Controls on diagenesis of the Triassic Kurrachine Dolomite, Syria

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ABSTRACT

The evaluation of major diagenetic processes affecting the main hydrocarbon-producing interval of the Triassic Kurrachine Dolomite, in the central part of Syria, has proved to be of importance in understanding its reservoir characteristics. To describe the paragenetic sequence, core samples from two wells were studied by conventional petrographic analysis. In the first stage, pervasive replacement dolomitisation occurred. The dolomite petrography can be best explained by evaporative dolomitisation in the case of tidal flat facies and by the hypersaline brine reflux model in the case of subtidal facies. During relatively longer periods of subaerial exposure dolocrete sequences were developed. Dolomitisation of subtidal sediments in a more open-marine setting was completed during further burial by rising temperature. As a result, pervasively dolomitised rocks, with minor intercrystalline porosity in subtidal deposits and supposedly in dolocretes, were formed. In the deep burial realm, solution seams and stylolites acted as conduits for migrating hydrocarbon. Overmature hydrocarbon was observed as insoluble residue. Following fracturing and leaching by sulphate-bearing warm fluids, significant vuggy porosity was created but was subsequently occluded by precipitated anhydrite cement. The effective vuggy and fracture porosity of the Kurrachine Dolomite was created by latest stage leaching, which was controlled by the previous deep burial diagenetic processes and fracturing. The selective leaching, on the evidence of dissolution of anhydrite cement, improved the reservoir potential. Taken all together, the Kurrachine Dolomite exhibits evidence of important porosity development in burial conditions. Accordingly, the analysed core porosity and permeability data within the formation varies by location.

INTRODUCTION

The studied area lies in the northeastern part of the Palmyrides, in Central Syria, and is partly located within the Bishri block (Figures 1a and 1b). The hydrocarbon potential of this region became evident in 1967 with the Soukhneh-1 gas discovery. Throughout the 1970s to 1990s considerable exploration success was achieved with major discoveries in Palaeozoic and Triassic reservoirs. In the region, several independent hydrocarbon plays were distinguished ranging from Palaeozoic to Cretaceous in age. The importance of these plays varies within the region. Generally, the deeper Palaeozoic Markada Play and the Triassic Kurrachine Play are the most prospective (Figure 2).

The Palaeozoic Markada sandstone reservoirs produce gas in the fields situated to the south of the studied area (Figure 1b). In the northeastern part of the Palmyrides, the source rock of this deeper play is thermally mature to overmature; dry gas generation can be expected. The interbedded shale of the Markada Formation itself and the overlying Permian sequence provide adequate seals.

In the case of the Triassic Kurrachine Play (Figure 2), dark grey dolomites and mudstones of the Kurrachine Dolomite proved to contain fair to good-quality source rocks. The mudstones have an average TOC of 2%, with reported Type I and Type II kerogen. Based on burial and thermal history modelling of the studied area, the source rocks entered the oil window during Cretaceous–Palaeogene times. They reached the bottom of the oil window, entering the wet-gas generating phase during trap formation (late Miocene to Pliocene times). The expelled hydrocarbons migrated within the Kurrachine Dolomite, or in some cases, down to the Permian sandstone sequence.

Fractured, finely to coarsely crystalline dolomites and dolomitic limestones of the middle part of the Kurrachine Dolomite form the most significant reservoir rocks in the Palmyride belt. In Syria’s oil
industry practice this zone is considered as the ‘Main Pay Zone’ (MPZ), with very good porosity and permeability values. The average porosity is 10% but may reach 18–20%. Mudstones and anhydrite of the overlying Kurrachine Anhydrite provide the regional seal. This play is proven in a few gas fields and in oil fields situated to the north of the studied area (Figure 1b). Estimated STOOIP of the oil fields in the region generally ranges from 25 to 150 million barrels. Oil characteristics differ from one field to another. Oil gravities range between 11° and 38°API and the sulphur content is between 0.5 and 3.5%.

There are reservoirs of minor importance lying above the Triassic Kurrachine Play, in the uplifted and partly eroded higher levels of the Palmyrides. This is due to the lack of an effective seal allowing freshwater invasion and biodegradation. The Jurassic–Early Cretaceous and Cretaceous Plays are of secondary importance; however, structural trapping of these higher reservoirs is a possibility.

This paper focuses on the diagenetic alterations of the Kurrachine Dolomite. It describes a project that involved a conventional transmitted-light microscope-petrographic study of core samples from two wells to evaluate diagenetic events and porosity evolution, in order to understand the reservoir characteristics as well as fluid migration during the imbibition and drainage processes.

The objectives are to:
(1) define and describe each diagenetic event within and around the Main Pay Zone of the Kurrachine Dolomite;
(2) determine their relative timing according to their cross-cutting relationships;
(3) describe the petrography of the dolomites and characterise the dolomitisation processes; and
(4) interpret the burial history of the Kurrachine Dolomite and evaluate its effect on porosity evolution.

The main points are discussed according to the paragenetic sequences.

A wide variety of porosity types can occur in dolomites. However, porosity in dolomites is not necessarily related to dolomitisation processes (Purser et al., 1994). A number of studies have recognised the genetic link between dolomitisation and saline pore fluids, as well as the pore occluding role of early diagenetic evaporite cement associated to dolomite successions (summary in Tucker and Wright, 1990). This study provides an example for the importance of sulphate-bearing warm basinal fluids that determined the reservoir potential in the dolomites. In the case of the diagenesis of the Kurrachine Dolomite, dissolution and anhydrite precipitation took place in the deep burial diagenetic realm following dolomite formation and chemical compaction. Accordingly, this study emphasizes the role of burial processes in developing the effective porosity.

GEOLOGIC SETTING

The intraplate Palmyride Belt suffered tectonic deformations in several stages. The main basin configuration and sedimentation pattern were determined by the E–W trending trough developed in Late Palaeozoic times. They were modified by inversion of NW–SE and N–S striking fault systems in the Late Cretaceous, and subsequently by repeated inversion and right-lateral transpressional movements in the Neogene (McBride et al., 1990; Chamoiv et al., 1992; Best et al., 1993; Brew et al., 1999, 2001).

Two main hypotheses for the formation of the Palmyrides have been proposed. The first one, proposed by Searle (1994), emphasises the role of Triassic salt as a regional detachment level, and relates all major folds to folding above this subhorizontal interval. The second, best exemplified by Salel and Séguret (1994), regards the Triassic evaporites as one of several potential detachment levels, along all of which subhorizontal thrusting could take place. The folds in this model are interpreted as ramp-related.

All authors dealing with the area emphasise the role of strike-slip faulting. One of the main strike-slip faults is the Jhar Fault, limiting the Bishri (–Bilas) Block to the south (McBride et al., 1990). Many authors suggest a link of the Jhar Fault (as an antithetic fault) with the Dead Sea transform fault,
although direct evidence is lacking. According to some studies (e.g. McBride et al., 1990), the Bishri Fault is the continuation of the Jhar Fault (Figure 1a), but the present geologic situation indicates that it is more practical to separate them, in spite of possible common origins.

The stratigraphy of Cambrian–Ordovician–Lower Silurian, which is not particularly relevant to the studied area, is not described here. The Hercynian orogenic phase led to regional uplift and erosion; therefore Devonian sequences are unknown in Syria. No well has reached the deeper part of the Palaeozoic in the Palmyride region. In the Carboniferous alternating beds of claystones, siltstones and sandstones with thin limestone streaks were deposited in a shallow-marine environment (Markada Formation; Figure 2).

