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# Lower Cretaceous carbonate platform of the eastern Levant (Galilee and the Golan Heights): stratigraphy and second-order sea-level change

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**Abstract**

The marine succession of the late Early Cretaceous carbonate platform of the eastern Levant was located at the southern border of the Tethyan Ocean. The studied areas of Galilee and the Golan Heights represent a transect across the shallow inner platform. The investigations were focused on carbonate platform biostratigraphy and facies analysis. A precise stratigraphic interpretation of the Upper Barremian–Albian succession was compiled on the basis of the definition of larger benthic foraminifer biozones allowing subdivision of the succession into six well-dated intervals. Detailed analyses of facies and sedimentological parameters allow interpretation of platform development, in connection with platform geometry, as well as relative third-order and second-order sea-level changes. The observed facies patterns reflect a depositional geometry changing from a ramp to a flat-topped platform during Late Barremian–Middle Albian times.

Three second-order depositional sequences were recorded in the studied mid-Cretaceous succession of the eastern Levant (MCEL-1 to MCEL-3). The facies analysis clearly indicates their origin in relative sea-level variations. The stratigraphic framework allows biochronostratigraphic calibration of these depositional sequences (MCEL-1: Upper Barremian–Lower Aptian, MCEL-2: uppermost Lower Aptian–middle Upper Aptian, MCEL-3: middle Upper Aptian–Middle Albian) and correlation with stratigraphic charts of local and regional sequences. The second-order sequence boundaries and maximum flooding surfaces correlate with basic sea-level variations recorded on the Arabian Plate, here interpreted as originally eustatically enhanced by subsidence. Tethyan signals are recorded around the Aptian/Albian boundary. A noticeable deepening in the upper Lower Aptian correlates with an extended platform drowning during the Selli Level (Oceanic Anoxic Event 1a: OAE 1a). Orbitolinid beds at this level suggest a deepening facies and a possible response to nutrient enhancement developing at the continental margin during OAE 1a. Eight third-order depositional sequences were observed in the Upper Barremian–Albian interval. They comprise successions of the inner ramp facies from open marine to restricted lagoons or tidal flats. The age and frequency of the Upper Barremian–Lower Aptian sequences correlate with those observed on the Pacific guyots or the Arabian Plate suggesting influence by regional sea-level cycles.


*Keywords:* Lower Cretaceous; Eastern Levant; Carbonate platform; Orbitolinids; Biostratigraphy; Sequence stratigraphy

## 1. Introduction

The late Early Cretaceous carbonate shelf of northern Israel and the Golan Heights represents a part of the North African/Arabian Plate located at the southern border of the Tethyan Ocean (Fig. 1A). This study is focused on the Upper Barremian–Albian carbonate platform deposits. The eastern Levant carbonate platform, reaching from southern Lebanon to northern Egypt, is an excellent example of southern Tethyan platform development. It represents a location between the well-analysed platforms on the Arabian Plate and those located in the northern Tethyan Ocean. The region is characterised by extensional and compressive tectonic processes related to the opening and closure of the Neotethys

