

Genesis of siderite in the Upper Miocene offshore Sarawak: constraints on pore fluid chemistry and diagenetic history

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Abstract: The cored sequence of the upper Miocene reservoir of Baram field, offshore Sarawak, consists of cyclic quartz-rich sandstones and mudstones interpreted to have been deposited during storm events in shallow to midshelf water depths. The sequence is intercalated with minor tidal intervals. Authigenic siderite is common in sandstones throughout the sequence. Siderite cemented zones are up to 2 m thick. The cement is found in five different sandstone types: laminated sandstone, massive sandstone, bioturbated sandstone, heterogeneous sandstone, and in association with mud intraclasts and shell fragments horizon. Whole-rock XRD gives estimate of 20 to 40% of siderite in bioturbated and heterogeneous sandstones and 10 to 25% for the others.

Petrographic analysis reveals that diagenetic siderite occurs in four different crystal morphologies: rhombic, "bundle", acicular and cylindrical. The rhombic siderite, which commonly occurs in bioturbated and heterogeneous sandstone, has the most adverse effect on the poroperm characteristics of the sandstones, reducing porosity to 10% and permeability to 2 md.

$\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ plots show groupings based on morphology. Bundled and acicular siderite show ranges of $\delta^{13}\text{C}_{\text{PDB}}$ of -15 to -25 and $\delta^{18}\text{O}_{\text{PDB}}$ of 0 to -1. The late Miocene seawater $\delta^{18}\text{O}$ estimate for the region is -0.8 PDB. This would give the bundle and acicular siderite a temperature of formation range of 25° to 30°C. The $\delta^{18}\text{O}$ values are compatible with precipitation at shallow burial depth from unaltered seawater; $\delta^{13}\text{C}$ values are inherited from sulfate reduction horizons.

Rhombic siderite has ranges of $\delta^{13}\text{C}_{\text{PDB}}$ of -5 to -15 and $\delta^{18}\text{O}_{\text{PDB}}$ of -3 to -4. The range of $\delta^{13}\text{C}$ indicates that siderite diagenesis occurred within both the shallow sulfate reduction zone and at deeper levels within the zone of decarboxylation. The maximum temperature of formation here is 38° to 48°C at depths of about -450 to -800 m, assuming precipitation from unaltered seawater. These results are consistent with those of ICP geochemical values which indicate that the rhombic siderite are Mg-rich relative to the acicular and bundle types.

The cylindrical siderite shows isotope values between these two extremes.

These results reveal the pathways of early pore water evolution and diagenetic history of the Upper Miocene succession of Baram Field.

INTRODUCTION

Petrographic studies carried out on core samples of the Upper Cycle V (Late Miocene) sandstones of Baram Field, in the Baram Delta offshore of Sarawak, have identified significant occurrence of siderite cement. The siderite cemented sandstone intervals can be up to 2 m thick, and are associated with laminated sandstone, bioturbated sandstone and siltstone, massive coarse sandstone and heterogeneous sandstone. Diagenetic siderite occurs in four different crystal morphologies: rhombic, acicular, 'bundle' and cylindrical shape.

Locally, the occurrence of this diagenetic siderite has strongly affected the reservoir quality of the sandstones within the Baram Field. In extreme cases, the cementation reduces the porosity to 10% and permeability to 2 md from the average porosity 15% to 25% and permeability of 10 to 200 md.

Carbon and oxygen stable isotope analyses were made on these siderite samples. The residual solution were analyzed for chemical elements using the ICP technique. This paper discusses of the possible fluid chemistry conditions for the formation of the different types of siderite and the textural evidence for their time of formation. It will also briefly describe the effect of siderite cementation on the cored reservoir intervals.

GEOLOGICAL SETTING

The Baram Delta Province is located in the northern part of Sarawak (Fig. 1). It extends north-eastward through Brunei and into the southern part of Sabah (Scherer, 1980; James, 1984; Johnson *et al.*, 1989). The province is separated from the more stable Central Luconia Province to the

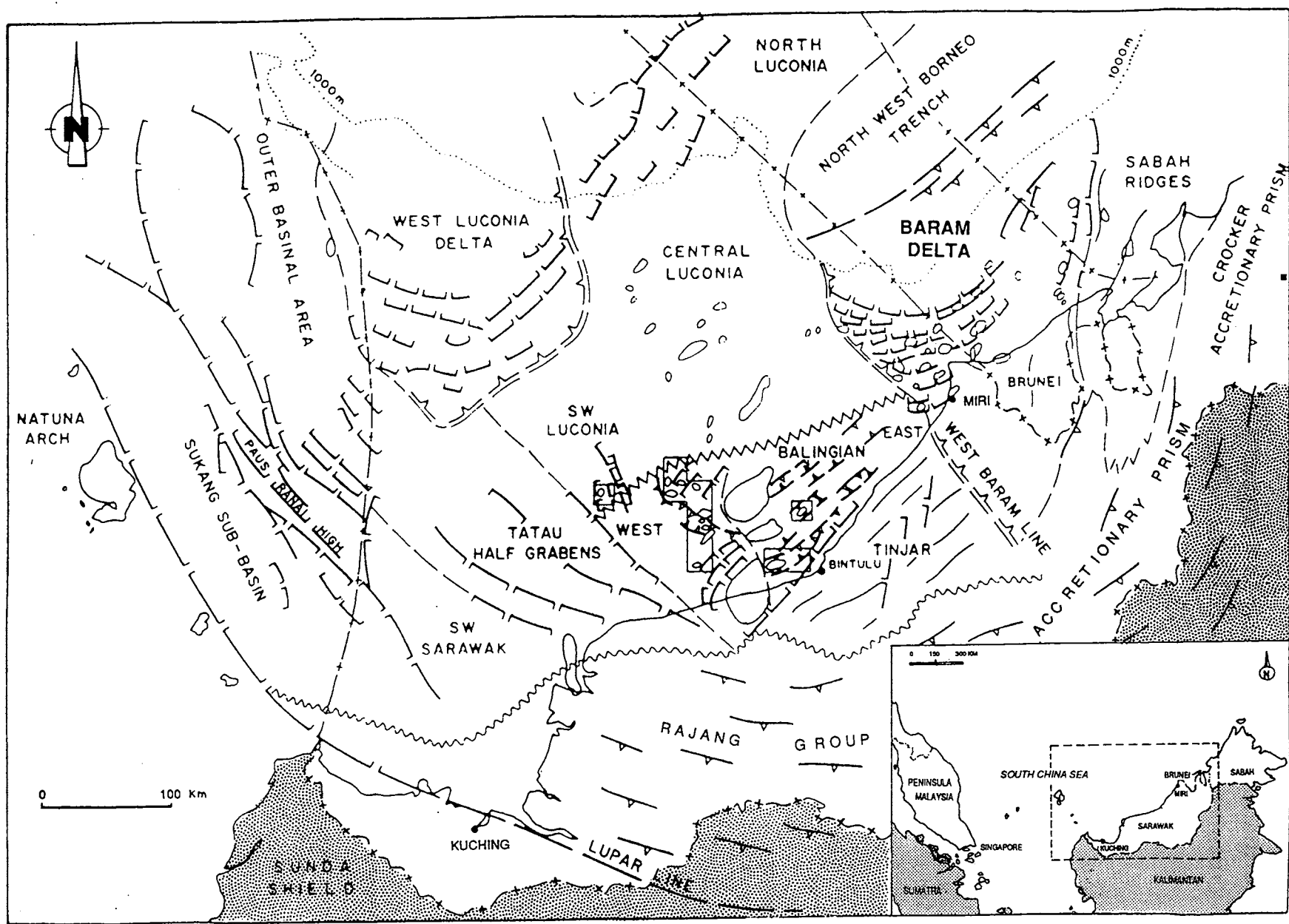


Figure 1. Structural geological map of Baram Delta and its surroundings.

southwest by the major NW-SE trending West Baram hinge-line (Fig. 1), which is a possible transform fault (James, 1984). This Tertiary basin developed in Late Eocene times after orogenic uplift and folding of Cretaceous to Eocene sediments. These sediments which acted as hinterland and the source area for the delta system now lies towards the south-east of the province.

The Baram Delta Province has been classified as a basin peripheral to a continental fragment. Its relatively low geothermal gradient ($28^{\circ}\text{C km}^{-1}$) (Wan Ismail, 1990) suggests that the basin is formed on 'cold' oceanic crust, within a setting similar to the Niger Delta (Hutchison, 1984, 1986).

Baram Field itself is a moderate-sized field located about 30 km offshore, north of Miri town, within the deltaic province (Fig. 2).

STRATIGRAPHIC FRAMEWORK

Eight major sedimentary cycles separated by rapid and widespread transgression (Ho, 1978), are recognised in the Baram Delta. A cycle is recognised on two criteria; i) the base coincides with a transgression, ii) the sequence in a cycle is regressive (Fig. 3).

From the Late Eocene to the Early Miocene, Cycles I to IV were deposited under deep marine conditions, resulting in a sequence of up to 2,286 m (7,500 ft) thick of marls, silts and shales (Rijks, 1981). Cycles V to VII, which are best developed within the Baram Delta, were deposited from the Middle Miocene onwards, comprising a thick (6,046–9,144 m/20,000–30,000 ft) succession of coastal to coastal-fluviomarine sands and shales, deposited in a wave influenced deltaic environment (Johnson *et al.*, 1989).

The cored intervals of Wells BA-8 and BA-16 of Baram Field belong to the Upper Cycle V (Late Miocene) section of the deltaic sequence. The stratigraphic logs for the cored intervals are shown in Figures. 4 (a) and (b) and 5 (a) and (b). These cores record eleven lithofacies grouped into two environmentally significant facies associations:

- i) Swaley Cross-stratified Facies Association. This consist of seven different facies, which are swaley cross-stratified (SCS) sandstone, hummocky cross-stratified (HCS) sandstone, sandy heterolithic facies, bioturbated mudstone, silty laminated mudstone, ripple cross laminated sandstone and massive coarse sandstone. The sharp-based SCS sandstone, commonly with basal mudstone intraclasts horizon and occasionally with bioturbated top, is interpreted to represent storm and wave influenced deposits of a prograding shoreface during rapid relative sea-level fall. All the

other facies are the sub-product of this progradation and storm/wave events.

- ii) Heterogeneous Mud-draped Facies Association. Three different facies are present; flaser bedded sandstone, heterogeneous medium/fine grained sandstone, fining-upward, laminated shelly sandstone and associated mudstone. The mud drapes, flaser beds and coarser grained sand suggest deposition within a tidally influenced environment, possibly somewhere within the inner shelf.

SIDERITE GEOCHEMISTRY

Siderite ($\text{Fe}^{+2}\text{CO}_3$, ferrous carbonate) has a trigonal crystal structure. It forms two solid solution series with magnesite (MgCO_3), and with rhodochrosite (MnCO_3) of the calcite group. It is yellowish brown, or brown to dark brown. In thin section it is colourless to yellowish. Siderite usually occur as rhombohedral crystals; however tablets, prisms and scalenohedra forms have also been observed (Deer *et al.*, 1962).

A considerable number of studies have been carried out on the geochemistry and origin of siderite concretions (Curtis *et al.*, 1975; Coleman and Raiswell, 1981; Gautier, 1982; Curtis and Coleman, 1986; Curtis *et al.*, 1986). The cored sandstone samples of the Upper Miocene Baram Field display, in most cases, the occurrence of siderite as disseminated crystal cement; only in one sample does siderite occur as rim cement around a calcitic concretion (Sample SID8-P28).