Upper Permian to Lower Triassic, predominantly fine-grained siliciclastics represent fluvio-deltaic to littoral depositional environments. The Amanus Sand and Shale Formation consists of shales interbedded with sandstone and siltstone beds of variable thickness and frequency, as well as
occasionally thin limestone layers (Figure 2). The reservoir potential of the Permian–Triassic Amanus Formation depends on the thickness and silt content of sandstone intercalations of the fluvio-deltaic siliciclastic sequence. In the two studied wells only slight gas shows were encountered. In the studied area the source rock of this play is at the top of the oil window, or is overmature for oil generation. The overlying Amanus Shale provides an effective seal.

A Middle Triassic transgression resulted in the deposition of widely distributed thick, shallow-marine carbonates (Kurrachine Dolomite; Figure 2). According to the published well data this formation is regionally distributed and of significant thickness. Up-section the carbonate–evaporite succession, exhibiting metre-scale cycles, was deposited in a hypersaline marginal-marine environment (Kurrachine Anhydrite Formation). The unit is composed mainly of an alternation of anhydrite and shales, with several claystone, marlstone, dolomitic marlstone, dolomite and halite interbeds (Figure 2). Both thickness and frequency of the halite layers decrease from west to east in the Palmyra zone. In Well A no salt layers were identified, while in Well B the thickness of salt layers ranges from 4 to 20 m. The Kurrachine Anhydrite is considered to be an effective seal for the Triassic dolomite reservoir.
The overlying Triassic succession (Figure 2), the Butmah, Adaiyah and Mus formations, also represents shallow-marine, lagoonal sedimentation with frequent periods of sabkha facies indicated by similar cyclic sequences as those in the Kurrachine Dolomite and Anhydrite. However, halite was formed only in the Kurrachine Anhydrite.

The stable-shelf conditions that persisted throughout the Palaeozoic until the Middle Triassic changed in the Late Triassic. Rapid facies changes in the Alan and Sargelu formations, unconformity horizons and the siliciclastic sequence of the Sargelu Formation suggest regional uplift and erosion related to the tectonic evolution of the Mesozoic Neo-Tethys Ocean. In the Palmyride Belt the Permian–Triassic and Jurassic formations were previously called the Mulussa Group.

Continuous transgression took place in Jurassic times and led to the deposition of deeper-water carbonates of variable thickness, such as dolomites, calcareous dolomites, and limestones with claystone streaks (Brew et al., 2001). Minor inversion tectonics occurred in the Late Jurassic, as indicated by uplift and erosion. Jurassic deposits are completely absent to the south of the studied area. Therefore the widespread fluvial and continental sandstones of the Rutbah Formation that is the main reservoir in the Euphrates Graben, directly and unconformably overlie Triassic beds. During the latest Cretaceous the NW-striking faults that extended from the Euphrates Trough, determined the basin configuration (Litak et al., 1998; Brew et al., 1999). Pelagic carbonates, marls and sediments were deposited continuously in the subsiding Palmyra Basin during the Late Cretaceous–late Eocene interval.

The Palaeogene basin formation was interrupted by inversion in the Miocene. Mainly right-lateral transpressional movements determined the newly formed basins in the Palmyride Belt. In these basins claystones and limestones were deposited in the middle to upper bathyal region. These tectonic deformations were pene-contemporaneous with the opening of the Red Sea, the closing of the Bitlis–Zagros Suture Zone, and the main movements along the Dead Sea Fault (Chamoiv et al., 1990; McBride et al., 1990; Searle, 1994). During the Pliocene continental and predominantly fluvial sedimentation was restricted to isolated continental basins.

Sedimentary Evaluation of the Kurrachine Dolomite

The thickness of the investigated Anisian Kurrachine Dolomite Formation increases from Well A to Well B. Available thickness data of the Kurrachine Dolomite indicates westward thickening (from 300 m to 750 m) suggesting that it was formed in a differentially subsiding shallow basin. The lower part of the Kurrachine Dolomite, consisting predominantly of thick, massive mudstones to wackestones and argillaceous limestones of an open subtidal facies (Figure 3), was deposited over fluvial to marginal-littoral sediments during initial transgression. Upsection, shallow-marine claystones, argillaceous limestones, dolomitic limestones, dolomites and anhydrite alternate. The upper part of the formation is composed of thin beds of claystones, marls, dolomites, and anhydrite. The small-scale shallowing-upward units commonly start with open subtidal dark claystones, muddy limestones which grade upward into peritidal dolomites, anhydrititic dolomites, anhydrite or, in some cases, salt (halite) (Figure 3). The high-frequency cyclicity most likely reflects either sea-level fluctuation or tidal flat progradations. Taken all together the stacking pattern of the succession exhibits deepening and shallowing-upward ‘megacycles’.

Based on well data the lower section of the Kurrachine Dolomite has no reservoir potential. It may contain fair to good-quality source layers. In Syria, in the middle part of the Kurrachin Dolomite a well-correlatable shale–dolomite couplet has been identified, the so-called ‘Equivalent Zone’. Generally it consists of 5–15 m-thick shales in the lower part and 8–20 m-thick dolomites in the upper part. This zone is generally well-defined by G-R log and can be used as a stratigraphic marker horizon. However, the ‘Equivalent Zone’ is not well-developed south of the studied area where the role of deeper plays is more important than the Kurrachine Play. Accordingly, the couplet is thinner in Well A (approx. 10 m) and in surrounding wells than in Well B (31 m) (Figure 3). In general this dolomite interval in the upper part of the ‘Equivalent Zone’ can contain hydrocarbons within the Kurrachine Dolomite; thus, it is considered as the ‘Main Pay Zone’ (MPZ; Figure 3). Based on wireline log evaluation the thickness of the ‘Main Pay Zone’ is 7.5 m in Well A, and 19 m in Well B (Figure 3).
### Kurrachine Dolomite and Kurrachine Anhydrite Formations, Palmyra region

| Well B | Well A |
|--------|--------|
| **Stratigraphy** | **Stratigraphy** |
| Upper Carnian | Upper Carnian |
| Lower Ladinian | Lower Ladinian |
| **Triassic** | **Triassic** |
| **Lithology** | **Lithology** |
| **Gamma Ray (API)** | **Gamma Ray (API)** |
| **Porosity** | **Porosity** |
| Density | Density |
| 2 (gm/cc) | 2 (gm/cc) |
| **Lithological description and comments** | **Lithological description and comments** |
| Anhydrite with thin dolomite, claystone and occasionally marlstone layers. | Alternating beds of salt, anhydrite and shales. Thickness of salt layers ranges from 4 to 20 m in Well B, no salt bed was identified in Well A. |
| Alternating beds of anhydrite and claystones with thin dolomites and marlstones. | Dolomites and calcareous dolomites alternate with dolomitic limestones, argillaceous limestones, and claystone-marlstone streaks. |
| Equivalent zone: a well correlatable, shale-dolomite couplet. It consists of 5-15 m-thick shales in the lower part and 8-20 m-thick dolomites in the upper part. The couplet is thinner in Well A (10 m) and in the surrounding wells than in Well B (31 m). This zone is generally well defined by GR log, and it can be used as a stratigraphic marker horizon in the northern part of the studied area. The ‘Equivalent zone’ is not well-developed south of the studied area. | Equivalent zone: a well correlatable, shale-dolomite couplet. It consists of 5-15 m-thick shales in the lower part and 8-20 m-thick dolomites in the upper part. The couplet is thinner in Well A (10 m) and in the surrounding wells than in Well B (31 m). This zone is generally well defined by GR log, and it can be used as a stratigraphic marker horizon in the northern part of the studied area. The ‘Equivalent zone’ is not well-developed south of the studied area. |
| Main Pay Zone: dolomite interval having very good petrophysical parameters. Thickness of the MPZ is 19 m in Well B and 7.5 m in Well A. | Main Pay Zone: dolomite interval having very good petrophysical parameters. Thickness of the MPZ is 19 m in Well B and 7.5 m in Well A. |

