Mesozoic and Cenozoic carbonate systems of the Mediterranean and the Middle East: stratigraphic and diagenetic reference models – an introduction

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The contributions in this volume originally formed a set of presentations at a conference on the same theme held in Mallorca, Spain in 2006. The goal of this conference was to investigate the potential to develop age or architecture specific reference models for carbonate systems and reservoirs similar to those successfully developed for siliciclastic systems. The conference focused on the Mesozoic and Cenozoic carbonate sequences of the Mediterranean and Middle East. These sequences were chosen for a number of reasons. Firstly, they represent sequence development in a variety of basin settings within a contiguous geographical entity, the former NeoTethys Ocean (Fig. 1). The sequences were also formed predominantly within tropical or sub-tropical climatic zones (cf. Schlager 2003). Finally, the high levels of industry and academic interest in the region have generated many excellent multidisciplinary studies of these sequences, based on both the comprehensive datasets of hydrocarbon-bearing strata and the excellent surface exposures in the region.

In general, all Earth models underestimate the complexity of the subsurface and hence are intrinsically inaccurate. The value of developing such models, however, lies in the improved understanding of the processes controlling sequence development gained from their application (e.g. Ahr 1973; Read 1985; Burchette & Wright 1992; Handford & Loucks 1993; Pomar 2001; Bosence 2005). Extrapolating from data rich examples into areas where data coverage is poorer obliges us to distil out the generic from the specific and to propose appropriate subsurface analogues.

The two key variables in the development of carbonate sequences and reservoirs, which have a negligible effect on siliciclastic system development, are the biological origin and unstable chemical nature of the constituent material. Carbonate sequences are generated by dynamic, living systems that are *biologically reactive* and which frequently modify in response to changes in depositional environment. These responses can be both short term, for example when organisms react to locally induced palaeoecological changes in a particular depositional setting, or long term, as carbonate producing organisms evolve in response to physical changes in the Earth's biosphere (e.g. James 1983; Schlager 1991; James & Bourque 1992; Ager 1993; Kiessling *et al.* 1999, 2002; Simmons *et al.* 2007; Markello *et al.* 2008; Pomar & Hallock 2008; Pomar & Kendall 2008). A challenge for Earth scientists is to assess how the interaction of global processes (sea level, climate, plate tectonics, global carbon budget) along with biological evolution, determined the nature of both local and regional carbonate factories; and whether this interaction created an infinite variety of carbonate depositional systems, or a more limited and predictable number of sedimentation patterns distributed in a systematic manner in time and space. Similarly, the chemical reactivity of carbonate depositional systems introduces a complexity that is largely absent in quartz-dominated siliciclastic systems. The chemically reactive nature of carbonates is evident in the dissolution and precipitation of different mineral species in both the early phases of deposition (e.g. Choquette & James 1983; Budd *et al.* 1995) and in later burial and/or inversion phases controlled by geodynamic processes (e.g. Horbury & Robinson 1993; Purser *et al.* 1994; Braithwaite *et al.* 2004). This chemical reactivity commonly results in important alterations of the porosity/permeability patterns imposed by primary depositional textures and constituents. Similarly, the challenge here is to establish whether these processes generate an infinite variety of diagenetic end products or if certain generic and predictable patterns can be distinguished.

Most contributions in this volume deal with the stratigraphic architecture of carbonate depositional systems, whereas a smaller number of case studies also include the diagenetic aspects.