Siderite is a common constituent of many ancient marine sediments. It has been found to occur as cement in concretionary nodules and beds in mudstones or as disseminated crystal cement in sandstones. Theoretical geochemical requirements for the formation and stabilisation of siderite suggest that the mineral should be less common in marine sediments than what was observed (Sellwood, 1971). Curtis (1967) highlighted the common association of pyrite with marine sediments and of siderite with non-marine sediments. By comparing laboratory and field data, Curtis and Spears (1968) concluded that ferric compounds are the only stable solid species in normal marine waters even at low Eh values. They noted that siderite is unlikely to be stable in any depositional water body; ferrous compounds (pyrite, pyrrhotite, magnetite, siderite, chamosite) are only stable beneath the sediment/water interface.

More recent work on carbon isotopic composition of siderites indicate that carbon the isotope characteristics are largely controlled by biogenic carbon dioxide produced during diagenesis and is not indicative of the depositional environment of

the sediments (Fritz *et al.*, 1971; Curtis, 1977; Coleman, 1985; Pye *et al.*, 1990).

Mozley (1989), Mozley and Carothers (1992) summed up the significant usefulness of siderite as an indicator of fluid composition present during its precipitation:-

- 1) Siderite has no unstable polymorphs; thus under normal diagenetic conditions siderite does not undergo recrystallization and reequilibration.
- 2) Siderite forms under fairly restricted chemical conditions. Precipitation of siderite only occur

under low oxidation potentials together with high bicarbonate and very low sulfide concentrations.

- 3) The carbon and oxygen isotope compositions of siderite can be used to determine carbon sources and the origin or temperature of water during siderite formation, respectively.
- 4) Siderite is usually highly variable in composition due to substitution of Fe^{+2} by Mg, Mn and Ca. These elemental composition reflect the chemistry of the waters from which they precipitated.

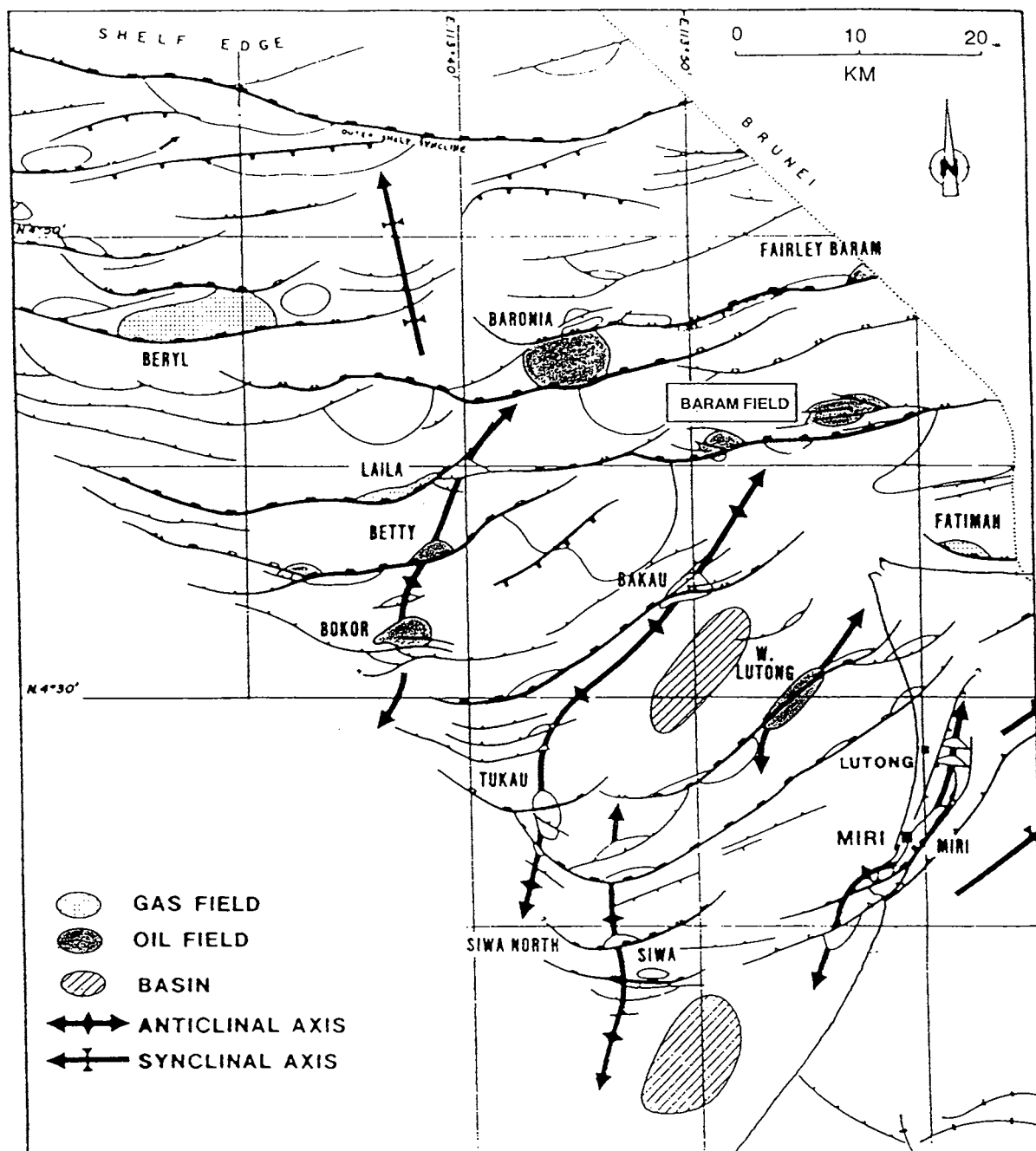


Figure 2. Structural and oilfield map of Baram Delta, showing the location of Baram field (modified from Johnson *et al.*, 1989).

ANALYTICAL METHODS

A total of 22 siderite cemented sandstone samples were analyzed. Fracture surfaces of small chips of these samples were mounted on aluminium stubs. These were then gold-coated and examined in a Philips scanning electron microscope in the secondary electron (SE) mode. X-ray powder diffraction results confirmed the presence of siderite and XRD result indicate the presence of up to 40% siderite in some samples. Selected samples were impregnated with epoxy resin for polished thin section preparation. The thin sections were carbon coated and examined initially with a transmitted light microscope, then later analyzed in the scanning electron microscope using the backscattered electron (BSE) mode.

For carbon and oxygen isotopic analysis, 16 samples were first plasma cleaned to remove organic carbon contaminants, then reacted with 100% phosphoric acid in a vacuum to release CO₂ from the siderite. Siderite is the only carbonate phase in all of these samples, except one (Sample SID8-P29). The gas produced was analyzed on a V.G. SIRA Series-II mass-spectrometer. The raw data were corrected for isotopic interferences and instrumental effects in the normal way (Craig,

1965). The residual solution were analyzed for the carbonate phase chemistry using the ICP technique.

RESULTS

Petrography

Four different siderite crystal morphologies were recognised under light microscopy and SEM: rhombic-, acicular-, 'bundle'- and cylindrical-type (Fig. 6). The identification of these crystals as siderites were confirmed by X-ray powder diffraction results. The rhombic type is dominant, followed by the acicular and 'bundle' types. The cylindrical form is an intermediate, minor phase observed only in three samples.

Two cementation styles are displayed here. Rhombic-type siderite usually occur as pore-filling cement, which affected the reservoir quality adversely. The acicular- and cylindrical-type siderite exhibited both pore-filling and grain-coating cement, while the bundle-type is exclusively a grain-coating type cement.

The stratigraphic occurrence of the different types of siderite is shown in Figs. 7a, b, 8 a, b. Table 1 summarizes the characteristics and facies association of the siderites. The occurrence of the

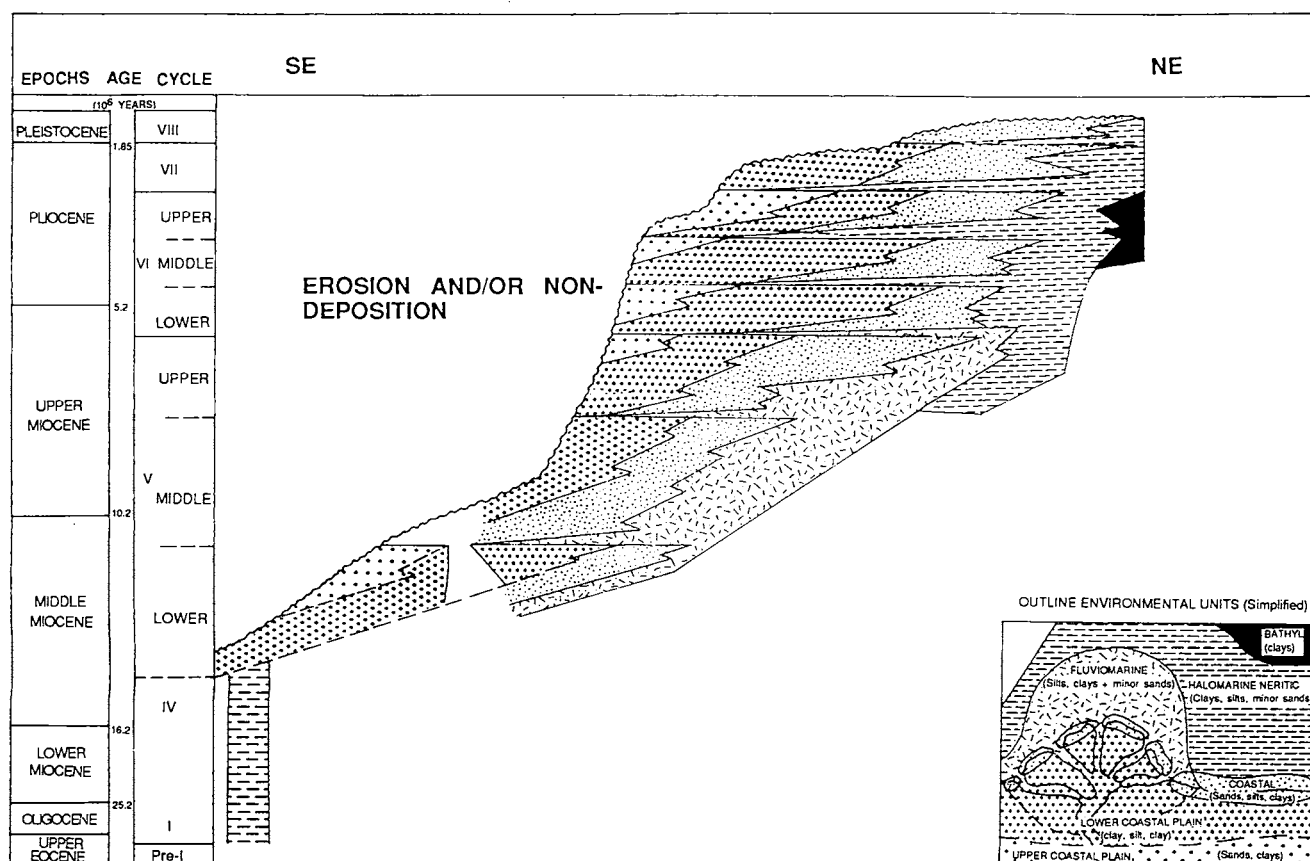


Figure 3. General stratigraphic cross-section across Baram Delta (modified from Ho, 1978).