**Figure 3:** Composite well log showing the position of the ‘Main Pay Zone’.

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- **Argillaceous limestones**
- **Limestones**
- **Dolomitic limestones**
- **Calcareous dolomites**
- **Dolomites**
- **Marlstones**
- **Sandstones**
- **Siltstones**
- **Claystones**
- **Anhydrite**
- **Salt**
METHODOLOGY

Twenty-five thin sections from core samples of the Kurrachine Dolomite Well A (Core: 2,591.60–2,600.60 m), and forty thin sections from Well B (Core 1: 2,380.0–2,389.0 m; Core 2: 2,389.0–2,394.5 m, Core 3: 2,433–2,442 m) were studied under petrographic microscope in order to identify the diagenetic events (Tables 1 and 2). The cross-cutting relationships provide the order of their relative timing (paragenetic sequence). Fourteen polished samples from the core of Well A and three from those of Well B were studied using a cathodo-luminescence (CL) microscope on a Nuclide ELM–3R Cold Luminoscope operating at 10 kV. Some samples were impregnated with blue resin in order to make the open porosity easily observable.

PARAGENETIC SEQUENCE OF WELL A CORE SAMPLES

Petrography

Event 1: Replacement dolomitisation

This was the main stage of dolomitisation, during which the sediments were pervasively replaced by dolomites. Three types of dolomites are distinguished on the basis of crystal size: crypto-, finely and coarsely crystalline. Crystals are yellow-brown under petrographic microscope, and dull red under CL.

Cryptocrystalline dolomites are less common and consist of closely packed dolomite crystals <4 μm in size. In this type planar, occasionally wavy, and crinkle, microbial-like laminae alternate with thin, massive laminae. In some layers bedding-parallel, planar-type fenestral porosity associated with tiny rounded biomoulds was encountered within clotted cryptocrystalline dolomite texture. Finely crystalline dolomites are common and consist of closely packed crystals from 4 μm up to 50 μm in size. The coarsely crystalline dolomites are volumetrically equal to the finely crystalline type and consist of subhedral to anhedral crystals ranging from 50 to 250 μm, sometimes up to 400 μm in size. Occasionally solution seam-enhanced mottles of various crystal sizes are visible in the texture. The coarsely crystalline dolomites are mostly fabric destructive; however, abundant ovaly-arranged inclusions commonly occur in a single or some neighbouring crystals (Figure 4). The crystals show slightly undulose extinction. Single coarse crystals occasionally preserve the precursor echinoderm fragments.

Anhydrite, in the form of nodules of lath-shaped crystals 20–400 μm in length, is randomly scattered throughout the finely and cryptocrystalline dolomites, and slightly distorts the lamination. Otherwise, it occludes the fenestral pores. Aragonite grains, such as fragments of molluscs and foraminifera, and evaporite crystals precipitated earlier were not preserved and formed moulds. Moulds of euhedral, lens-shaped crystals with planar crystal faces were subsequently filled by anhydrite cement.

Event 2: Dolomite precipitation

Euhedral to subhedral, limpid dolomite crystals 10–150 μm in size have planar and straight compromise boundaries. The non-luminescent cement crystals show a dull red final growth band. They generally have limited areal distribution, since they occlude the biomoulds and smaller fenestral pores. Otherwise, the crystals occur as uneven pore-lining cement in larger fenestral pores. The overgrowing cement can be distinguished from the replacement dolomites because of its clear and transparent appearance, which is well visible under petrographic microscope especially in the case of coarser crystals. According to the distribution of cement crystals cement precipitation post-dated the replacement dolomitisation.

Event 3: Silica nodules

Small silica nodules and spheres occur and occasionally replace the isolated anhydrite laths or nodules. They are composed of spherulated forms with radiaxial crystals, which are brown in colour with concentric-lines under petrographic microscope. In some cases, it is evident that their formation predated chemical compaction. They are of minor importance.
Table 1: Thin section observations in Well A.

Abbreviations: m: thickness of small-scale shallowing-upward depositional units; CH: hydrocarbon; S: stylolites; ICP: intercrystalline pores; ANH: anhydrite; IC: intercrystalline.

| No. of thin sections | Dolomite Petrography | Facies | Nodules | Sedimentary Structures | Baroque Dolomites | Solution Seams | Residual CH in ICP | Residual CH in ICP | Cement-Filled Secondary Porosity | Fracture | Part. Dissolved ANH | Enlarged IC | Vuggy | Others |
|----------------------|----------------------|--------|---------|------------------------|-------------------|----------------|--------------------------|--------------------------|----------------------------------|----------|------------------|-------------|-------|---------|
| 25                   | Coarsely crystalline | Subtidal | x       | x                      | Poikilotopic anhydrite | x               | x                        | Pyrite |
| 24                   | Massive and finely laminated cryptocrystalline with anhydrite nodules | Peritidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        | shell-replacing baroque dolomites |
| 23                   | Finely crystalline with crystal moulds and coarsely crystalline with round ghosts | Subtidal | x       | x                      | Pore-lining dolomite and anhydrite cement in vuggy pores | x               | x                        | Shell-replacing baroque dolomites |
| 22                   | Cryptocrystalline: boundstone texture with abundant globular biomolds (~foraminifers), pelucyprid biomolds, fenestral pores, ostracods, chicken wire anhydrite | Peritidal | x       | x                      | x                        | x               | anhydrite in larger fenestrae; anhydrite-replacing chert; pyrite |
| 21                   | Coarsely crystalline with closed-packed, round ghosts, quartz grains within a thin bed | Subtidal | x       | x                      | Poikilotopic anhydrite | x               | x                        | Chert |
| 20                   | Coarsely crystalline with closed-packed, round ghosts | Subtidal | x       | x                      | Poikilotopic anhydrite | x               | x                        | Chert |
| 19                   | Cryptocrystalline: solution seam-enhanced fine parallel and wavy lamination; scattered anhydrite nodules | Peritidal | x       | x                      | Anhydrite in thin fractures | Horizontal as well as vertical stylolites with residual hydrocarbon |
| 18                   | Coarsely crystalline with closed-packed, round ghosts | Subtidal | x       | x                      | Poikilotopic anhydrite | x               | x                        |
| 17                   | Coarsely crystalline | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        |
| 16                   | Cryptocrystalline with alternating fine parallel and crinkle lamination, and massive laminae with desiccation cracks; scattered anhydrite nodules | Peritidal | x       |                        | Desiccation cracks filled with dolomite cement |
| 15                   | Coarsely crystalline | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        | Chert |
| 14                   | Finely to coarsely crystalline; echinoderm fragments | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        | Chert |
| 13                   | Finely to coarsely crystalline | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        |
| 12                   | Coarsely crystalline with scattered round ghosts; echinoderm fragment | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        |
| 11                   | Finely and coarsely crystalline with scattered round ghosts | Subtidal | x       | x                      | Anhydrite in vuggy pores; poikilotopic anhydrite | x               | x                        |
| 10                   | Finely crystalline with solutions seam-enhanced bioturbation; in patches coarsely crystalline with round ghosts | Subtidal | x       | x                      | Anhydrite in vuggy pores; poikilotopic anhydrite | x               | x                        | Shell-replacing baroque dolomites |
| 9                    | Finely to coarsely crystalline | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        |
| 8                    | Coarsely crystalline with scattered echinoderm fragments | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        | Anhydrite-filled vuggy pores and stylolites cut across the vein-filling baroque dolomites |
| 7                    | Finely to coarsely crystalline | Subtidal | x       | x                      | Anhydrite in vuggy pores and intracrystalline pores of baroque crystals | x               | x                        | Styloildes cut across vein-filling baroque dolomites; pyrite; chert |
| 6                    | Finely crystalline, in and patches some crystalline | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        | Chert |
| 5                    | In (bioturbation?) patches finely to coarsely crystalline with some round ghosts; some echinoderm fragments | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        | Pyrite; chert |
| 4                    | Laminated cryptocrystalline with fenestral and globular biomold pores | Peritidal | x       | x                      | Dolomite cement in biomold and smaller fenestral pores; anhydride in larger fenestrae |
| 3                    | Finely and coarsely crystalline; solution seam-enhanced bioturbation | Subtidal | x       | x                      | Anhydrite in vuggy pores | x               | x                        | Pyrite; chert |
| 2                    | Cryptocrystalline with alternating fine parallel and crinkle lamination; scattered anhydrite nodules | Peritidal | x       | x                      | Anhydrite crystals along vertical wings of stylolite |
| 1                    | Massive finely crystalline | Subtidal | x       | x                      | Poikilotopic anhydrite | x               | x                        |
Table 2: Thin section observations in Well B.

