediment is produced, and the adjacent basin is carbonate starved (Moore et al., 1976;

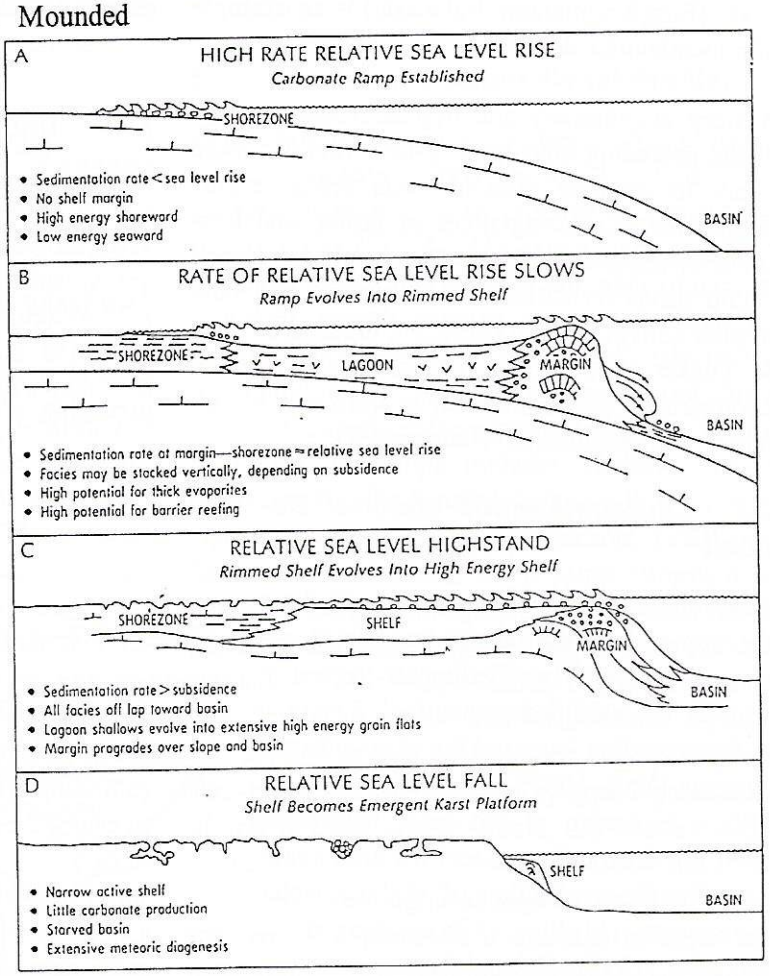


Fig. 2 Summary diagram showing the general response of shallow marine carbonate sedimentation during the high (A) and low (B) rate relative sea level rise, during the relative sea level highstand (C), and relative sea level fall (D) (Moore, 1989).

James, 1979).

Carbonate systems of the relative sea-level fall are characterized by three genetically different types of sediment generated during falling and lowstands of relative sea level: allochthonous material and autochthonous material.

5.1 *Allochthonous Material Deposit*

The allochthonous debris derived from erosion of the slope front. Important carbonate marine debris flows have been described as irregular patches with linear trends below major shelf margins and around perimeters of offshore banks. They occur as sheet-like masses tens of meters thick or spread in patches many kilometres out into basins beneath the slopes of carbonate shelf margins (Wilson, 1980). The deposits consist of calciclastic sediment transported mechanically from the preceding highstand (Sarg, 1988; Hunt & Tucker, 1993). Calcareous turbidite found in the Bengalon River (East Kalimantan, Indonesia) is an example of allochthonous deposit.

A steep accretionary and bypass/erosional slope of the preceding highstand system tract are more likely to produce allochthonous megabreccias (slope wedges) during times of falling and lowstand of relative sea level. The megabreccia and slump sheets formations are influenced by catastrophic collapse of the preceding highstand (Hunt & Tucker, 1993). Big megabreccias could be kilometres in dimension such as Kombeng Mountain in East Kalimantan (Indonesia 2).