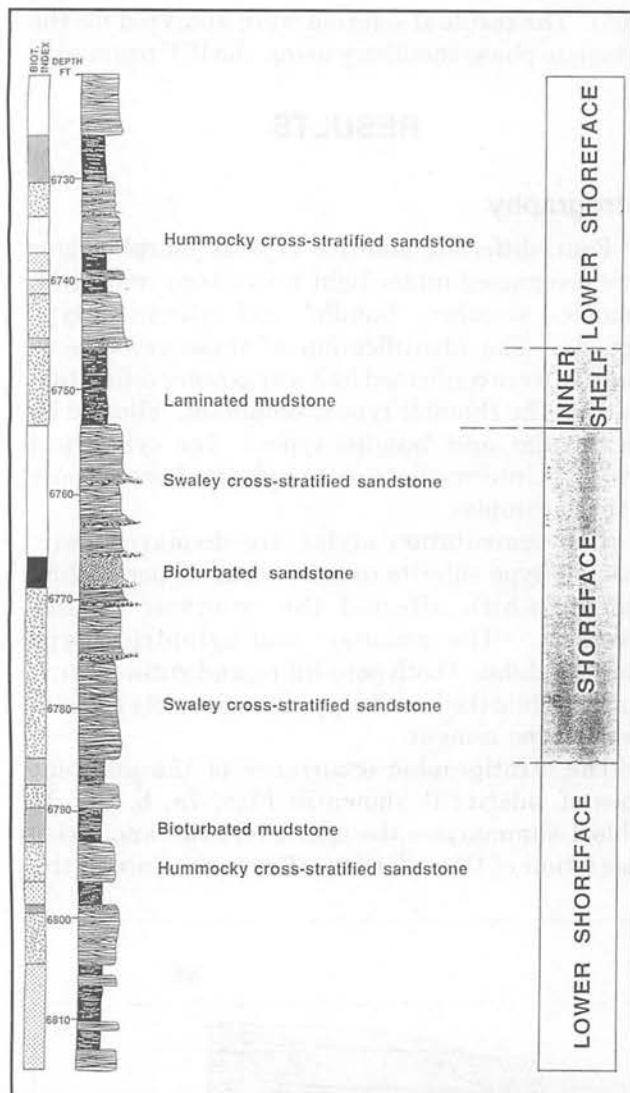


Figure 4A. Stratigraphic log for the cored intervals of Well 21-8-68: Depths 6,720–6,820 ft.

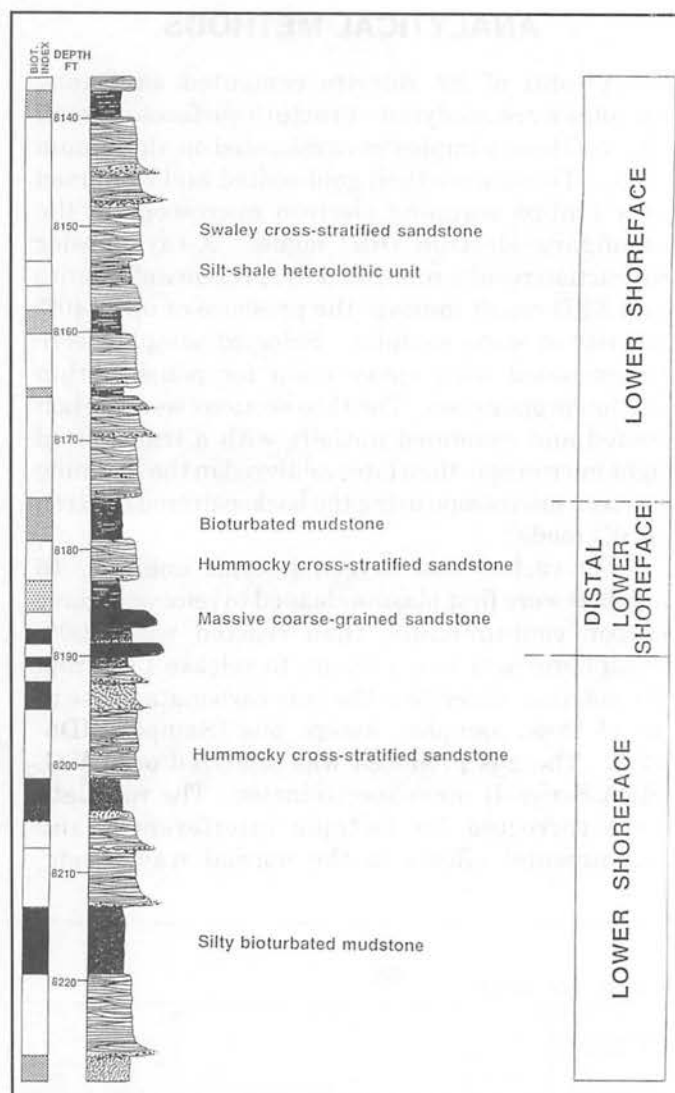


Figure 4B. Stratigraphic log for the cored intervals of Well 21-8-68: Depths 8,130–8,230 ft.

Table 1. Carbon and oxygen isotope values and chemical data for the siderite samples analyses.

Sample	Siderite Type	$\delta^{13}\text{C}_{\text{PDB}}$	$\delta^{18}\text{O}_{\text{PDB}}$	Fe (ppm)	Mg (ppm)	Ca (ppm)	Mn (ppm)
SID2-8-3	Acicular	-16.66	-0.429	31539.34	4130.55	8548.57	872.088
SID3-8-P74	Rhombic	-3.24	-2.74	36067.67	13199.05	4403.79	1031.72
SID4-8-7	Rhombic	-3.91	-2.94	44827.16	15240.52	5309.78	1268.12
SID5-8-P67	Rhombic	-1.73	-4.04	52607.37	12746.82	139.91	1065.53
SID6-8-9	Cylindrical	-5.84	-0.41	29684.47	4453.01	1317.41	394.412
SID7-8-P65	Rhombic	-2.44	-4.17	48563.43	10698.29	2700.16	993.14
SID8-8-P51	Acicular	-21.39	-0.12	45209.17	4130.55	8525.69	872.09
SID10-8-P29	Acicular	-20.83	-0.85	66765.56	6670.08	30667.82	3833.59
SID11-8-P23	Acicular	-17.44	-2.29	27484.52	3998.61	1782.94	1311.21
SID12-8-19	Acicular	-21.06	-0.49	18579.33	2286.65	806.88	450.99
SID13-8-P8	Rhombic	-14.43	-3.06	34666.25	6497.5	2537.92	1525.83
SID14-16-5	Cylindrical	-10.86	-1.8	48982.48	5109.87	3870.32	1486.78
SID15-16-6	Rhombic	-9.15	-4.15	99165	16020.97	5457.42	2045.64
SID17-16-9	Cylindrical	-9.19	-2.03	19399.01	4366.42	1919.67	810.82
SID18-16-17	Rhombic	-13.19	-3.77	43343.05	7569.89	3723.63	1404.45
SID-19-16-26	Rhombic	-9.25	-3.22	55947.63	6584.52	3316.3	1205.93

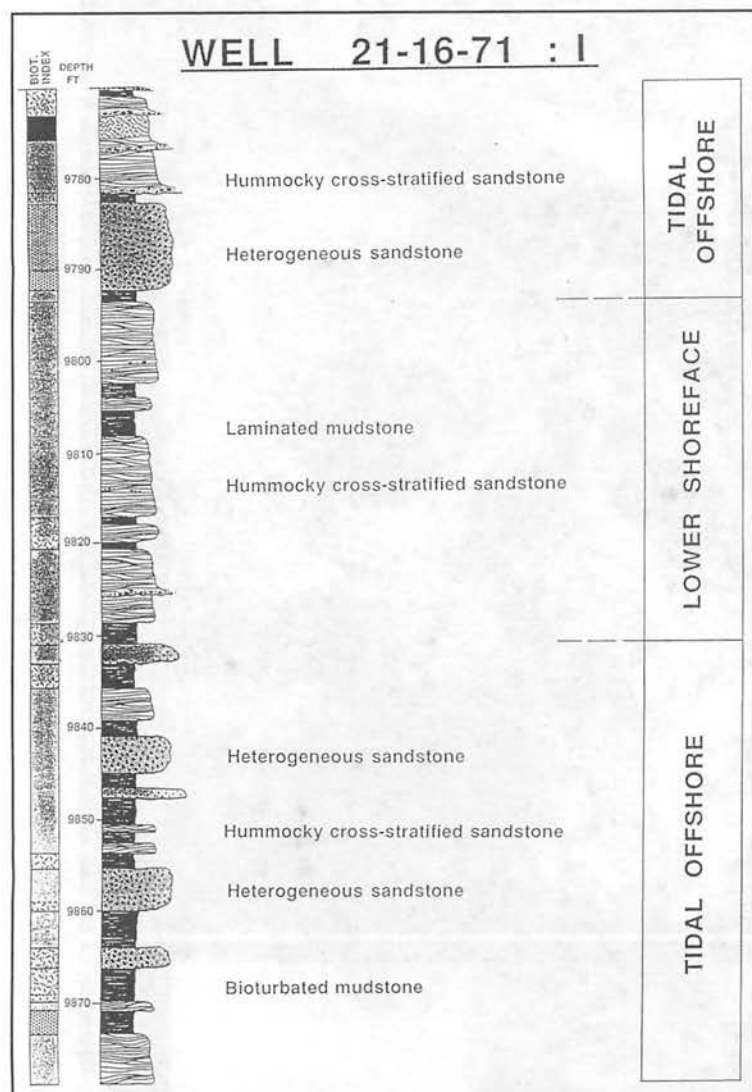


Figure 5A. Stratigraphic log for the cored intervals of Well 21-16-71: Depths 9,770–9,880 ft.

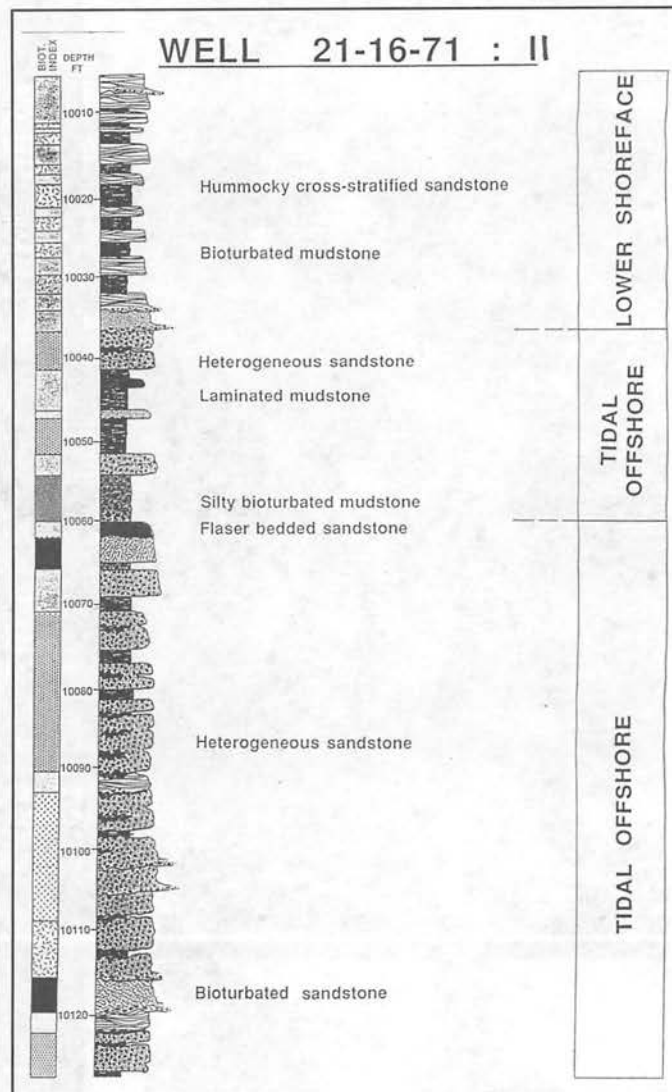


Figure 5B. Stratigraphic log for the cored intervals of Well 21-16-71: Depths 10,010–10,130 ft.

different types of siderite within the heterogeneous sandstone of well 21-16-71 (Depth 9,782–9,794 ft) (Fig. 8a) represents a typical vertical organisation/positioning of the siderites in most sandstone units. Rhombic-type siderite is commonly found at the basal to the middle part of a sandstone bed. Acicular- and 'bundle'-type usually occur in the middle to the top part of sandstone beds or in thin sandstone layers; the cylindrical-type occur at intermediate positions between the two dominant types.