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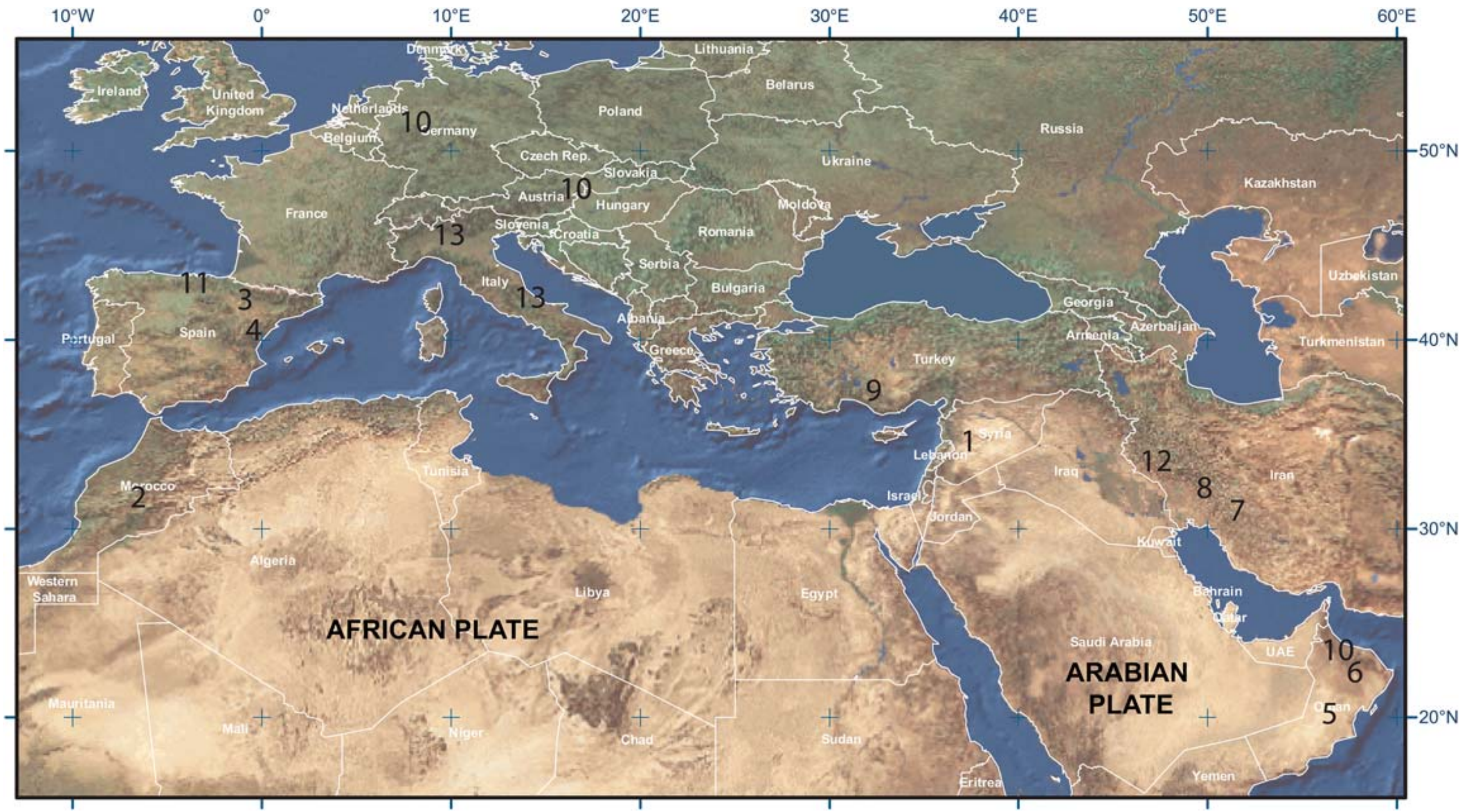

Fig. 1. Geographical map of the study area showing the locations of the case studies presented in this book. 1, Lucic *et al.*; 2, Pierre *et al.*; 3, Aurell *et al.*; 4, Embry *et al.*; 5, Droste; 6, Grelaud *et al.*; 7, Razin *et al.*; 8, van Buchem *et al.*; 9, Janson *et al.*; 10, Weidlich; 11, Rosales *et al.*; 12, Sharp *et al.*; 13, Ronchi *et al.*

Stratigraphic reference models

Carbonate-producing organisms are highly sensitive to changes in depositional environment, which makes them more precise recorders of physical and chemical, global- and regional-scale changes than siliciclastic systems. The biological evolution induced successive replacements of the main carbonate production modes, both in biotically-controlled skeletal production and biotically-induced precipitation (*sensu* Schlager 2003). Consequently, carbonate sequences show age specific stratigraphic characteristics (e.g. Kiessling *et al.* 2002; Markello *et al.* 2008), which suggest that any reference model classification of carbonate sequences should have a chronological aspect.

A key property of the hydrocarbon prospectivity of certain carbonate sequences is their capacity to be self-sourcing. This occurs when marine source rocks (organic carbon) are deposited as the basinal equivalents of shallow-water carbonates (mineral carbon) with reservoir potential within the same sequence. These intervals are of obvious economic interest and appear to be confined to specific intervals of the geological record (Tissot 1979; Klemme & Ulmishek 1990; Greenlee & Lehman 1993; van Buchem *et al.* 2005). Several examples of self-sourcing carbonate hydrocarbon systems are present in the area of interest. These were deposited during the Middle Triassic, Late Jurassic, Middle Cretaceous, Palaeogene and Oligocene–Miocene periods, and the industry interest is reflected in the comprehensive datasets and studies available for these intervals.