5.2 *Autochthonous Material Deposit*

Autochthonous materials are deposited on the upper slope during the interpreted eustatic lowstand. These sediments formed in situ on the modified/unmodified foreslope to the preceding lowstand fan of siliciclastic systems (Vail, 1987; Van Wagoner et al., 1990). Lowering of sea level below the shelf top drastically reduces the area available for the production of shallow water carbonates (Mullins, 1983; Droxler & Schlager, 1985). Critical factors in determining the volume of an autochthonous wedge are the angle and profile of the slope. As mud-dominated foreslopes tend to have lower gradients than grain-supported foreslopes (Kenter, 1990), the potential sediment production area available during a lowstand will be significantly greater upon mud-dominated than grain-supported slopes.

6. Shelf Margin Wedge System Tract

A shelf margin wedge is deposited during the eustatic lowstand. As relative sea level rises, the wedge onlaps onto and over the platform. The shelf margin wedges are predicted to be more extensive and better developed on low-angle ramps or banks, where there will be abundant area for shallow-water carbonate production (Sarg, 1988).

When sea-level rise equals to carbonate sedimentation rate (type 2 sea level fall: Tucker et al., 1993), aggradation of the inner-ramp sand bodies can take place. Such a sand body is analogous to a shelf-margin wedge, developed on siliciclastic shelves during this type of sea-level fall, when the position of sea level does not go below the shelf break (Van Wagoner et al., 1988, 1990).

7. Unconformity and Associated Processes

7.1 *Type 1 Sequence Boundary*

Two major processes occur during the formation of a type 1 sequence boundary, when sea level falls at a rate rapid enough to drop below the preceding platform / bank margin. These pro-

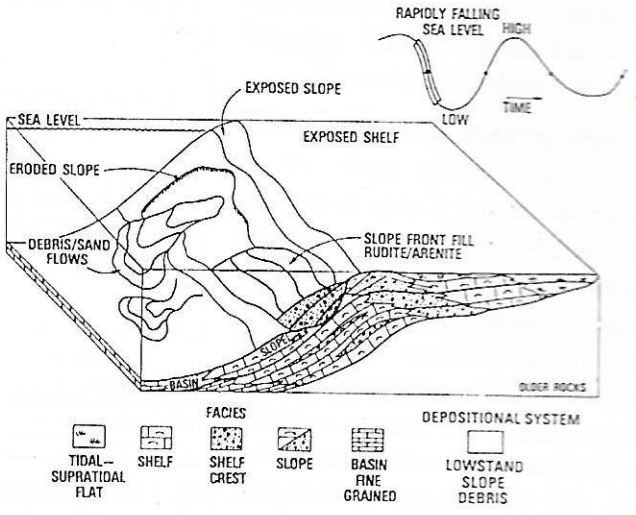


Fig. 3 Schematic diagram illustrating a rapid fall in sea level interpreted to occur at a type 1 sequence boundary (Sarg, 1988)

cesses are slope front erosion and seaward movement of the regional freshwater meteoric lens (Fig. 3). During the formation of a type 1 sequence boundary,
significant slope front erosion can occur and results in substantial loss of plat-form/bank margin and upper-slope material. The result is downslope depo-sition of carbonate mega-breccias and traction or density current deposition of carbonate sands. The erosion can be local or regional in extent.
The second major process that is interpreted to occur during formation of a type 1 sequence boundary is regional migration of the freshwater lens in a basin-ward or seaward direction. Regional diagenetic events affecting large portions of the carbonate highstand facies tracts will be associated with this meteoric water lens. The degree to which the lens extends down into the carbonate section is related to the magnitude and rate of sea-level fall as well as to the length of time that sea level remains below the platform / bank margin. This will affect the degree of meteoric and mixing diagenesis in each carbonate sequence.