Siderite geochemistry

Rhombic-type siderite show $\delta^{13}\text{C}$ range of -5 to -15 PDB and $\delta^{18}\text{O}$ range of -3 to -4 PDB (Fig. 9, Table 1). The acicular- and 'bundle'-type siderite plot within the same field; $\delta^{13}\text{C}$ range from -15 to -25 PDB while $\delta^{18}\text{O}$ values range from 0 to -1 PDB. The cylindrical-type siderite show intermediate values of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. The most striking feature

here is the distinct grouping of the different morphological types of siderite.

The same grouping of siderite morphologies is again apparent in plots of covariation of molar Mg/Fe , Ca/Fe and Mn/Fe ratios versus $\delta^{13}\text{C}$ (Figs. 10, 11, 12). The rhombic-type siderites are Mg-rich relative to the acicular and bundle types (Fe-rich). The very low Ca/Fe values for all the siderite (Fig. 11) could be suggesting minimum influence of primary biogenic carbonates during siderite precipitation. The sample contaminated with calcite concretion is also easily identifiable, showing anomalously high Ca/Fe .

DISCUSSION

Elemental composition

The elemental composition of siderite is influenced by the concentrations of Fe^{2+} , Mg^{2+} and

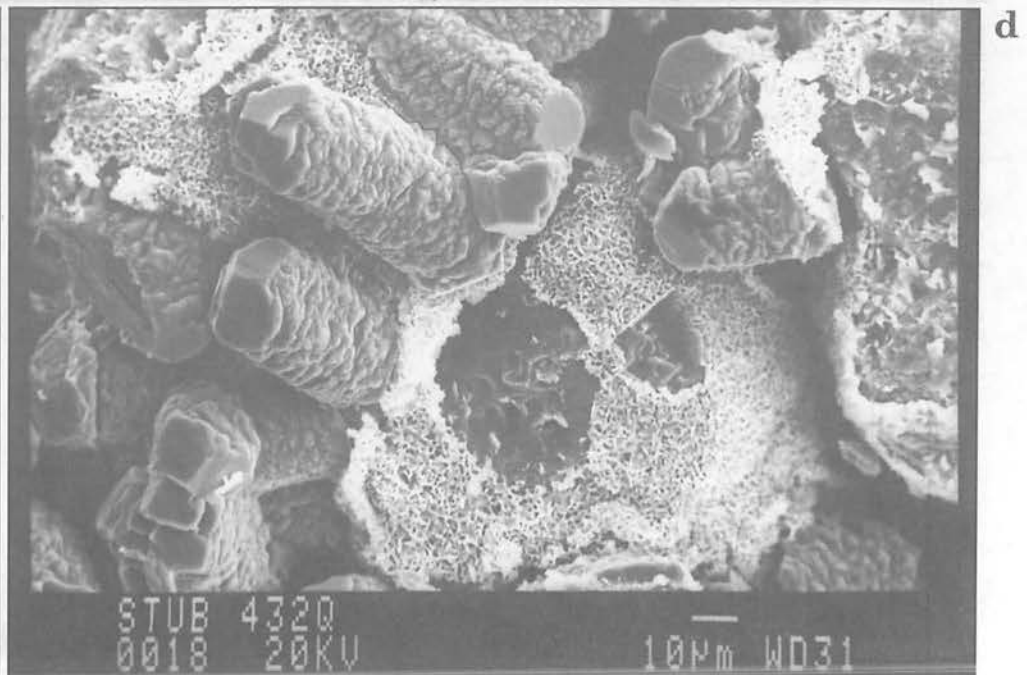
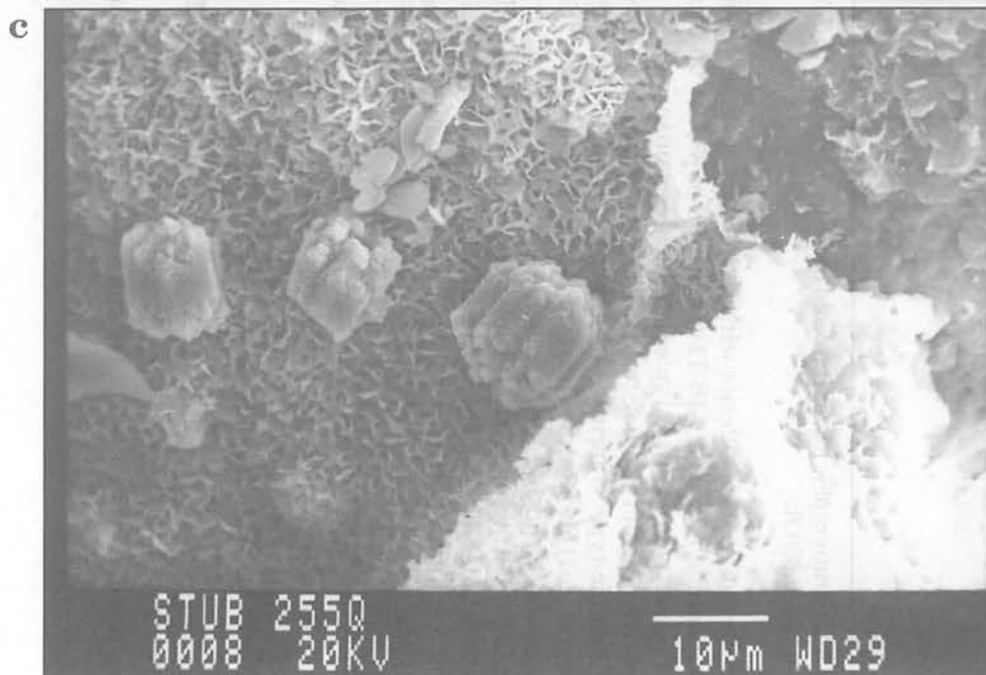
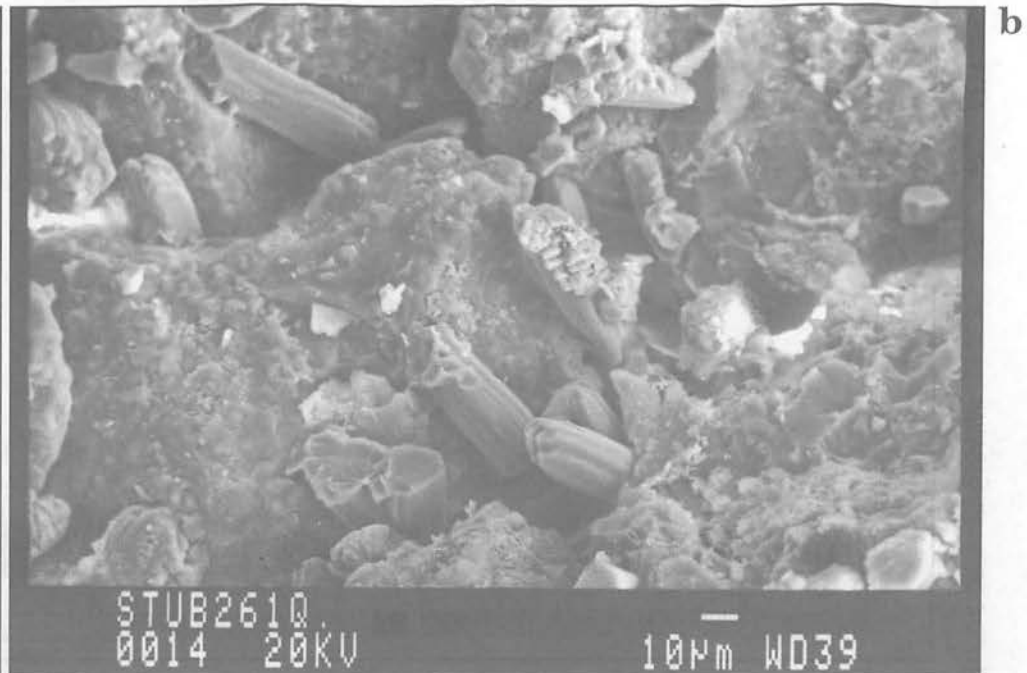
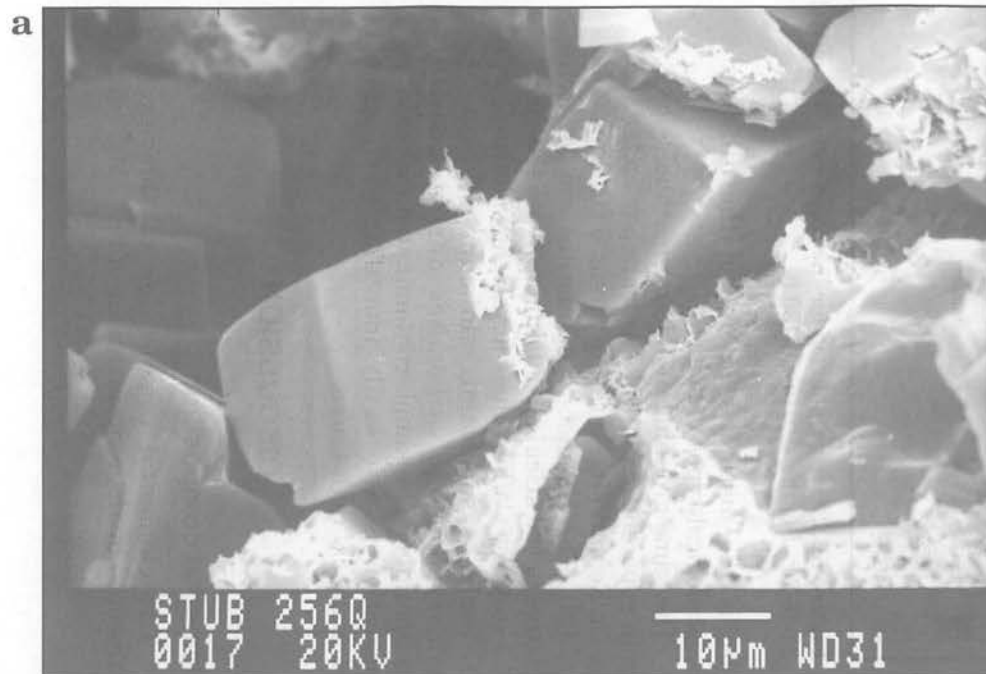


Figure 6. SEM view of the four different crystal morphologies of siderite of Baram Field; a) Rhombic; b) Acicular; c) 'Bundle'; d) Cylindrical-type.