The introductory contribution by **Gerdes *et al.*** illustrates how changes in regional tectonics, eustacy and basin architecture acted as first-order controls on the variation of accommodation space available for carbonate deposition through time. The structural controls evident in the deposition of carbonate sequences are illustrated to explain why strikingly different carbonate platforms are developed during the same stratigraphic time interval in adjacent regions. The paper also illustrates, through a series of maps, the expansion of accommodation space that occurred during the Jurassic period and that culminated in the Late Cretaceous; and the even more rapid destruction of accommodation space during the Cenozoic in the Tethyan realm. The contrasts in carbonate sequence development both spatially and temporally are also related to variations in the surfaces of deposition that were ultimately controlled by the evolving submarine basin architectures.

The Triassic carbonate sequences in the study area illustrate both the relatively rapid recovery of carbonate organisms after the mass extinction event at the Permo-Triassic boundary and the control of basin architecture on carbonate sequence development. Two strikingly different systems are developed on differing basin architectures:

(a) Very large, shallow water carbonate platforms characteristic of the post-rifted passive margin of the Arabian Plate (e.g. Sharland *et al.* 2001). These are typically organized in decametre-scale depositional sequences consisting of carbonates, evaporites and dolomites. **Lucic *et al.*** provide an overview of the Triassic hypersaline ramp sequences of Syria that are an example of this type of platform deposition. The lithological variability is demonstrated in a framework of third-order depositional sequences, constrained by new palynological age dating.

(b) Isolated buildups of limited areal size, but of great thickness, that are characteristic of syn-rift deposition on the rapidly subsiding tilted fault blocks created during active extension along the northern NeoTethys margins. These are now spectacularly exposed in the Dolomites of northern Italy and are extensively documented in the literature (e.g. Bosellini 1984; Maurer 2000; Brack *et al.* 2007).

The Jurassic carbonate sequences are characterized by a variety of depositional geometries and carbonate producers, including microbial mounds, oolitic and bioclastic ramp systems (e.g. Leinfelder *et al.* 1994; Kiessling *et al.* 2002). The platform type that has attracted most attention from the petroleum industry in the focus area is the oolitic ramp. Two well-illustrated examples are presented in this volume. **Pierre *et al.*** describe a Lower–Middle Jurassic oolitic ramp system in the Atlas Mountains of Morocco, which has continuous exposure over a distance of 37 km, and has been dated precisely with ammonites. This paper describes a suite of fourth-order sequences that can be followed over tens of kilometres. An important feature of this outcrop study is the observation of beds of muddy, low-relief, transgressive deposits alternating with grainy, oolitic, high relief, higher energy regressive deposits within the fourth-order sequences. This clear organization is attributed to an as yet poorly understood climatic–biota interaction. **Aurell *et al.*** present a comprehensive study of the Upper Jurassic ramp systems in NE Spain along a 200 km long transect. This analysis documents shallow to deep water lithological transitions of oolitic, bioclastic and microbial-algal facies. The sequence stratigraphy is chronologically constrained by ammonite dating and is summarized in a sequence framework of first to fifth-order sequences.

The Cretaceous carbonate sequences in the study area are characterized by large-scale carbonate platforms, illustrating high frequency variations in carbonate margin growth and the contemporaneous deposition of extensive organic-rich shales in the oceans and intrashelf basins. Two time intervals, the Barremian/Aptian and Cenomanian/Turonian, have attracted particular attention due to their hydrocarbon content and as suitable sections with which to study the effect and extent of global events such as oceanic anoxic events (OAEs) on carbonate deposition. Barremian/Aptian times are characterized by the deposition of specific depositional facies that can be traced along the NeoTethyan coastlines from the Mediterranean to the southern margin of the Arabian Plate. These grainy, rudist-dominated facies of the 'Urgonian' platforms, contain the characteristic 'Orbitolina Beds' and the Lithocodium/Baccinella microbial facies, and pass laterally into the organic-rich basinal deposits of the Aptian OAE la or Selli event (e.g. Menegatti *et al.* 1998; Pittet *et al.* 2002; Wissler *et al.* 2002; Weissert & Erba 2004; Follmi *et al.* 2006; van Buchem *et al.* 2009). **Embry *et al.*** provide a good example of this facies succession exposed in excellent outcrops that illustrate a full carbonate sequence from platform to basinal setting along a 16 km transect in NE Spain. A particular aspect of this study is the description of well-preserved, Upper Aptian shallow-water deposits. These facies, which are absent in most peri-Tethyan localities, provide an example of an almost continuous Aptian carbonate sequence in outcrop. **Droste** provides a well documented subsurface study of the Aptian shallow-water platforms of Oman, based on a comprehensive dataset of 3D and 2D seismic data, well logs and core material. The similarity in the overall depositional architecture and facies distribution between these two localities, which are 5000 km apart, is striking, and makes a strong case for proposing an Aptian rimmed platform/intrashelf basin reference model (see also van Buchem *et al*. 2010).