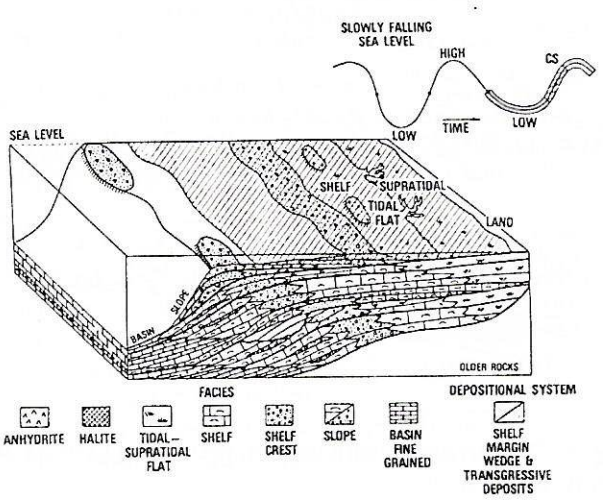


Fig. 4 Schematic diagram showing a slow fall in sea level interpreted to occur at a type 2 sequence boundary (Sarg, 1988).

7.2 Type 2 Sequence Boundary

The processes and deposition associated with a type 2 sequence boundary are different from those of the type 1 sequence boundary. During the formation of a type 2 sequence boundary, sea level is interpreted to fall to a position at or just below the bank margin, and the inner-platform area is exposed (Fig. 4). The outer-platform and platform margin areas may experience brief sub-aerial exposure. Generally the dominant meteoric effect will be in the inner platform. These, meteoric diagenetic processes will be similar to the effects interpreted to occur during a small scale type 1 eustatic fall. These effects include dissolution of grains, especially unstable aragonite and high - Mg calcite; precipi-tation of minor amounts of vadose and phreatic cement; and mixing - zone dolomitization. Hypersaline dolomitization may be initiated during formation of a type 2 sequence boundary. In contrast to the type 1 sequence boundary, sea level is interpreted to begin rising within a relatively short time and to floodback over the outer-platform area. Deposition of a platform/bank margin wedge will commence at or below the underlying platform margin and onlap in a landward direction. In contrast to the occurrence of erosion, in type 1 sequence boundaries, slope front erosion does not appear to be a major process associated with type 2 sequence boundaries.

8. Carbonate Depositional Profiles

Hydrocarbon accumulation were oftenly found within carbonate ramps, developed in type 1 geometry condition of transgressive and highstand system tracts (Fig. 5). The ramps vary widely in thickness from a few to many hundreds of meters, and their growth patterns range from aggradational to progradational. These carbonate ramps were built away from positive areas and down gentle regional palaeoslopes (Wilson, 1975). Reservoir on ramps includes shallow water banks, such as the Pennsylvanian shallow phylloid algal mounds (Baars and Stevenson, 1982) that formed isolated banks on a ramp subjected to repeated transgression and regression. Downslope buildup reservoirs on ramps include the Mississippian of Texas (Ahr & Ross, 1982). Transgressive deep-ramp, slope and basin facies deposits can develop as seal rocks (Read, 1985). Rimmed shelves, which are produced by type 2 geometries of transgresive system tracts, are shallow platforms.
The outer wave-agitated edge of the platform is marked by a pronounced increase in slope into deep water. They have a semicontinuous to continuous rim or barrier along the shelf margin that restricts circulation and wave action to form a low-energy lagoon to landward (Ginsburg and James, 1974). The reservoirs in the shelf-edge