Abbreviations: m: thickness of small-scale shallowing-upward depositional units; CH: hydrocarbon; S: stylolites; ICP: intercrystalline pores; ANH: anhydrite; IC: intercrystalline.

| m  | No. of Thin Sections | Dolomite Petrography Sedimentary Structures | Facies | Baroque Dolomites Solution Seams | Solution Stems | Stylolites | Residual Crystallinity in ICP | Cement-Filled Secondary Porosity | Fracture | Part. Dissolved ANH | Enlarged IC | Vuggy | Others          |
|----|---------------------|--------------------------------------------|--------|---------------------------------|----------------|-----------|-------------------------------|----------------------------------|----------|------------------|-----------|-------|------------------|
|    | Core 1              |                                            |        |                                 |                |           |                               |                                   |          |                  |           |       |                   |
| 34 | Coarsely crystalline | Subtidal                                   |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 33 | Coarsely crystalline | Subtidal                                   |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 32 | Finely and coarsely crystalline | Subtidal                               |        |                                |                | x         | Dolomite and anhydrite in vuggy pores | x                  |          |                  |           |       |                  |
| 31 | Finely and coarsely crystalline | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 30 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 29 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 28 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 27 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 26 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 25 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 24 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 23 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 22 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 21 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 20 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 19 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 18 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 17 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 16 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 15 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 14 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 13 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 12 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 11 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 10 | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 9  | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 8  | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 7  | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 6  | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 5  | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 4  | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 3  | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 2  | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
| 1  | Massive, wavy and parallel lamellated fine- crystalline with oolitic calcite, with fine-grained detrital sands | Subtidal                               |        |                                |                | x         | Anhydrite in vuggy pores       | x x x x x                        |          |                  |           |       |                  |
Figure 4: Photomicrograph of coarsely crystalline replacement dolomite (Event 1) with ovaly-arranged inclusions as a reflection of relict sedimentary grains. Smaller dissolutional vugs (Event 7) are filled by clear dolomite crystals (Event 8; e.g. in the middle) and larger ones (on right hand side) are occupied by anhydrite (Event 10). Well A, thin section No. 18, plane polarised light.

Figure 5: Photomicrograph of coarsely crystalline baroque dolomites (Event 4) in finely crystalline replacement dolomite host (Event 1). Note the undulose extinction of the large crystals, and the secondary, dissolutional intracrystalline pores (Event 7) within them that were subsequently filled with anhydrite cement (Event 9; yellow, pink, and blue in colour, in the middle and left on the Figure). Well A, thin section No. 7, crossed polars.

**Event 4: Baroque dolomite**

One particular type of dolomite, which is also referred to as a saddle dolomite, is characterised by undulose extinction under crossed polars (Figure 5). It has a warped crystal lattice as well as curved crystal faces and curved cleavage planes (Radke and Mathis, 1980). The dolomite crystals of 300–1,750 μm in size generally have a cloudy appearance in thin section because of abundant inclusions, and dull red luminescence under CL. Baroque dolomite rhombs are patchily scattered through the replacement dolomite host. However, they also occur in veins (Figure 6). Relict shell fragments were recognised by the shape of enclosed inclusions. Scattered pyrites are often related to the baroque dolomite crystals. In some cases formation of vein-filling crystals before chemical compaction is evident.

**Event 5: Chemical compaction**

Chemical compaction (dissolution under pressure) affected the previously lithified dolostones and generated solution seams and stylolites. Solution seams characterise the finer crystalline rocks. Stylolites cut across solution seams and all the above-mentioned diagenetic features. Vertically elongated anhydrite crystals are arranged along the vertical wings of the stylolites implying presence of anhydrite prior to chemical compaction.
Event 6: Hydrocarbon migration
Along the stylolites (Figure 6) and in the intercrystalline porosity of coarsely crystalline dolomites (Figure 7) blackish brown residual hydrocarbon is preserved as insoluble residue.

Event 7: Fracturing and dissolution
A wide variety of secondary channel and vuggy porosity was created through fracturing and non-selective dissolution of dolomites. Baroque dolomites were also affected. The porosity types encompass microporosity between and inside the dolomite crystals (Figure 5), as well as larger vugs that are visible to the naked eye (Figures 4 and 6–7). In many cases the vugs cut across the stylolites that preserve an insoluble residue of hydrocarbon.

Event 8: Dolomite precipitation
Pore-lining, coarse, limpid, euhedral dolomite cement occurs in limited amounts in the secondary voids created by dissolution (Figure 4). The cement crystals generally overgrow etched replacive dolomite crystals with optical continuity. They show brighter red luminescence in comparison with the replacement crystals, and are of minor importance.
Event 9: Anhydrite precipitation
Coarse mosaic spars, occasionally as poikilotopic spars (Figure 8), overwhelmingly filled up the secondary dissolutional vugs (Figures 4–7). Crystals are clear under petrographic microscope and contain two-phase fluid inclusions.

Event 10: Fracturing and dissolution
A system of thin, open fractures (50–100 μm in width) cut across all kinds of earlier replacement and cement crystals, as well as the stylolites. Most of them are approximately parallel with the bedding planes, but some are oblique. Dissolution at microscopic scale created enhanced intercrystalline porosity, and widened parts of the fractures. Micropores, which are less than 20 μm across, were observable only after blue resin impregnation of the samples. Dissolution of anhydrite (Event 9) is evidence where it was partial, and in some cases created intracrystalline porosity.

Interpretation of the Paragenetic Sequence of Well A
A total of ten paragenetic events have been identified in the dolomites. The same events were recognised all along the entire 9 m-long core. No sharp surface was identified at the cycle top which would have divided the section into parts of diagenetically different evolution.