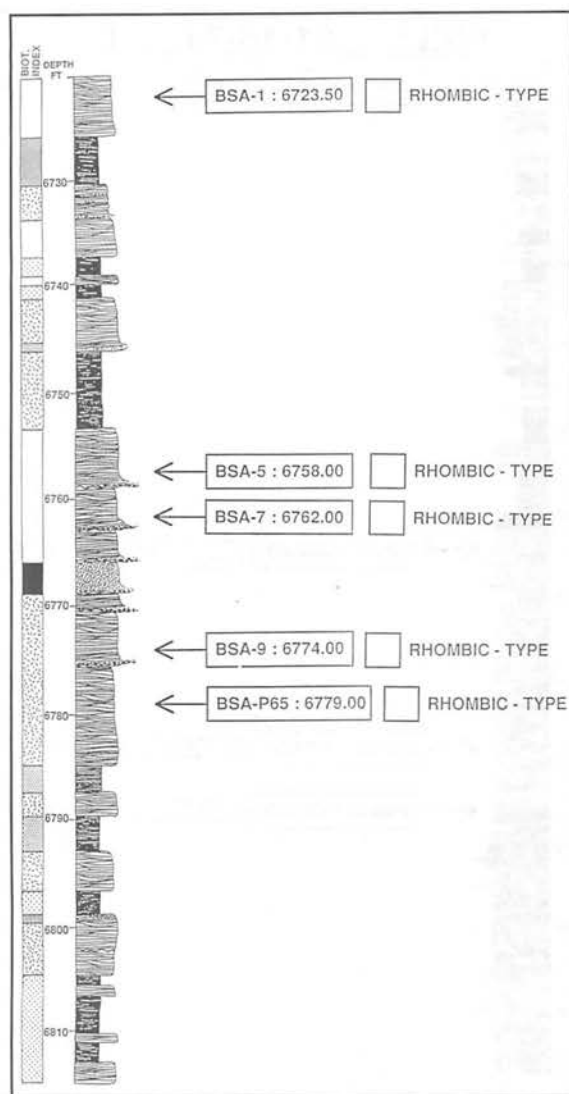


Figure 7A. Stratigraphic occurrence of siderite in Well 21-8-68: Depths 6,720–6,820 ft.

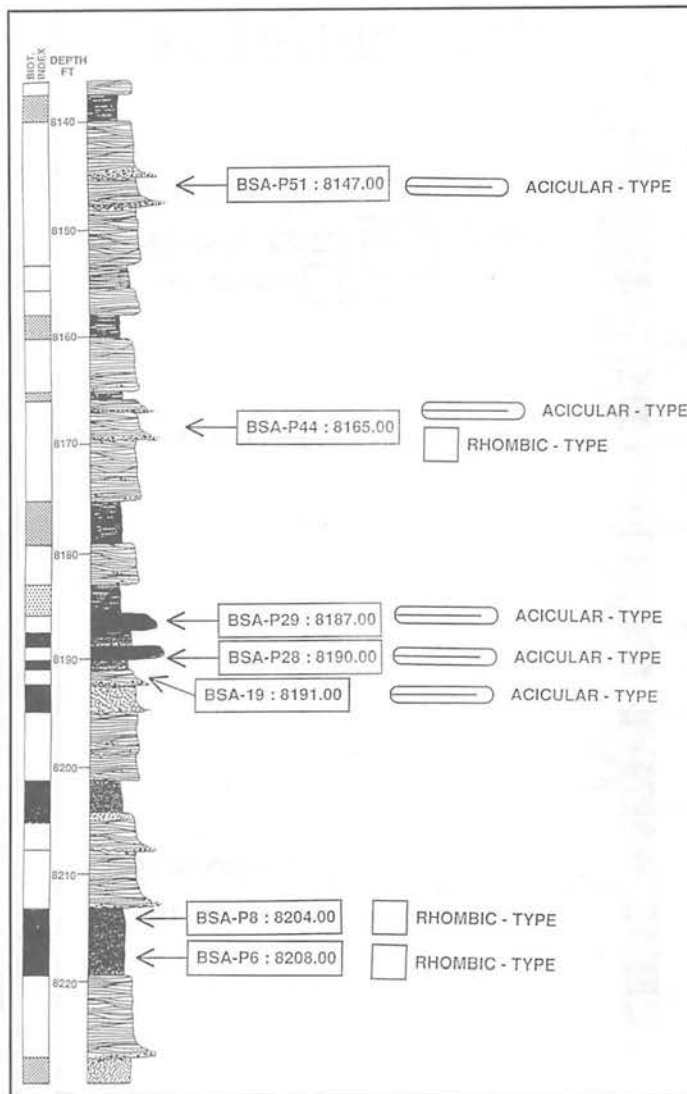


Figure 7B. Stratigraphic occurrence of siderite in Well 21-8-68: Depths 8,130–8,230 ft.

Ca^{2+} of the pore water from which it precipitates (Matsumoto and Ijima 1981; Curtis and Coleman 1986; Mozley, 1989a). Early Fe-rich and late Mg-rich siderite has been reported by several authors (Curtis and Coleman 1986; Curtis *et al.*, 1986; Mozley and Carothers, 1992). The increase in Mg/Fe ratio in solution can occur by precipitation of siderite in a closed system (Curtis and Coleman, 1986). This suggests that Fe-rich acicular and 'bundle' type have precipitated earlier, and later Mg-rich rhombic siderite precipitated in Fe-depleted pore waters in a closed to semi-closed system. This paragenetic sequence is further supported by the evidence of the observation of the precipitation of rhombic-type siderite around an earlier acicular-type siderite (Fig. 13).

$\delta^{18}\text{O}$ values

Oxygen isotope composition of carbonate minerals depends principally on the isotope

composition of the water from which precipitation occurred and on the temperature of precipitation. Provided one of these variables is known, or can be assumed, the other can be estimated. Modern seawater shows a relatively narrow range of $\delta^{18}\text{O}$ values from -1 to $+1\%$ with respect to SMOW.

The acicular and 'bundle' type, Fe-rich siderites have $\delta^{18}\text{O}$ values close to equilibrium with sea water (0 to -1 PDB). These siderites may have been precipitated very early and close to the water sediment interface. On the other hand, the negative $\delta^{18}\text{O}$ for Mg-rich rhombic siderite suggests precipitation from a more evolved pore water composition and/or at higher temperature resulting from precipitation at deeper levels.

The average geothermal gradient for Baram Delta is $28.6^\circ\text{C}/\text{km}$ (Wan Ismail, 1988; Hutchison 1984). The Late Miocene seawater $\delta^{18}\text{O}$ estimate for the region is -0.8 PDB (Savin *et al.*, 1975). Based on these values, the temperatures of

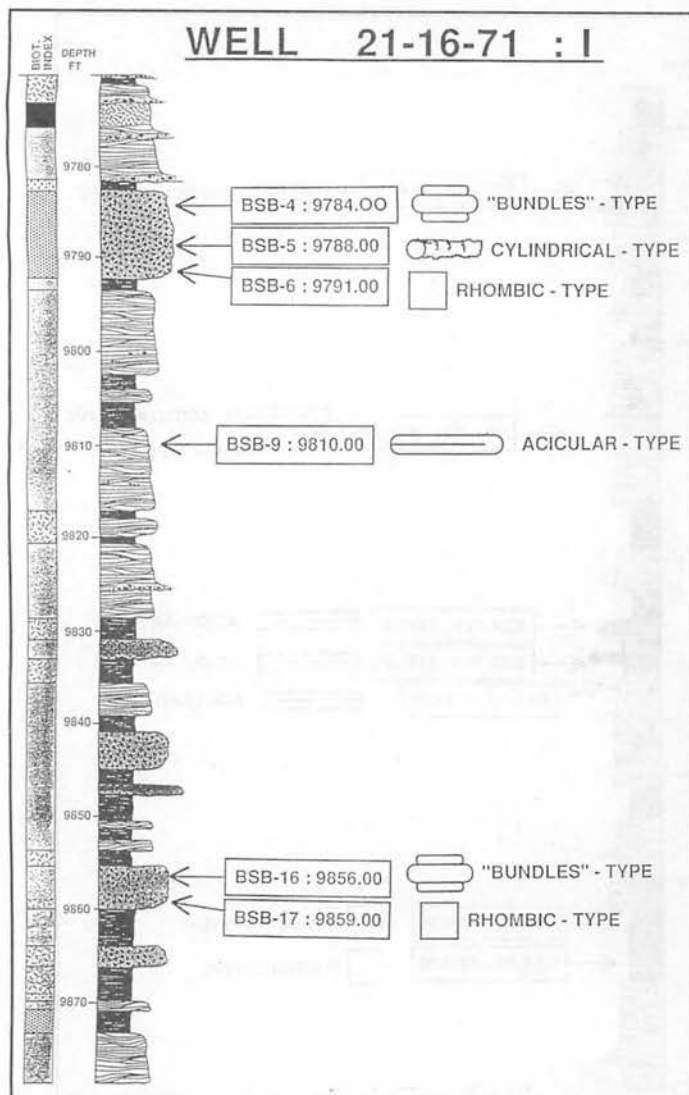


Figure 8A. Stratigraphic occurrence of siderite in Well 21-16-71: Depths 9,770–9,880 ft.

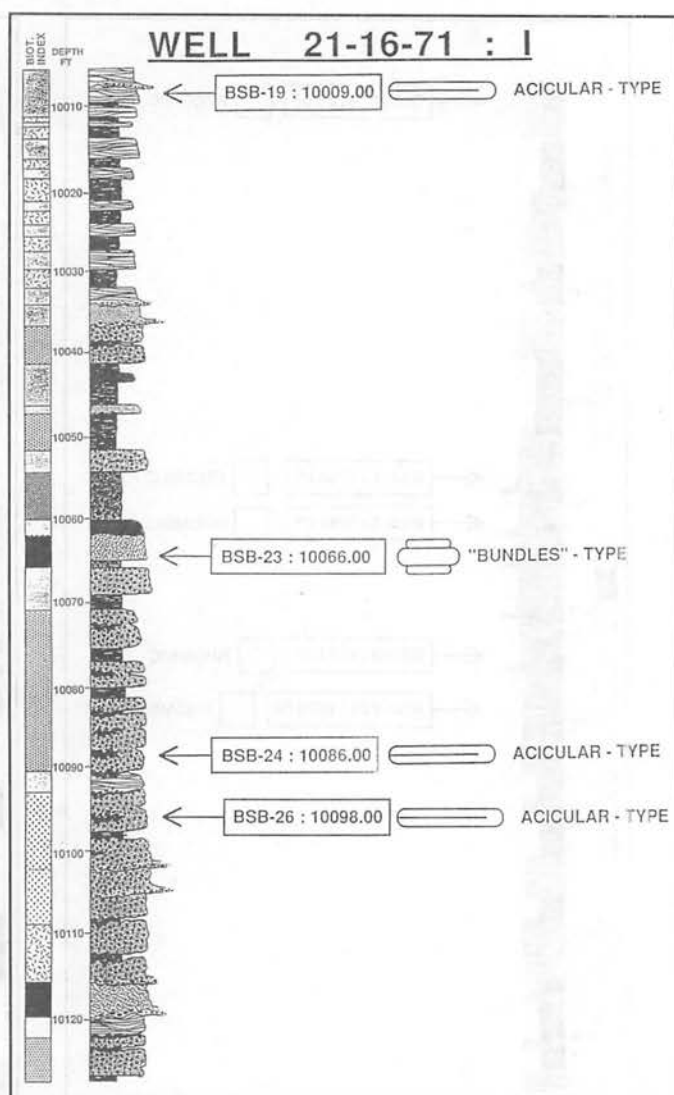


Figure 8B. Stratigraphic occurrence of siderite in Well 21-16-71: Depths 10,010–10,130 ft.