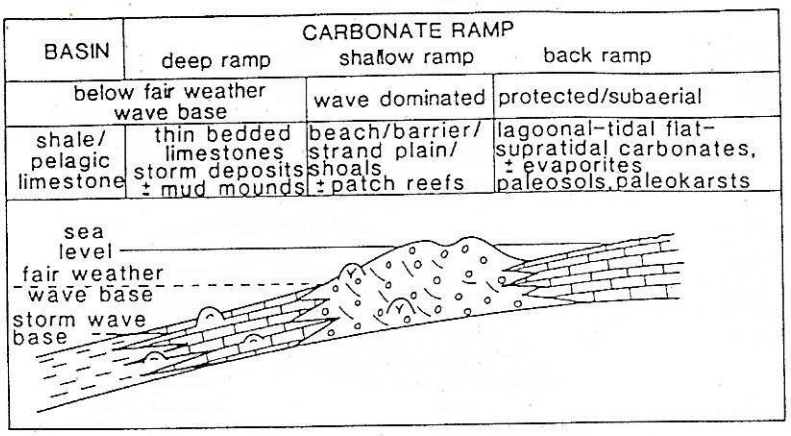


Fig. 5. The carbonate ramp depositional model (Tucker and Wight 1990).

complex of rimmed shelves include the Cretaceous Stuart City trend, Gulf Coast (Griffith, et al., 1969; Cook, 1979), and the Permian Townsend - Kemnitz field (Malek-Aslani, 1970). Pinnacle reefs located on gentle slopes seaward of the rim are common reservoirs in the Silurian of the Michigan basin (Mesolella et al., 1974) and Intisar D field, Palaeocene, Libya (Brady, et al., 1980).

The highstand system tract condition can produce isolated platform carbonate deposits. The isolated shallow water platforms offshore from continental shelves commonly are tens to hundreds of kilometres wide. These platforms are located above rifted continental or transitional crust and surrounded by deep water (commonly several hundred meters and even exceeding 4 km). Some of these platforms have been termed atolls, especially where they have a deeper lagoon and elevated reefal rim. These atolls, however, are different from true oceanic atolls which rise from volcanic foundations on oceanic crust (Read, 1985). Giant fields in isolated platforms include the upper Paleozoic Horseshoe Atoll, Texas, where the reservoirs occur in the raised rim (Vest, 1970) and the Tamabra periplatform debris of the Poza Rica trend (Enos, 1977).

Where subsidence or sea level rise exceeds upbuilding, ramps, rimmed shelves and isolated platforms may undergo incipient or complete drowning. The drowning occurs where rate of relative sea level rise exceeds vertical accumulation rate and the platform is submerged below the euphotic zone, terminating rapid production and accumulation of carbonate by photosynthetic organism (Kendall and Schlager, 1981; Schlager 1981). The euphotic zone in the open ocean may extend down to 100 m, but may be as little as 30 m in basins where fine-grained carbonate or clastics are abundant. Reservoirs on drowned ramps include Devonian Ondaga bioherms, New York (Kissling and Polase, 1982).

Near shore deposits, such as supratidal deposits that often are subjected to minor fluctuations in sea level, resulting in cyclic sequences of evaporites and fine-grained carbonates. These sequences usually are thin, have a restricted areal distribution, and are strongly stratified. Although porosity in individual beds may be bery high, permeability rarely exceeds a fracation of a millidarcy (Jardine, et al. 1977).

9. Conclusion

Cycles of sea-level changes are very important for carbonate reservoir creation. During the relative high sea-level, spaces for carbonate sediments are accommodated. Low level sea stands are important in secondary porosity development by the meteoric water leaching. Therefore, the carbonate reservoir creation needs multitude cycles of sea-level changes.

The ratio of sea level rise rate to sedimentation rate in transgressive system tract controls the geometric stacking patterns. Carbonate ramps reservoir are generally established in type 1 geometries of the transgressive system tracts, when the rates of the relative sea level rise are greater than the sedimentation rate. In type 2 geometries of transgressive system tracts, when the rate of relative sea level rise is less than, or equal to sedimentation rate, the ramps carbonate evolve into rimmed shelves. Platforms, ramps, or prograded banks carbonate reservoir are formed within thick aggradational-to-progradational geometry of highstand system tracts. Karstification, which increase the secondary porosity, occur during the lowstand system tract, together with allochthonous and autochthonous material deposit.

Further study about the associated depositional environments such as deep marine clastic deposits, lagoon, and sabkha are needed. These deposits can act as cap rocks of the reservoir and also cause the heterogeneity.

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