The Cenomanian/Turonian platforms of the Arabian plate are presented in three case studies: both **Droste** and **Grelaud *et al.*** present subsurface and outcrop examples from Oman, and **Razin *et al.*** present a study of a fully exposed sequence along a 10 km transect in SW Iran. These papers provide complete and detailed pictures of the stratigraphic architecture that is considered typical of carbonate deposition on the margins of NeoTethys during this time interval. These authors describe a stratigraphic organization of four to five third-order depositional sequences, two of which include organic-rich source horizons in intrashelf basinal settings. The subtle variation in carbonate facies is thought to be in response to increased rates of sea level rise. These sequences are considered to have been initially eustatically driven and illustrate well-developed Mid-Cenomanian incised valley systems. Carbonate deposition became tectonically influenced during the late Cenomanian and Turonian, as obduction around the margins of the Arabian Plate caused regional inversion that was followed by another phase of surface incision. This tectonostratigraphic pattern is documented by the integration of the mapping of world-class outcrops, the interpretation of 3D seismic data, core descriptions and well log interpretations. These examples provide good sample sets upon which to base a Cenomanian/Turonian high angle rimmed platform/intra-shelf basin reference model for the Arabian Plate.

Carbonate sequences deposited during the Palaeogene and Neogene range from large Eocene platforms in a foreland basin setting, dominated by *Nummulites*, to smaller, more complex Oligocene and Miocene carbonate systems developed on submerged extensional and thrusted fault block crests (e.g. Esteban 1996; Franseen *et al.* 1996; Pomar 2001; Kelling *et al.* 2005; Gerdes *et al*. 2010) This variation in sequence type was influenced by a combination of structural control, depositional substrate morphology and the climatic changes associated with the passage from the Palaeogene thermal maximum, into the ice-house conditions that commenced at the Eocene–Oligocene boundary (Miller *et al.* 2005). The high amplitude, glacio-eustatically driven sea-level fluctuations typical for this time interval, had significant implications for the depositional geometries developed and led to the temporary isolation (and periodic desiccation) of the intramontane/intraplate basins in the area of interest such as the Dezful Embayment and Mediterranean. **van Buchem *et al.*** present a basin scale study, constrained by Sr isotope stratigraphy and a revised biostratigraphic zonation, for the Dezful Embayment (SW Iran) that contains the prolific Oligo-Miocene Asmari Formation reservoirs. This paper suggests that glacio-eustatically driven sea level fluctuations strongly controlled the depositional geometries of the third-order sequences and led to the isolation of the basin and deposition of extensive evaporites during two well documented periods. The paper by **Janson *et al.*** describes a third-order, transgressive–regressive depositional sequence from the early Miocene (Burdigalian) in southern Turkey. The geometrical evolution and faunal content of the parasequence is described with reference to a 1.5 km outcrop section that provides a continuous view of the platform to basinal facies transition. This study shows a clear change from an oligotrophic fauna to a mesotrophic fauna, which the authors attribute to the significant climatic change from colder to warmer conditions that is thought to have occurred midway through the Burdigalian.

In summary, the above case studies provide material on which to base stratigraphic reference models such as the Jurassic oolitic ramp/low angle rimmed shelf sequence, the Cretaceous rudist-rimmed platform/intra-shelf basin sequences, and the Oligo-Miocene coral-foraminifera dominated buildup sequences. Notably the studies that are based on continuous exposures of entire carbonate sequences along platform/ramp to basin transitions, provide the ideal geometrical framework for the integration of different analyses and are the best basis for reference models. It is also in this type of outcrop that progress can be made in our, as yet, poor understanding of the exact interaction between the biological processes and the changing physical conditions of the Earth.