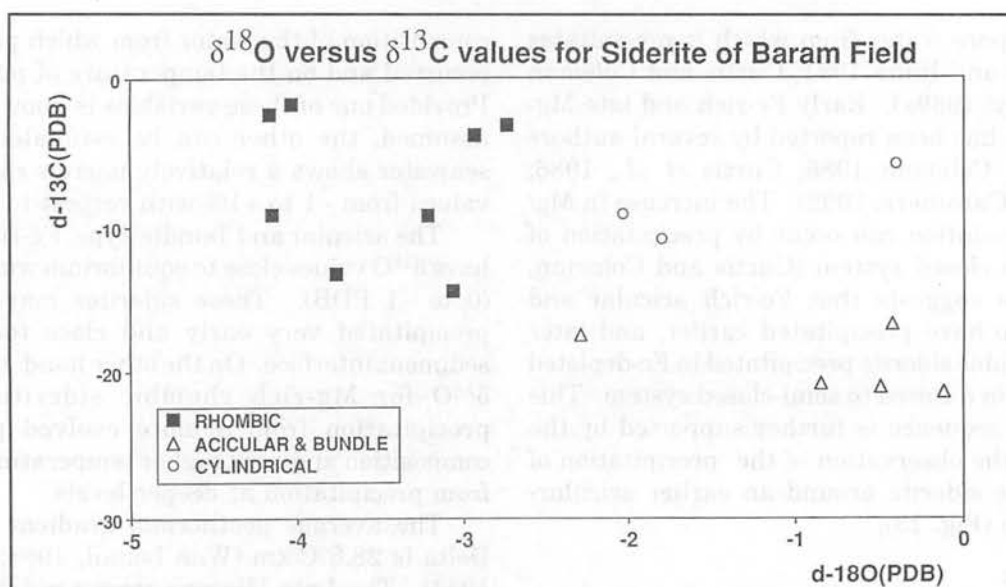


Figure 9. Plot of $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ values for the siderites of Baram field. Data are differentiated by morphological types.

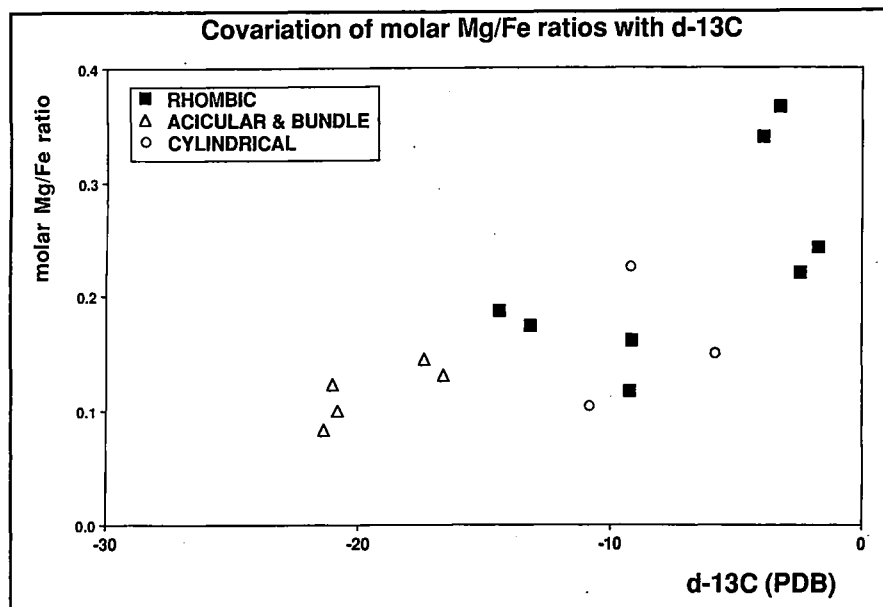


Figure 10. Covariation of molar Mg/Fe ratios with $\delta^{13}\text{C}$ of siderite cement of Baram Field.

Figure 11. Plot of molar Ca/Fe ratios against $\delta^{13}\text{C}$ values.

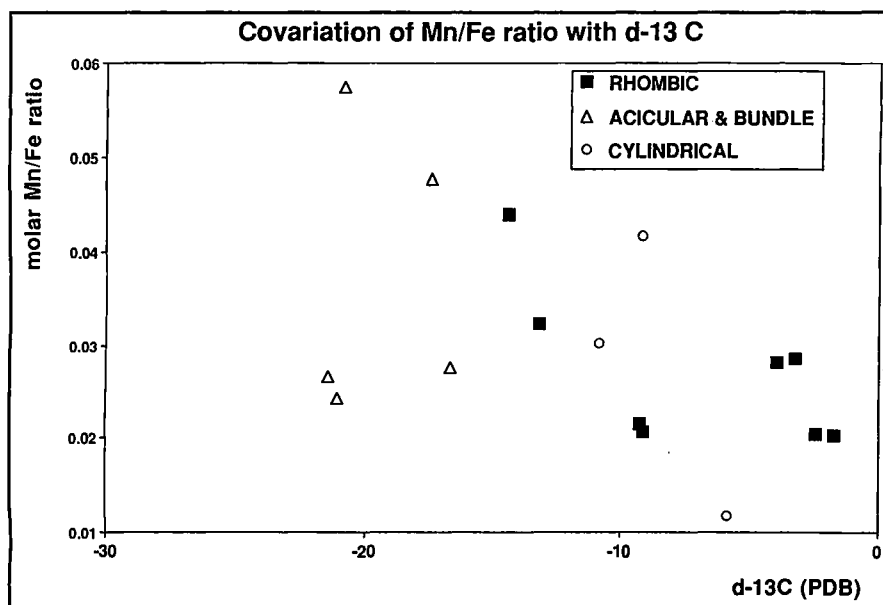
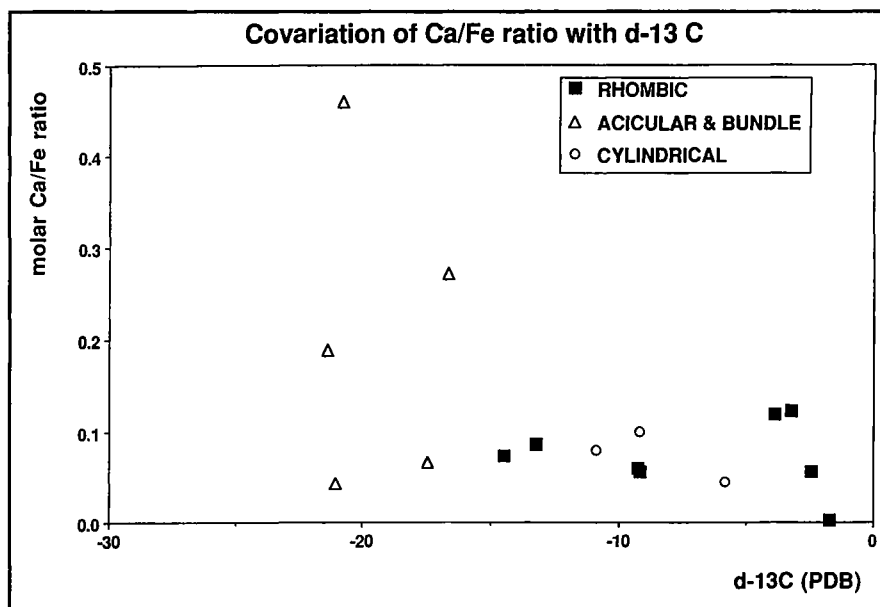


Figure 12. Plot of molar Mn/Fe ratios against $\delta^{13}\text{C}$ values.

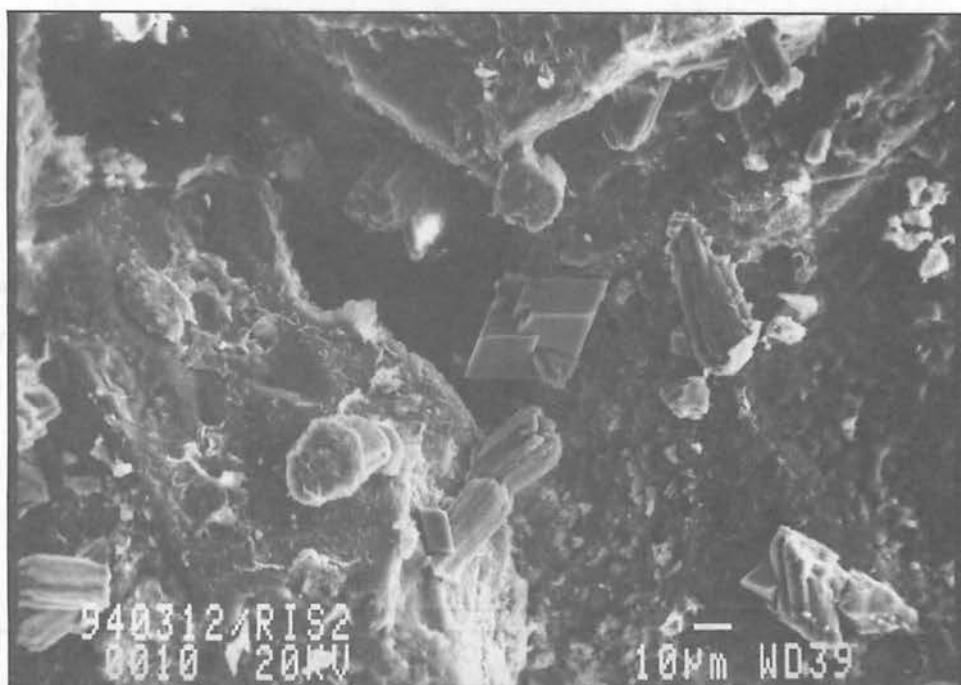


Figure 13. Acicular-type siderite enveloped by later precipitation of rhombic siderite.

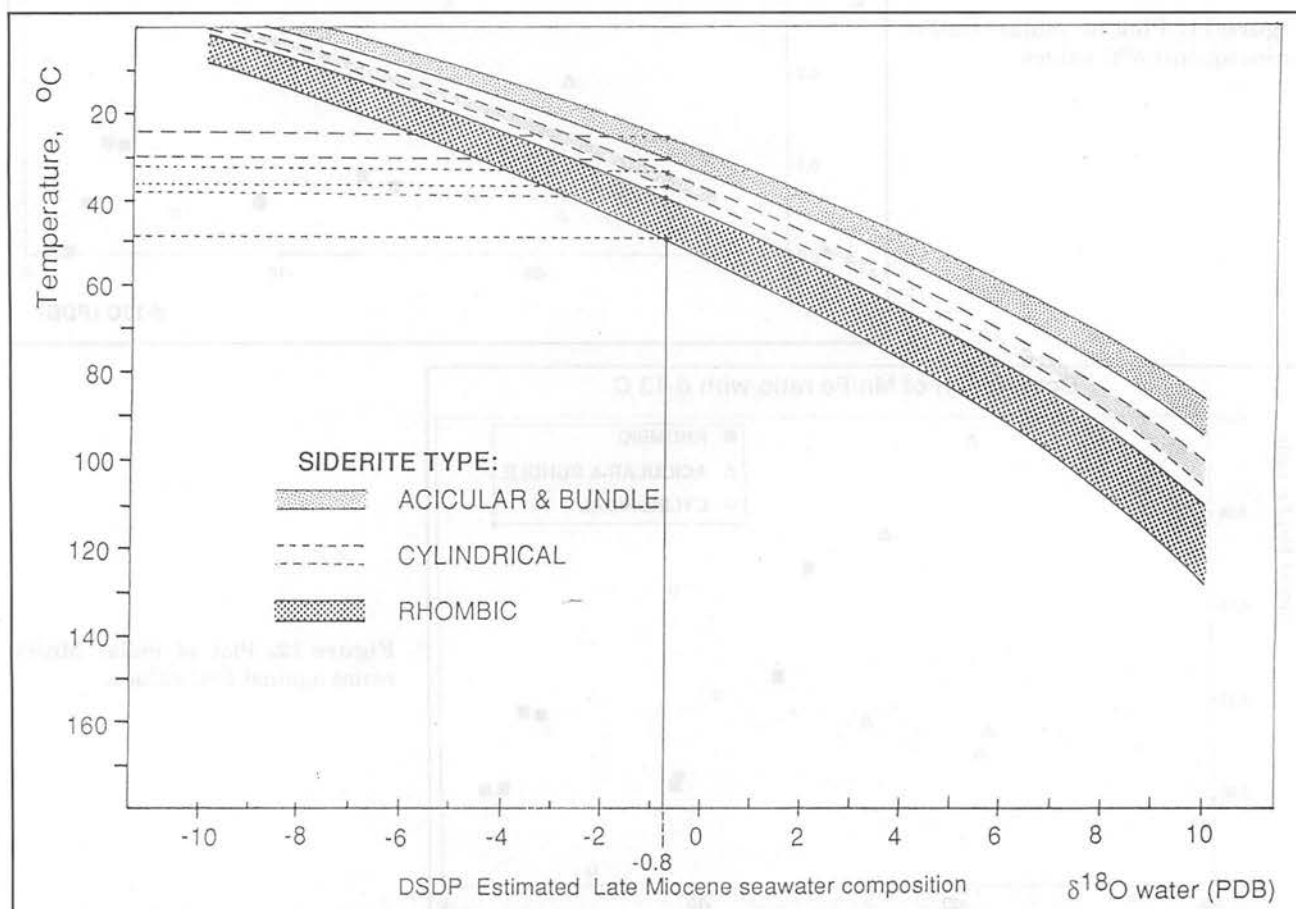


Figure 14. Plot of calculated temperatures for the formation of siderites against carbon isotope compositions.

precipitation can be estimated (Fig. 14).