Deposition
The preserved sedimentological features reveal that the depositional site was an arid to semi-arid tidal flat and shallow subtidal zone of a ramp. Cryptocrystalline dolomites show a high degree of fabric preservation. Preservation of crinkle microbial-like, fine planar and wavy lamination, in addition to fenestral porosity in cryptocrystalline dolomites provides criteria for recognition of ancient tidal-flat facies. Fenestral pores were developed during shrinkage of the microbial mat. The very fine lamination, associated with microbial lamination, is a reliable criterion for recognition of supratidal storm deposits. The massive laminae of the dolomites may have formed as early-lithified supratidal crusts (Shinn, 1983). Early diagenetic evaporite precipitation supports this facies interpretation, by comparing it to modern tidal flats where evaporite minerals are commonly present within sediments in a semi-arid climate (Shinn, 1983). The precursor of finely crystalline dolomite most likely was carbonate muds. Solution seam-enhanced mottles are interpreted as bioturbation formed in subtidal deposits. Otherwise, ovaly-arranged inclusions within coarsely crystalline dolomites are interpreted as ghosts of carbonate sand grains characterising the subtidal facies. Relict structures within dolomite crystals most likely imply an original texture of loose carbonate sand grains including rounded bioclasts or coated grains. Repetitive metre-scale vertical facies changes from shallow subtidal to peritidal facies define high-frequency shallowing-upward cycles. Their stacking pattern suggests an upward shallowing tendency (Table 1).
Shallow burial diagenetic processes
The diagenetic evolution of the rocks occurred in two main diagenetic realms, the shallow burial and deep burial ones. Early diagenetic, referring to near-surface, processes began to operate syndepositionally and involved evaporite precipitation from saline pore waters. Distorted lamination around the evaporite crystals indicates their early precipitation within soft sediments. In the shallow diagenetic realm, replacive dolomitisation of the sediments, and successively pore-lining, or pore-occluding dolomite cement precipitation took place (as described by Sibley, 1982; Kaldi and Gidman, 1982). Dolomite cement filled biomoulds indicate a stage of aragonite dissolution prior to dolomite precipitation that most likely occurred during replacive dolomitisation (Sun, 1992; Sun and Esteban, 1994; Purser et al., 1994). Anhydrite was continuously precipitated from saline pore waters and completed the filling of the fenestral pores.

Deep burial diagenetic processes
Several hundreds to thousands of metres of overburden is generally necessary to initiate dissolution under pressure (Tucker and Wright, 1990). Chemical compaction, which is usually referred to as a late diagenetic process, produced solution seams and stylolites, and reduced porosity with increasing overburden in deeper burial realm. Solution seams usually formed beneath thinner overburden whereas with further burial, stylolites were formed (Tucker and Wright, 1990). Recrystallisation of earlier precipitated anhydrite took place via pressure dissolution, indicated by the vertically elongated crystal-forms along the vertical wings of the stylolites.

Concurrently hydrocarbon migrated into the dolomites. Stylolites could have acted as important conduits for fluid migration (Tucker and Wright, 1990) since the dolomites had low porosity in the deep burial diagenetic environment. With increasing overburden the hydrocarbon became overmature. During progressive compaction the insoluble material was further concentrated along stylolites. Following fracturing a significant vuggy porosity was created via non-selective dissolution. Minor amounts of pore-lining dolomite cement and thereafter, toward the pore centre, anhydrite cement was precipitated from sulphate-bearing warm fluids and occluded all the free pore space. Vapour-bubbles enclosed within the inclusions reveal that the original trapping temperature was much higher than the Earth’s surface temperature (Goldstein and Reynolds, 1994). In many cases anhydrite-filled vugs cut across the stylolites, an indication of the deep burial formation of these diagenetic features. Thin open fractures associated with dissolution cut across all earlier diagenetic features (as well as the anhydrite-filled secondary voids) and acted as a pathway for hydrocarbon migration.

PARAGENETIC SEQUENCE OF WELL B CORE SAMPLES
Petrography
Event 1: Replacement dolomitisation
The major part of the sediments first underwent pervasive replacement dolomitisation. Two types of dolomites are distinguished on the basis of crystal size, such as finely and coarsely crystalline ones (Figure 9). Dark coloured, slightly argillaceous, finely crystalline dolomites (4–50 μm) contain well-preserved, fine horizontal, wavy lamination and slump structures. Detrital quartz silts along laminae and as well as in burrows are observed. In one sample ostracode shells are abundant and in some others echinoderm fragments are preserved.

Coarsely crystalline dolomite is composed of inclusion-rich, hypidiotopic to xenotopic mosaics of dolomite crystals 100–350 μm, exceptionally up to 500 μm, in size. The closely packed crystals mostly have curved, serrated intercrystalline boundaries, whereas the subhedral crystals possess straight compromise crystal boundaries and crystal-face junctions. Especially in the case of larger crystals
slightly undulose extinction is very characteristic. This type of replacement dolomites does not show any indication of the pre-existing limestone fabric. However, some samples retain the original texture in the form of dense, ovaly-arranged inclusions. Both finely and coarsely crystalline dolomites exhibit dull red luminescence.

**Event 2: Multiple alteration resulted in dolocrete intervals**

Two fabric types of dolocretes were distinguished. In the Core 3 samples, one of these types is characterised by massive or clotted, dense, finely crystalline dolomites, which occasionally contain lath-shaped anhydrite and detrital quartz silts. The lowermost part of the Core 2 represents the second type of dolocretes (Figure 10a and 10b). The microfabric is consists of clotted, peloidal micrites which contain dissolution channels and cracks, filled up by cement (Figure 10b). Peloids occur either as isolated particles or as coalesced masses within the dense cryptocrystalline dolomites. Otherwise, circumgranular cracks separate the glaebules from the surrounding finely crystalline groundmass. Many particles are micritized; however, fragments of foraminifers are still visible. Microscale dissolutional features include vertical solutional channels and vugs; additionally, partial leaching of the peloids was common. In the solutionally enlarged pores brownish, and successively greenish, dolomite crystal silts with small intraclasts and quartz sands form internal sediments exhibiting geopetal structures. Finally, non-luminescent, clear, drusy blocky dolomite spars fill up the remaining pore space. The above described texture is entirely dolomitised. The erosional surface in the sedimentary sequence is constrained by truncation that is covered by rip-up clasts and sand-sized detrital quartz grains embedded in a greenish dolomite silt matrix (Figure 10a). Above this 4 cm-thick green shale bed occurs.

**Event 3: Chemical compaction**

Microstylolites in coarsely crystalline dolomites at the contacts of crystals as well as stylolites and solution seams are expressions of dissolution under pressure. They mark some stages in the diagenetic succession.

**Event 4: Hydrocarbon migration**

The first stage of hydrocarbon migration is proved by scattered traces of insoluble residual hydrocarbon and pyrite in intercrystalline pores of coarsely crystalline dolomites and along solution seams and stylolites (Figure 9).

**Event 5: Fracturing**

Two stages of cross-cutting fractures, filled with cement, are observed in the samples. There is a generation of tensional fractures filled only with anhydrite cement.
**Event 6: Anhydrite cementation**
Mosaic or lath-shaped anhydrite cement filled the secondary pores created by fracturing (Event 5).

**Event 7: Fracturing and dissolution**
Solutionally enlarged fractures forming channel porosity are also identified (Figure 9) that cut across the first stage cement-filled fractures. The latter is associated with dissolution in the surrounding intercrystalline pores and often connects non-fabric-selective vugs.

**Event 8: Dolomite precipitation**
Medium to coarse (50–500 μm) euhedral dolomite rhombs occur in the secondary voids created by dissolution (Figure 11). However, there are intervals where they do not appear, whereas in other intervals they can occlude the relatively thinner veins and smaller pores. As a rule the crystals of this cement stage are limpid, or involve less inclusion than the replacive dolomite (Figure 11) and exhibit zonation (Figure 12a). Thus, they can be clearly distinguished under microscope, even if they are of the same size. Internal discontinuities within the crystals are revealed by CL, produced by a phase of dissolution interrupting cement precipitation (Figure 12b). The dolomite cement always post-dates the leaching of replacement dolomites (Event 7), although crystal overgrowth with optical continuity commonly occurs on top of coarse replacive dolomite.