Diagenetic reference models

The classification of diagenetic reference models used in this volume, is based upon the geometrical relationship between the diagenetic bodies and the original sequence geometries. This creates a classification based on whether geobodies are concordant (stratabound), partially concordant (stratabound/non-stratabound) or discordant (non-stratabound) with the original stratal surfaces. This classification implies that the original stratigraphic architecture of the target sequence is known. The expression of these three types of reference models is principally controlled by the interaction of the stratigraphic architecture of the primary sedimentary system, with the fractures and faults created during post-depositional tectonics and the timing and composition of fluid flow.

A major challenge in diagenetic studies is the three-dimensional representation of diagenetic bodies. The stratabound diagenetic patterns are easiest to address because of their close link with the geometries of the sequence stratigraphic framework (e.g. Budd *et al.* 1995; Moore 2001; Ehrenberg *et al.* 2006; Lucia 2007). In rocks affected by burial diagenesis this geometrical aspect is much more difficult to document, and therefore relatively poorly illustrated in the literature. High resolution 3D seismic data and subsequent detailed seismic attribute analyses can generate images of diagenetic bodies in sequences where the acoustic impedance contrast between the host rock and the diagenetic products is sufficiently large. There are a number of examples of non-stratabound 'porosity aureoles' caused by hydrothermal diagenesis, which have been mapped using 3D seismic data from other parts of the world (Kidston *et al.* 2005).

A good example of stratabound diagenesis is provided by **Weidlich**, who compares the effect of diagenesis at sub-aerial exposure surfaces on Triassic sequence boundaries in different climatic zones. This outcrop-based study clearly demonstrates the importance of the consideration of global factors such as climate in the interpretation of diagenetic observations.

Rosales & Perez-García in an outcrop study from the Lower Cretaceous of Spain, provide a good example of a mixed stratabound/non-stratabound case study, where a detailed stratigraphic understanding is combined with a thorough diagenetic analysis. Distinction is made between sub-aerial exposure related meteoric diagenesis along the main sequence boundaries, controlled by the contrasting diagenetic responses of the primary sediment composition of the different platform environments, and later burial diagenesis caused by fluid circulation along restricted fault and fracture zones. The latter is interpreted to have had a minimal effect on the small-scale porosity and permeability of the samples studied. Another excellent example of a mixed stratabound/non-stratabound case study is presented by **Sharp *et al.*** This case study is exceptional because of the scale and continuity of the outcrop exposure upon which the study is based. The authors describe the mapping of three-dimensional seismic scale exposures of mid-Cretaceous carbonate sequences from the Zagros Mountains of Iran. The paper describes the extent to which the primary sedimentary facies and post-depositional fractures and faults have controlled the distribution and extent of diagenesis in the subsurface. The resultant reservoir is clearly non-stratabound at the seismic scale. However, detailed analyses reveal that there is a local stratal control on the distribution of porosity and permeability at the reservoir scale.

A clear example of non-stratabound, burial diagenesis is presented by **Ronchi *et al.*** who present diagenetic case studies from two different thrust belt settings that is, the Southern Alps and the Apennines. In both settings, pervasive dolomitization was observed, but the dolomitization can be traced to compositionally contrasting fluids using isotope geochemistry. The authors relate this difference to the contrast in the two tectonic settings at the time of dolomite formation. In the example from the southern Alps, high sub-aerial relief generated a large hydrodynamic head that resulted in an abundant fresh water intake into the carbonate sequence. This contrasts with the tectonic setting of the Apennine example where the sequences were submarine at the time of dolomite precipitation. Although different in composition, both cases display similar diagenetic trends. The authors propose that the 'diagenetic front' of dolomitizing basin fluids followed the lateral migration of the developing foreland basins in each case and hence the penetration of these diagenetic fronts was ultimately controlled by the structural evolution of the individual mountain chains.

Conclusions

This volume contains a number of stratigraphic and diagenetic case studies, some elements of which may serve as the basis for age and architecture specific reference models of carbonate sequences. The development of such models is considered to be an essential step in the incremental improvement of our understanding of carbonate sequences and the controls on their development.

The challenge to Earth scientists studying carbonate sequences now and in the future will be to integrate the ever-expanding volume and range of geological, geophysical, geochemical and reservoir performance information effectively to generate internally consistent models for carbonate deposition, sequence development and reservoir performance. Ideally such models, suitably scaled, will be equally applicable to academic studies, the exploration and development phases of the field life cycle and in the prediction of future reservoir performance.

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