The acicular- and 'bundle'-type siderite shows a temperature of formation range of 25° to 30°C. The $\delta^{18}\text{O}$ values are compatible with precipitation at shallow burial depths from unaltered sea-water. The temperature range from 38° to 48°C for rhombic siderite implies depths of about 450 to 800 m, assuming precipitation from unaltered seawater (Savin *et al.*, 1975). The cylindrical siderite shows isotope values between these two extremes, suggesting intermediate depths for precipitation.

$\delta^{13}\text{C}$ values

The negative $\delta^{13}\text{C}$ values (−16 to −21) of the acicular siderite (Fig. 13) are inherited from sulfate reduction horizons (Fig. 15), consistent with precipitation at shallow depth. The rhombic siderite $\delta^{13}\text{C}$ values (−1 to −15) imply mixing of carbonate produced by sulfate reduction with carbonate from the zone of decarboxylation. Astin and Scotchman (1988) have shown the persistence of carbonate of the sulphate reduction origin within sediment pore waters from depths appropriate to the methagenesis or decarboxylation zones. The progressive modification of the sulphate reduction zone $\delta^{13}\text{C}$ signature with depth recorded by the rhombic shows a similar persistence, with relatively slow rates of organic matter oxidation occurring during intermediate burial.

Pathways for siderite precipitation

Siderite cementation in well bioturbated sediments can be explained (Fig. 16) by the model proposed by Sellwood (1971). In anaerobic conditions, ferrous iron is mobilised and migrates upward toward the sediment/water interface, into highly bioturbated sediments which has free access to oxygenated sea waters (Stage II). Because bioturbated sediments usually remain for long period near sediment/water interface, these sediments experience iron oxide concentration during periods of slow deposition. With renewed sedimentation, these sediments are brought to depths where reducing conditions prevail (Stage IV). Reduction of ferric ions causes high concentration of ferrous ions, which can react with CO_2 from bacterial decay, resulting in the precipitation of siderite (Stage III).

Figure 17 illustrates how two phases of siderite cementation can be accommodated by shallow marine storm sedimentation processes. Storm sedimentation in a prograding, regressive regime bring in thick pile of fine grained sands, with a high percentage of organic matter. This can either happen in one storm event, of several storms (Stage 1). A high subsidence rate increases the preservation potential of these sediments. As the

shelf quietens, mud is being deposited. Mud sedimentation can be further enhanced through a slight, relative sea level rise.

Fe-rich, acicular and 'bundle' siderite precipitated just below the sand-shale boundary in pore water close to marine water composition, in sub-oxic iron-reduction or anoxic sulphate reduction zone. Pyrite precipitation is inhibited by the sealing effect of the overlying mud, which limits the rate at which sulphate can diffuse into the sediment from depositional waters (Curtis and Spears, 1968; Berner, 1970; Curtis, 1977; Berner, 1978).

Renewed storm sedimentation resulting from relative sea level fall, followed by progradation, will rapidly deposit thick sand and shale into the environment (Stage III). The earlier deposited sand will undergo rapid burial, passing through all the diagenetic zones, and finally reaching the thermal abiotic decarboxylation zone. Here, Mg-rich, rhombic siderite will precipitate and inherit the negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ composition of the pore waters.

Some peculiarities

The noticeable lack of any obvious contribution of positive $\delta^{13}\text{C}$ from bacterial methagenesis must be explained. Ideally, buried sediments will pass through all the different diagenetic zones (Coleman *et al.*, 1979). Siderites with strong positive $\delta^{13}\text{C}$ have been reported by many authors and has been attributed to bacterial fermentation processes (Irwin *et al.*, 1977; Matsumoto and Ijima, 1981; Matsumoto, 1989; Mozley and Wersin, 1992). However, none of the siderites of Baram Field show positive $\delta^{13}\text{C}$. Two possible explanations can be offered here. Firstly, it could have been possible that the fluctuating sedimentation rate has been functioning in such a way that the sediments bypass the zone of bacterial methagenesis. Thus, no positive $\delta^{13}\text{C}$ have the opportunity to be incorporated into the siderites.

Bacterial fermentation process could have also been suppressed by poisoning. This inhabitation process could have operated by itself, complementing the rapid burial effect.

Another peculiarity of the siderite cementation observed in these sandstone is that only some intervals/horizons are cemented. There seem to be no regular stratigraphic pattern; siderite precipitation is also not facies selective. Even in thick cemented sandstones (≈ 2 m), banding of sideritised horizons is observed. Siderite cementation seem to be stratified, but it does not follow the primary depositional stratification. The lateral extent of these cemented horizons remain to be investigated. The authors believe, from analogous outcrops in Miri, that these horizons have considerable lateral extent, although probably

they do not extend the full spread of the sandstone layers.

Stratification of pore waters in sediments have been reported by some authors. Two mechanisms seems attractive here. Primary pore water stratification can be caused by differential compositional/mineralogical layering during sedimentation. This would give rise to vertical/stratigraphical variation in pore water composition.

Thus, any diagenetic alteration will be 'pore-water layer' selective, rather than lithologically/facies selective.

Pore water stratification can also happen due to upwelling of chemically evolved 'diagenetic' waters from deeper levels, due to compaction. This process will complement and further enhance primary pore water stratification, and influence the pattern for siderite cementation.

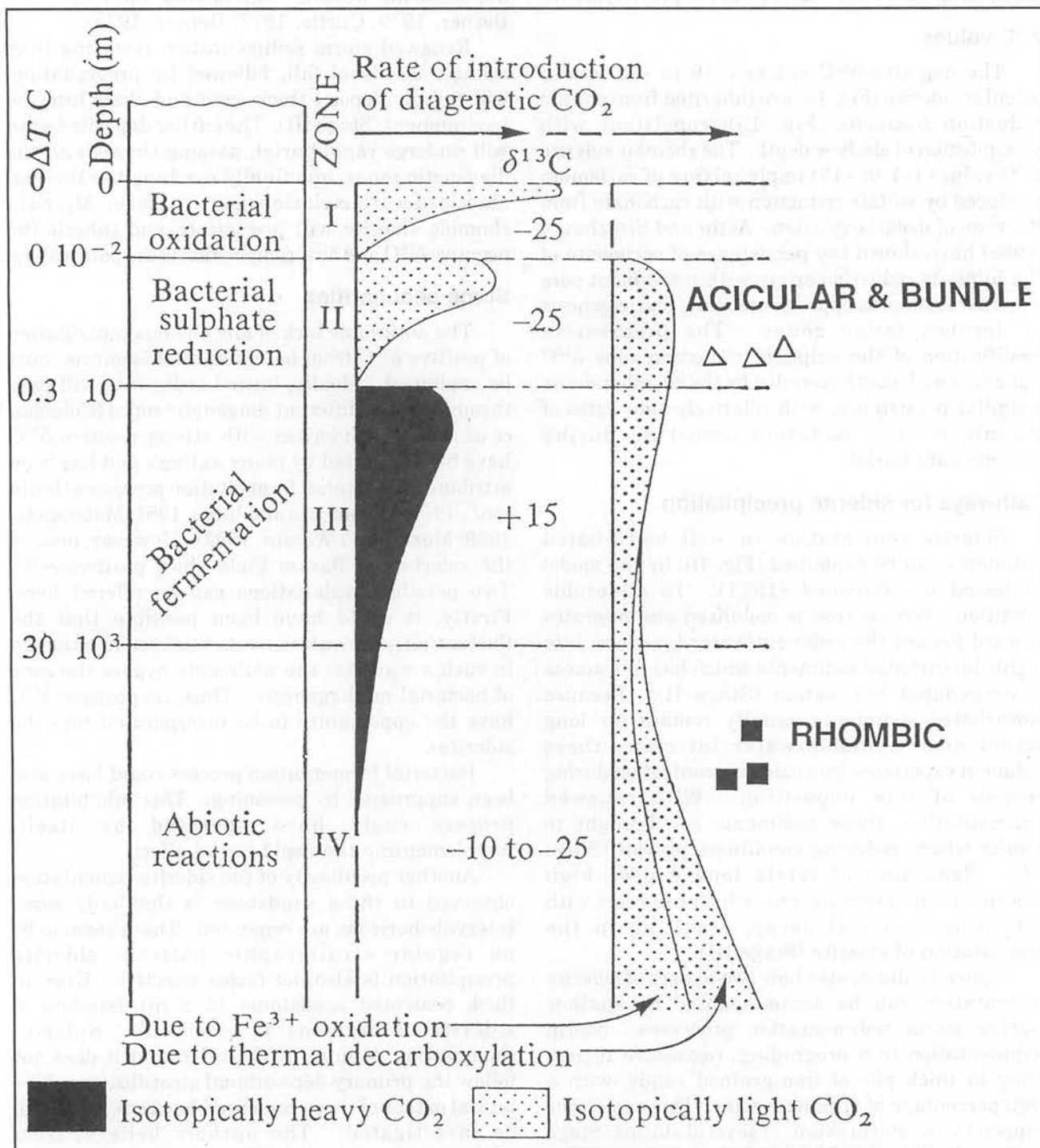


Figure 15. Introduction of diagenetic CO_2 within different diagenetic zones (from Irwin *et al.*, 1977).