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*Figure 10: Photomicrograph of beta dolocretes (Event 2). (a) Undulose eroded surface of clotted micrites (bottom) is covered by rip-up clasts embedded in dolomite silt matrix. (b) Details of the dolocrete fabric. Note clotted micrites with glaebules and vertical solutional channels filled with crystal silts and dolomite cement. Well B, Core 2, thin section No. 15, crossed polars.*
Figure 11: Photomicrograph of brownish coarsely crystalline replacement dolomites (Event 1) and clear, large pore-lining dolomite cement (Event 8) in a solutional vug (Event 7). Final pore-filling is anhydrite (Event 10; red). Well B, Core 2, thin section No. 21, crossed polars.

Figure 12: Photomicrograph of zoned rhombohedral dolomite cement. (a) Anhydrite cementation (Event 10; variable colour, bottom part) post-dates the dolomite precipitation (Event 8) in a vuggy pore. Detail of residual hydrocarbon-enriched stylolite is shown as a black irregular zone to the right. (b) CL image exhibiting mottled dull red core of the dolomite cement crystals, and two successive growth bands: non-luminescent and brighter dull red, respectively (Event 8). Note dissolution features post-dated the first, non-luminescent growth band but predated the second growth band. Note dull red finely crystalline replacement dolomite on top and right bottom corner (Event 1), and non-luminescent anhydrite cement on bottom (Event 10). Well B, Core 1, thin section No. 31, A: crossed polars.
Event 9: Pyrite precipitation
In some cases precipitation of minor idiopic pyrite cement predated anhydrite precipitation.

Event 10: Anhydrite cementation
Beside the dolomite cement (Event 8) and pyrite (Event 9), mainly anhydrite cement occurs within the secondary pores created by fracturing and dissolution (Event 7) (Figures 9, 11, 12a). Mosaic, lattice, or rarely poikilotropic anhydrite spar filled up all (but last generation) fracture and vuggy pores. Usually, the larger the pores the more elongated crystals were precipitated.

Event 11: Fracturing and dissolution
The last generation of fractures is still open and cuts across every other diagenetic feature. Etched edges of pore-filling anhydrite toward the open pore space in the partly open and partly cement-filled pores, and scattered traces of anhydrite in vuggy pores, reveal dissolution of the anhydrite precipitated in the previous stage (Figure 13). Open vugs are also common. Micropores, less than 20 μm across, were observable only after blue resin impregnation of the samples. Hydrocarbon migration was possible along open fractures, as well as along connected vuggy and intercrystalline pores.

Interpretation of the Paragenetic Sequence of Well B

Eleven successive diagenetic events have affected the carbonates, including dolomitisation. Early, syndepositional multiple diagenetic alterations occurred most likely pene-contemporaneously the dolomite replacement, but other processes had already operated in dolostones in the deeper burial realm.

Deposition and shallow burial diagenetic processes
There are only vague indications of the depositional environment. Occasionally wackestone texture with scattered echinoderm fragments is observed. The original depositional structures are sometimes well-preserved in finely crystalline dolomites, in the form of thin, horizontal and wavy lamination, bioturbation and slump structures. They point to an originally fine grain size of sediments and deposition in a low-energy subtidal environment. Otherwise, except for some samples, no relicts of primary sedimentary grains or textures can be recognised in the coarser crystalline fabric. In these cases ovaly-arranged inclusions most likely indicate rounded grain precursors in closely packed carbonate sand sediments, probably of a higher-energy subtidal facies. But as a rule dolomitisation obliterated all primary structures in the other part of the coarsely crystalline dolomites.

In Core 3 diagnostic features of peritidal deposits are observed, in the form of bundles of microbial filaments, clotted micrite of most likely microbial origin, and very fine lamination of most probable supratidal storm origin (Shinn, 1983). However, these textures are generally overprinted by pedogenic dolocrete formation that includes surficial diagenetic alterations under the influence of meteoric water (Wright and Tucker, 1991). Chalky texture of massive dense, finely crystalline dolomite with lath-shaped evaporite crystals is a characteristic feature of the alpha calcretes–dolocretes which are formed under arid climatic conditions (Wright and Tucker, 1991). A relatively thick series of pedogenic dolocretes is found in the lower part of the Core 3 that is overlain by a small-scale shallowing-upward unit of subtidal to peritidal–dolocrete facies.

Deposits in the lowermost part of Core 2 were affected by multiple diagenetic alterations, which resulted in pedogenic beta dolocretes, by means of which a disconformity surface was recognised. This sequence of a few dm thickness suggests development of a subaerial exposure surface under arid or semi-arid climatic conditions. This type of dolocrete was developed by predominantly biogenic influence and may reflect slightly different climatic control compared to the alpha type (Wright and Tucker, 1991). The lower part of Core 2 is composed of slightly argillaceous finely crystalline dolomites which change upsection with bed alternations into the coarser crystalline type (Cores 2 and 1). This succession may reflect an upward-coarsening unit of initial deposits that could be produced by a facies shift from deeper to shallower subtidal. A relatively great thickness of subtidal facies, which overlies a disconformity surface, supports the interpretation of a transgressive unit deposited on top of lowstand one (Table 2).
Except for the pedogenic dolocrete formation, in which dolomitisation and meteoric alteration processes operated together, the pervasive replacement dolomitisation was the first diagenetic alteration process for most of the deposits.

**Deep burial diagenetic processes**
Dolostones suffered diagenetic processes in the deeper burial realm, such as chemical compaction, hydrocarbon emplacement, fracturing and dissolution, and cement precipitation. In many cases there is clear evidence for their relative timing. The long-lasting chemical compaction, which is a crucial process in the deep burial diagenetic realm, operated in parallel with other processes, and marks more stages. Solution seams and stylolites most likely acted as conduits for hydrocarbon migration, and hydrocarbon filled-up the open intercrystalline pores. With increasing burial the hydrocarbon became overmature. As a result of chemical compaction the insoluble residue was probably further concentrated along stylolites. Alternating cross-cutting relationships prove that fracturing and subsequent anhydrite cementation took place in two stages during burial. Leaching is associated with the second stage of fracturing.

Open but partially anhydrite cement-filled vugs imply leaching of anhydrite precipitated in the previous stage. Open vugs might have been produced by total dissolution of anhydrite cement. Consequently, this stage of leaching post-dated anhydrite precipitation and was mainly mineral-selective.