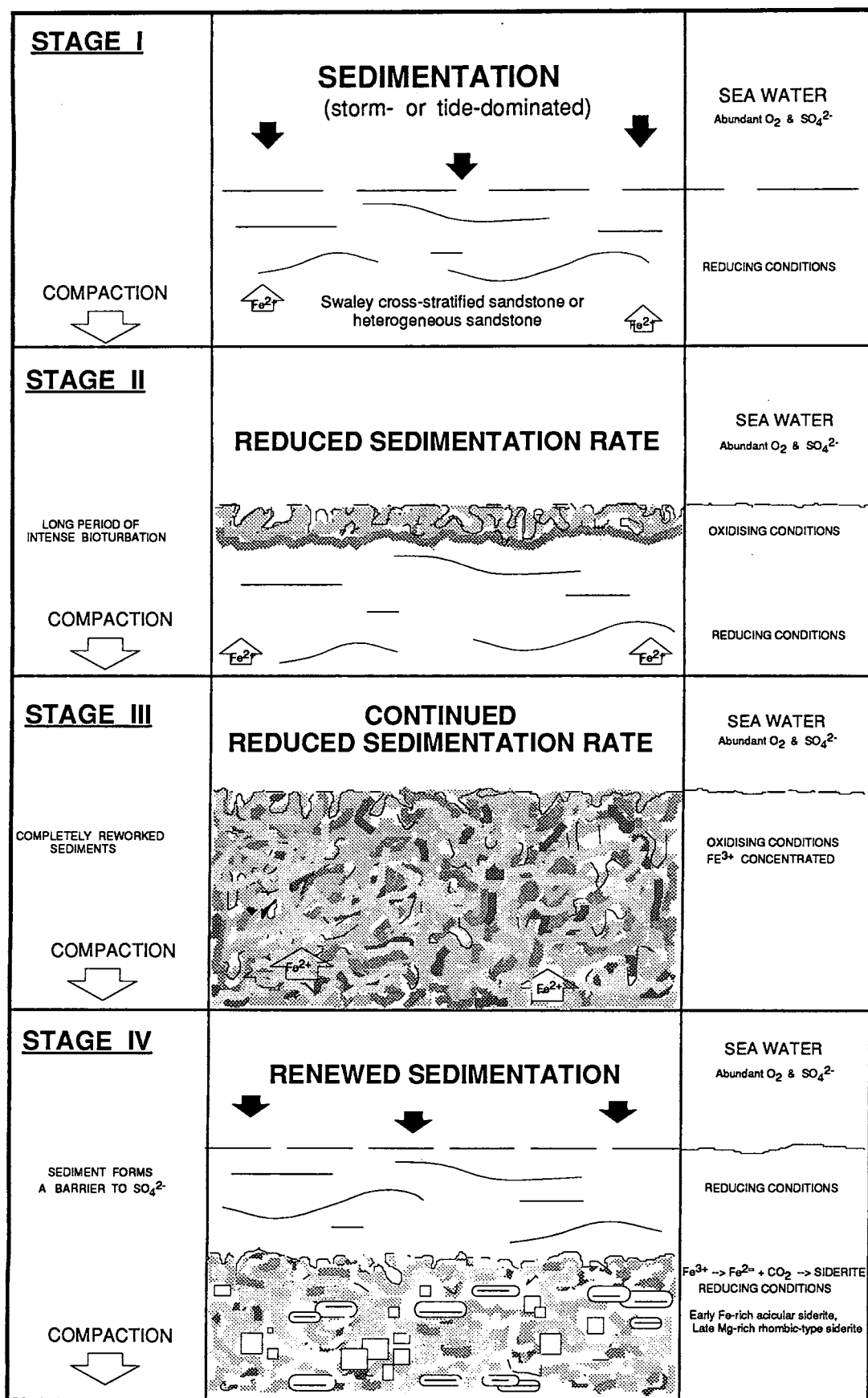


Figure 16. Scheme for siderite precipitation in well bioturbated sandstones (modified from Sellwood, 1971).

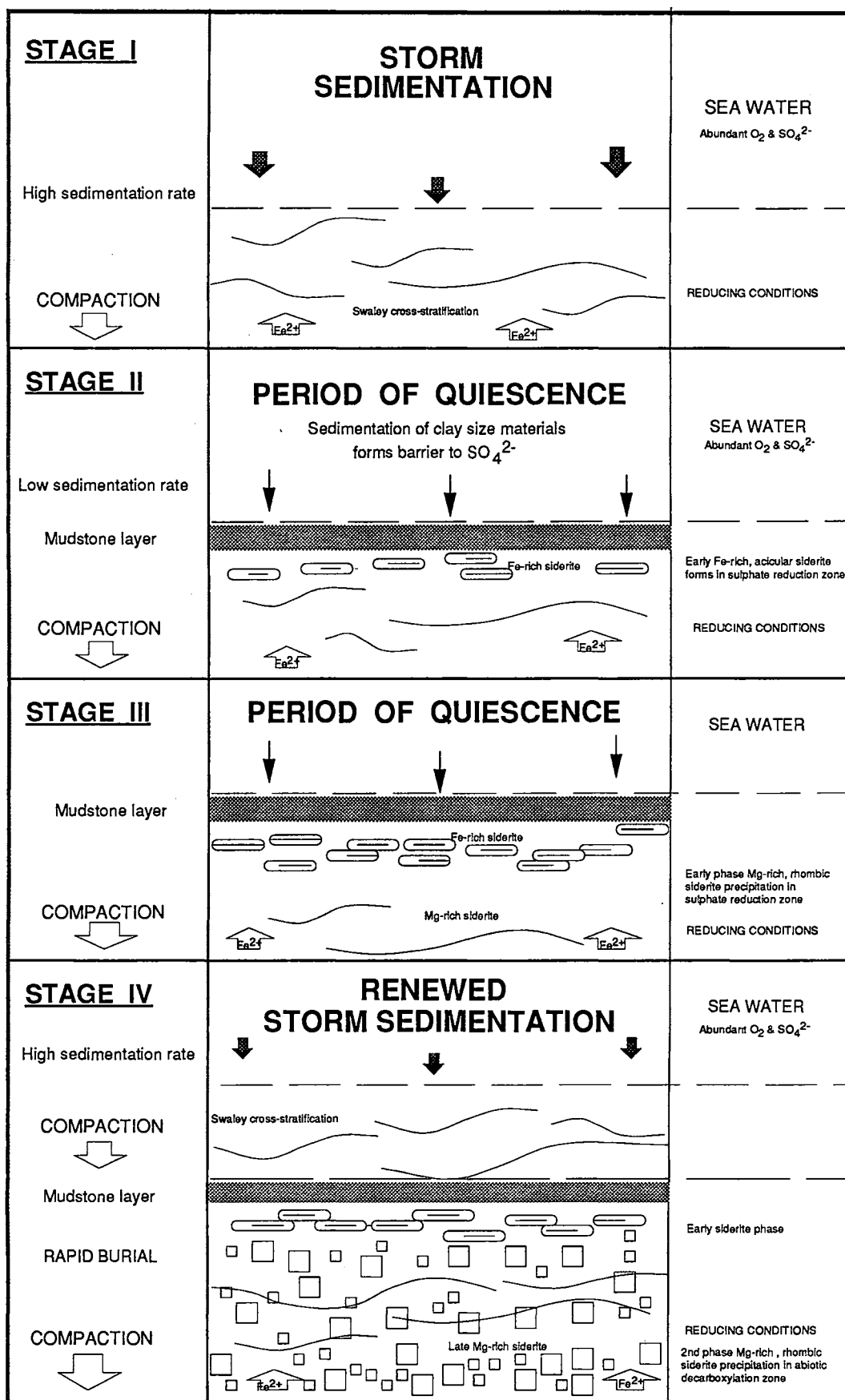


Figure 17. The different phases in the development of siderites in storm deposited sandstones.

RESERVOIR GEOLOGY

Figures 18 and 19 illustrate how siderite cementation has affected the quality of the reservoir sandstones as measured from core plugs. Samples showing grain density of 2.7 g/cm³ or more are strongly affected by siderite cementation. In one extreme case, the porosity has been reduced to almost 10% and the permeability 2 md. These siderite cemented horizons are effectively permeability barriers that must be taken into consideration in reservoir characterisation and modelling. However, the three-dimensional nature of these layers remain to be investigated.

CONCLUSIONS

1. Siderite cement is an important, and the only, carbonate phase in the Upper Cycle V (Late Miocene) reservoir sandstones of Baram Field.
2. Acicular and 'bundle' siderite is an early, Fe-rich carbonate form. Carbon and oxygen isotopes result indicate that this siderite type forms at very shallow depths in young, close-to-marine composition pore waters within suboxic Fe-reducing and sulphate reduction diagenetic zones.
3. Rhombic-type siderite precipitated from Mg-rich, evolved formation waters. The low

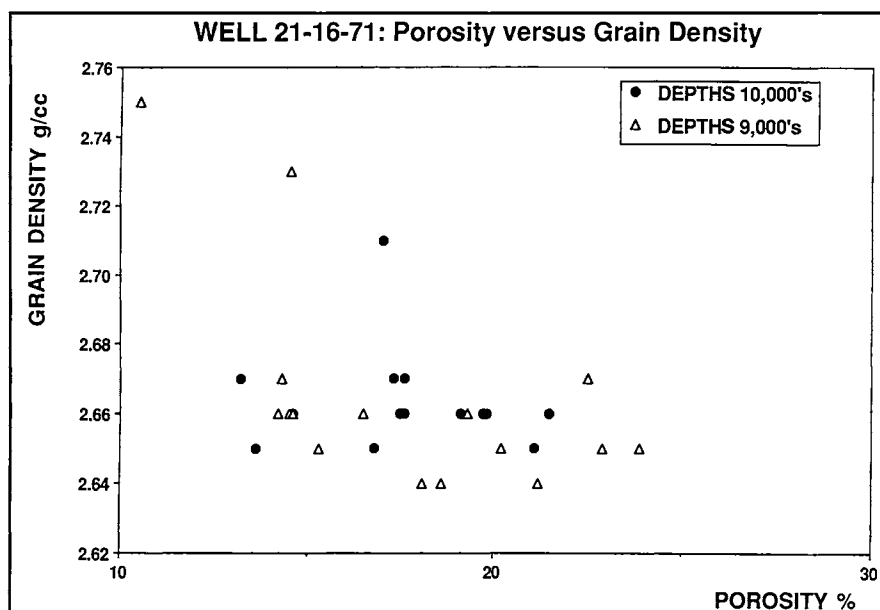


Figure 18. Plot of porosity against grain density for sandstones of Well 21-8-68.

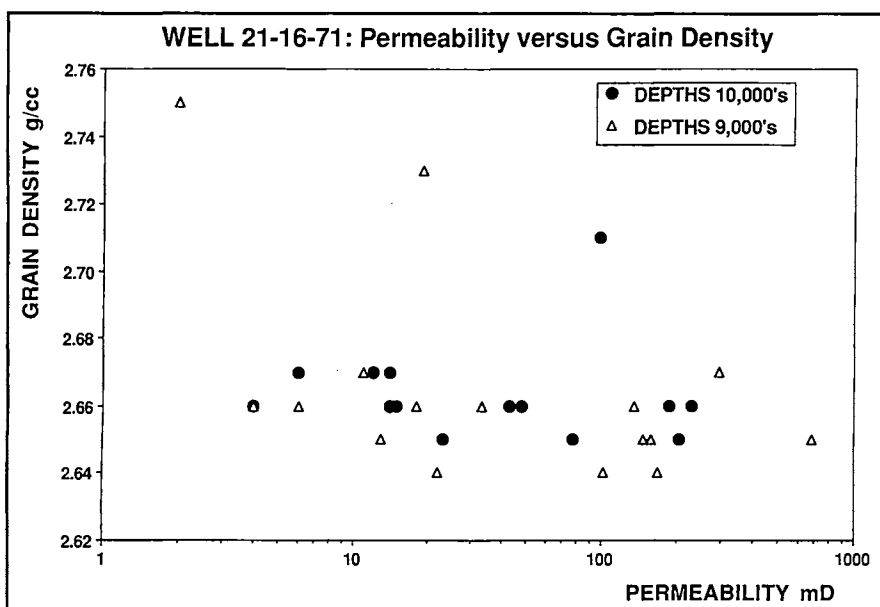


Figure 19. Plot of permeability against grain density for sandstones of Well 21-8-68.

negative $\delta^{13}\text{C}$ indicate origin from sulphate reduction and decarboxylation zones. Oxygen isotope data gives estimates for depth of formation of about 450–800 m.

4. High sedimentation/burial rate and H_2S poisoning is thought to have been crucial in determining the shallow burial diagenetic pattern within these reservoir intervals.
5. Siderite cementation within the sandstones of Baram Field locally strongly affected the reservoir quality. These siderite cemented horizons represent additional permeability barriers. Their lateral extent remains to be investigated.

ACKNOWLEDGEMENTS

The authors wish to thank to Dr. Khalid Ngah (PETRONAS PRSS) for his support on the project, and PETRONAS PRSS for permission to publish this article. Mike Isaac (PRIS) is thanked for the stable isotope analysis.

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Manuscript received 25 October 1994