**Correlation of Paragenetic Sequences**
Correlation of the observed paragenetic events is straightforward between the two cores. The same imprints of the main processes are identified in both sections; however, there are differences in details, or their relative importance (Table 3). The first major stage was the pervasive dolomitisation. Additionally, early diagenetic processes affected some intervals of the Well B succession and resulted in dolocrete formation. The same post-dolomitisation burial diagenetic events are present in both well samples in accordance with their regional or basin-wide effective range, i.e. fracturing, leaching, dolomite precipitation, anhydrite cement precipitation, hydrocarbon migration and chemical compaction. However, their activity can have varied locally. Moreover, an additional fracturing and subsequent anhydrite cementation stages occurred only in the Well B succession.
Table 3
Correlation of paragenetic sequences of core samples of the Kurrachine Dolomite.

| Diagenetic Events | Well A | Diagenetic Events | Well B | Porosity Increase/Decrease | Shallow Burial Relative timing | Deep Burial Relative timing |
|-------------------|--------|-------------------|--------|---------------------------|-------------------------------|----------------------------|
| Replacement dolomitisation | Replacement dolomitisation | + | - | | A | B |
| Dolocrete formation | Dolocrete formation | + | - | | |
| Dolomite precipitation | Dolomite precipitation | - | | | |
| Silica nodules | Indifferent | | | | |
| Baroque dolomite | Baroque dolomite | - | | | |
| Chemical compaction | Chemical compaction | - | - | | |
| Hydrocarbon migration | Hydrocarbon migration | - | | | |
| Fracturing | Fracturing | + | | | |
| Anhydrite precipitation | Anhydrite precipitation | - | | | |
| Fracturing and dissolution | Fracturing and dissolution | +++ | | | |
| Dolomite precipitation | Dolomite precipitation | - | | | |
| Pyrite precipitation | Pyrite precipitation | Indifferent | | | |
| Anhydrite precipitation | Anhydrite precipitation | - | - | | |
| Fracturing and dissolution | Fracturing and dissolution | ++ | | | |
| Hydrocarbon migration | Hydrocarbon migration | | | | |

**DISCUSSION**

**Dolomitisation Model**

The different types of dolomites most likely indicate a relationship between the depositional environments and dolomitisation processes. Two end-varieties of replacement dolomite crystalline fabric were identified in the core samples: fabric preserving cryptocrystalline and fabric destructive coarsely crystalline. The dolomite crystallinity is interpreted as a function of a combination of precursor grain size and timing of dolomitisation (Murray and Lucia, 1967). Accordingly, the different types of dolomites can be correlated to the original depositional facies of the precursor carbonates. In the case of the cryptocrystalline dolomites the many nucleation sites result in the retention of the sedimentary structures. This is well documented in modern arid supratidal dolomites where lime muds are commonly dolomitised preferentially (Shinn, 1983; Tucker and Wright, 1990). The coarsely crystalline dolomite type had fewer nucleation sites and the crystals grew and replaced many microcrystals of the grains, producing fabric destructive dolomite types from most probably subtidal precursor deposits (Sibley, 1982). Accordingly, the samples from Well A and Core 3 of Well B represent subtidal–peritidal cycles developed in a more marginal setting, whereas samples from most of Cores 1 and 2 of Well B supposedly reflect subtidal deposits developed in more basinward, open marine environments.

The evaporative and hypersaline reflux model is inferred from textural features and the presence of early diagenetic evaporite precipitates. According to the evaporative and hypersaline brine reflux dolomitisation model under arid climate conditions and in periods of small sea-level fluctuations (Read and Horbury, 1993), initially only tidal flat laminites are dolomitised. But with repeated progradation, carbonate cycles deposited during high frequency sea-level fluctuation become completely dolomitised by the downward penetrating hypersaline waters (Tucker and Wright, 1990; Mutti and Simo, 1994; Nicolaides, 1995; El-Tabakh et al., 2004). Applying this model to the Kurrachine Dolomite core samples is justified by the following characteristics: shallowing-upward subtidal and subtidal–peritidal depositional cycles, evidence of subaerial exposure, textural retention of replacive dolomitisation in the case of fine crystal size, and regional pervasive dolomitisation.
Synsedimentary diagenetic origin is assumed for the fabric preserving cryptocrystalline dolomites, where sediment replacement was triggered by evaporative pumping of hypersaline pore water (Shinn, 1983). Desiccation fenestral pores formed during subaerial exposure were preserved because they formed in an active diagenetic environment, where early lithification was common. This is an argument for the early and relatively rapid replacement dolomitisation in shallow subsurface tidal flat environment (Shinn, 1983). Minor dissolution, creating crystal moulds, most likely took place during wet seasons.

Over a relatively longer period of subaerial exposure, sequences of pedogenic dolocretes developed under the influence of meteoric pore water (Wright and Tucker, 1991). Alfa dolocretes occur in Core 3 of Well B that are characterised by dense, fine crystals, assumed to have been formed via replacement-recrystallisation, and autigenic crystal precipitates (anhydrite). Beta dolocretes and a disconformity surface are recognised in the lower part of Core 2 of Well B. Characteristic features are (1) desiccation cracks, (2) multiple effects of precipitation and dissolution within clotted dolomites, (3) micritization, (4) erosional surfaces and (5) overlying intraformational conglomerates with dolomite silt matrix, capped by green shales. Non-luminescent crystals are thought to have been precipitated under oxidizing conditions.

Dolomitisation of the subtidal sediments could have been related to downward migrating Mg2+-rich fluids that derived from the evaporative supratidal environment (Clark, 1980). During the gradual replacive dolomitisation, fine-grained sediments were dolomitised early and preferentially while coarser-grained, sandy subtidal carbonates were replaced later on during diagenesis. In the latter case ghosts of probable precursor carbonates were preserved. For coarsely crystalline dolomites, which are completely fabric destructive, deeper burial dolomitisation is inferred from petrographic evidence. Slow replacement with a relatively low dolomite saturation level during rising temperature is assumed, leading to a diminishing of the original sedimentary textures (Sibley and Gregg, 1987). Dull red luminescence of crystals of this latter type implies formation from negative Eh waters where Mn2+ and Fe2+ ions were also present (Tucker and Wright, 1990).

In addition, dull red cathodoluminescence of previously-formed shallow subsurface dolomites could provide evidence of further interaction with basal pore fluids. It may reflect stabilization and recrystallization during progressive burial (Land, 1985), since early diagenetic tidal flat dolomites commonly form as metastable dolomites (McKenzie, 1981; Mazzullo, 2000). However, integrated geochemical data would be needed to support these interpretations (e.g. Montañez and Read, 1992; Mazzullo, 1992).

Precipitation of dolomite continuously succeeded the replacement dolomitisation in the shallow subsurface of the tidal flat environment, since most likely there was a continuous supply of dolomite reactants into the open system, which stimulated further crystal growth (overdolomitisation, Sun and Esteban, 1994). As a consequence dolomite cement occluded most of the remaining porosity left open by replacement dolomitisation in the peritidal deposits. The dolomite cement was probably precipitated from a similar marine-derived fluid that was responsible for the early diagenetic formation of replacement dolomite. The CL pattern of crystals is thought to relate to the increasingly reducing nature of pore fluids.

The appearance of baroque dolomites as vein-infilling or scattered replacive crystals reveals a successive dolomitisation stage, which was controlled by rising temperature during further burial (Radke and Mathis, 1980). Silica probably migrated with the dolomitising fluid and replaced anhydrite before compaction.

**Burial Dissolutions and Cementation**

After dolomite formation had been completed, significant porosity was created during burial. In order to create such a vuggy porosity, fluid undersaturated with respect to dolomite and high capability of dissolution was required. Since anhydrite precipitated successively in the secondary pores one can assume that the same sulphate-bearing, warm basinal fluids were responsible for this as well as for leaching. Burial dissolution of sulphate evaporites of the overlying Kurrachine Anhydrite Formation,
as a consequence of chemical compaction, might have led to the generation of Ca\textsuperscript{2+}-rich fluids capable of dissolving dolomite (Tucker and Wright, 1990). Structural deformation could have generated deep fractures along which such formational fluids could have migrated. Accordingly potential control factors appear to have been the proximity to major faults or fault zones and the presence of evaporitic units.

Significant leaching of dolomites may have led to supersaturation of formational fluids with respect to dolomite, which favour dolomite cement precipitation. Fluids probably repeatedly recharged the pathways and led to the interrupted precipitation of dolomite by temporal dissolution, which is reflected in the CL zonation of the cement crystals. This may be characteristic for the relatively stagnant zones. The CL zoning of the dolomite crystals also reflects the subtle variations in the ratio of Fe and Mn that records slight changes in chemistry of the formational porewater (Tucker and Wright, 1990). Subsequently, anhydrite cement was precipitated in the rest of the pore space or exclusively in the entire pore space from the Ca-rich residual fluids. The latter possibility may occur in more active zones of fluid circulation, where pore waters could remain undersaturated with respect to dolomite. Two-phase fluid inclusions of anhydrite indicate elevated temperatures of pore fluids during precipitation. The cement precipitation rates are usually low in the burial environment and as a result large crystals were developed. Especially the large poikilotopic spar cement reflects the very low nucleation rate and slow crystal growth. For example, similar late diagenetic pore-occluding anhydrite cement, which post-dates dolomitisation, was described by Nicolaides (1995) and El-Tabakh et al. (2004). The appearance of pyrite was triggered by reduction of sulphate of the formational fluids by dolomite rocks, containing iron, at their contact.

The last leaching stage selectively affected the anhydrite cement. Thus the responsible fluid had to be different from that which precipitated anhydrite cement in the previous stage. Vuggy porosity formation through anhydrite leaching is interpreted to have been created by CO\textsubscript{2}-rich waters generated during hydrocarbon maturation, which migrated ahead of hydrocarbon (Tucker and Wright, 1990; Esteban, 2005). A similar corrosion feature was described from Miocene carbonates deposited under arid climate conditions (Sun and Esteban, 1994). The latest stage of hydrocarbon migration was possible along open fractures, and as well as along connected vuggy and intercrystalline pores. Accordingly possible control factor would have been the mixing of brines and local inflow of organically-derived CO\textsubscript{2} associated to fracturing.

**Diagenetic Control on Porosity Evolution**

For modelling the diagenetic control of porosity evolution of the dolomites a number of analogies for the Kurrachine Dolomite are provided from the literature. The conceptual model of Lucia and Major (1994) for porosity evolution through hypersaline reflux dolomitisation illustrates how porous and non-porous dolomites can form in the ramp system capped by tidal flat deposits. The most porous dolomites are located in the subtidal intervals, similar to the carbonate examples of Sun and Esteban (1994). They found that the replacive dolomite porosity is a function of the tidal flat time span associated with high-stand sea-level. The volume of the porosity occlusion by dolomitisation increases with the time span of tidal flat conditions, and as a consequence the porosity reduction in subtidal carbonates is more pronounced from seaward to landward. According to the dolomitisation model of carbonates deposited in small-scale sea-level fluctuation cycles under arid or semi-arid climate conditions, the predicted reservoir shows strong potential for multiple pay zones and stratigraphic traps (Read and Horbury, 1993). Tidal flat carbonates and evaporites can provide extensive top and lateral updip seals (Sun and Esteban, 1994).

In the core section of the Kurrachine Dolomite the initial porosity was little altered or reduced by replacement dolomitisation. In the case of peritidal carbonates the fenestral porosity could have been locally high but was not preserved because of the successively precipitated dolomite and anhydrite cements. Otherwise there was a continuous supply of dolomite reactants into the open system that resulted in tight carbonates and porosity loss. Replacement dolomites exhibit a mouldic secondary porosity due to the pene-contemporaneous dissolution of probably aragonite skeletal components. Because of the limited number of bioclastic components and soluble evaporite crystals mouldic porosity was not significant. Almost all of the mouldic pores were occluded by dolomite cement soon after their generation. In the precursor finely crystalline as well as sandy subtidal limestones,
replacive dolomitisation produced intercrystalline porosity, on the evidence of residual hydrocarbon. In the deep burial realm stylolites formed conduits, serving as pathways for hydrocarbon migration. Hydrocarbons filled up the intercrystalline pores and with further burial and related temperature increase, the overmatured hydrocarbon plugged the pores in the form of insoluble residue.

In the core sections of Well B, pedogenic dolocretes relatively commonly cap the finely- or cryptocrystalline peritidal deposits. In these intervals the predominant alteration processes were most likely controlled by aridity of the climate (Wright and Tucker, 1991). In the case of the Kurrachine Dolomite the beta dolocretes are tightly cemented whereas alpha dolocretes possess a chalky texture. Some microporosity, associated probably with low permeability, is interpreted to have been created during alpha dolocrete formation and most likely survived into later diagenetic stages. The remnant of early intercrystalline pores could highly enlarge the effective surface and promote the later-stage deep burial dissolution. This would explain the high porosity values observed in the dolocretes.

The latest stage dolomitisation, triggered by rising temperature (baroque dolomites), only insignificantly altered the porosity. Further porosity and permeability destruction was related to intense pressure dissolution conditioned by lithostatic pressure that formed solution seams, micro-stylolites, and stylolites. A significant secondary vuggy porosity was generated as a consequence of dissolution by migrating basinal warm fluids. All these pores were subsequently filled by dolomite and anhydrite cements, which are precipitates of the same fluid. As a result, the vuggy porosity formed through leaching was entirely eliminated. Accordingly, at this stage of diagenesis, the anhydrite precipitation substantially lowered the reservoir potential.

The reservoir is characterized by latest-stage fracturing, which created fracture porosity which is still open. Since it opened pathways for fluids, CO₂-rich waters could thus be emplaced ahead of migrating hydrocarbon. It produced dissolutional vuggy porosity through its corrosive effect. The recent effective porosity is a function of the co-occurring fracturing and anhydrite leaching.

**CONCLUSIONS**

It is generally difficult to predict reservoir porosity and permeability trends in the Kurrachine Dolomite, since late diagenetic processes affected the dolostones and determined the reservoir potential. The diagenetic features indicate that pedogenic alpha dolocretes and coarsely crystalline replacement dolomites are more prospective for higher porosity values (up to 20%). Alpha dolocretes could have formed under arid climate conditions and in more marginal settings, or during lowstands of relative sea-level where sediments were exposed to meteoric water. Coarse crystalline dolomites are more likely related to shallow subtidal deposits consisting of sand-sized grains.

The effective vuggy and fracture porosity of the Triassic formation was created in dolomites; however, its development was not directly connected to dolomitisation process. The reservoir potential of the Kurrachine Dolomite in the two studied wells depends exclusively on the latest stage leaching that was controlled by the previous deep burial diagenetic processes. Because of mineral selectivity of the dissolution, vuggy pores most likely appear where abundant anhydrite was present previously. Fracturing opened the pathways for corrosive fluids, which migrated ahead of hydrocarbon.

Accordingly the previous stage of leaching of dolomites by sulphated fluids was essential. It was more pronounced in the active zones of flow; thus relatively wider channels and larger vugs occurred than in the more stagnant zones. Furthermore the fluid could remain undersaturated with respect to dolomite; therefore mainly anhydrite cement was precipitated in vuggy pores.

Fracturing preceding the leaching in both stages was essential since it opened the pathways for fluids, created fracture porosity and enhanced permeability. The higher porosity values of replacement dolomites are generally observed in coarsely crystalline dolomites; this might be due to the difference in the rheological behaviour of finely and coarsely crystalline dolomites. Calcrete–dolocrete facies generally have low porosity potential and their reservoir qualities are generally below economic viability (Esteban and Klappa, 1983). In the Kurrachine Dolomite the alpha dolocretes are interpreted to have preserved some early stage intercrystalline micropores with low permeability. Fracturing in these cases could highly enhance the connectivity and permeability before the leaching.
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