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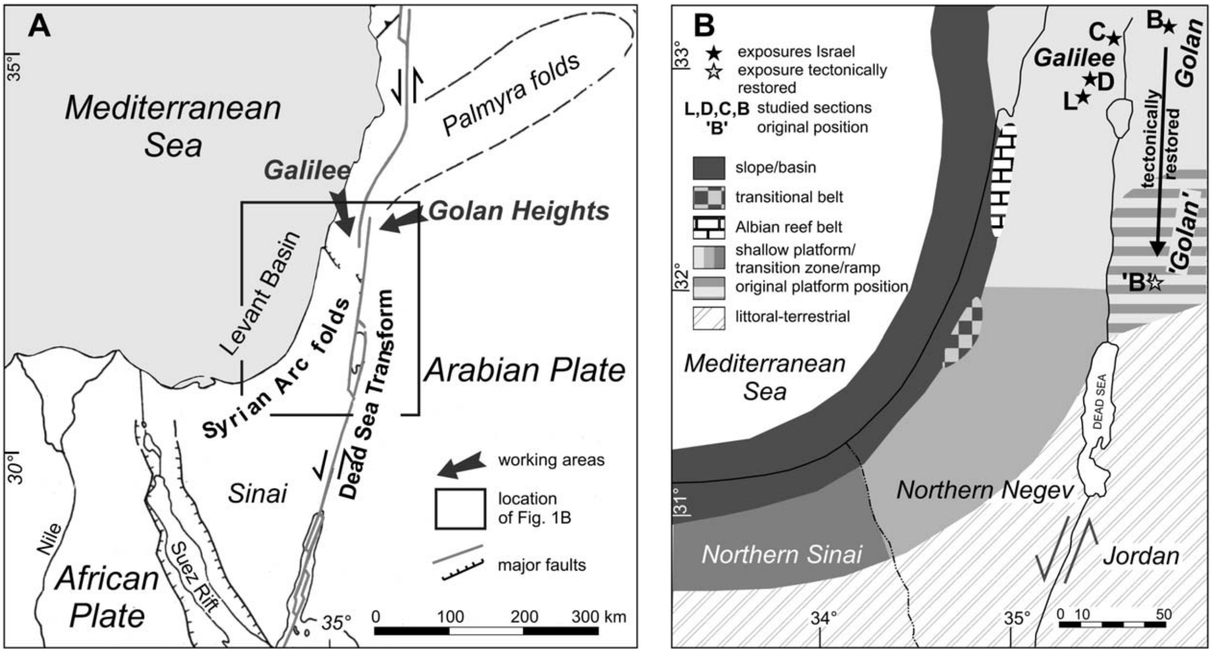


Fig. 1. A, tectonic map, simplified after Garfunkel (1998) with location of the study area straddling the Dead Sea Transform Fault. B, Aptian palaeogeographic map of eastern Levant, modified after Rosenfeld et al. (1998) and supplemented by results from northern Sinai (Bachmann and Kuss, 1998). The Albian reef belt is after Sass and Bein (1982). Asterisks indicate the four sections studied: L, Ein Netofa; D, Wadi Nabi Said; C, Har Ramim; B, Ein Quniya. 'B' indicates the tectonically restored position of Golan Heights section B.

(e.g., Keeley, 1994; Hirsch et al., 1995). However, the analysed interval represents a consistent platform development, indicating relative tectonic quiescence between these two phases. Former studies have concentrated on lithostratigraphy, and biostratigraphy based on ostracods and ammonites (Rosenberg, 1960; Eliezri, 1965; Hirsch et al., 1994; Rosenfeld et al., 1995, 1998), or on the tectonic background (Garfunkel, 1998). Few microfacies studies exist for single locations (Reiss, 1961; Eliezri, 1965; Babinot, 1995) or for southern Lebanon (Saint-Marc, 1974). The aim of this paper is to describe in detail the sedimentological parameters and a precise stratigraphic subdivision of the succession on the basis of benthic foraminifers (especially orbitolinids), allowing the interpretation of short-term and long-term platform development in connection with relative third-order and second-order sea-level changes.

Facies analysis has allowed reconstruction of platform facies zones, varying platform configurations, and the determination of depositional sequences. Detailed stratigraphic dating is the basis of the correlation of those sequences with the sequence-stratigraphic chart of Hardenbol et al. (1998), as well as with local and regional studies, and thus has led to the identification of local or regional controlling factors. It has also allowed identification of an interval corresponding to the major platform drowning in the Early Aptian (Föllmi et al., 1994; Masse et al., 1995), which is possibly linked to an important oceanic anoxic event (OAE 1a, Selli Level: Weissert et al., 1998), resulting in the interpretation of its possible impact on southern Tethyan platform development.

## 2. Material and methods

The underlying methods are the detailed determination of sedimentological data in the field, the analysis of microfacies and of larger benthic foraminifers. Four sections were sampled from two areas: three outcrops are located in Galilee (Har Ramim, Rama, and Ein Netofa) and one on the Golan Heights (Ein Quniya; Fig. 1B). Outcrops of marine Lower Cretaceous sediments are generally rare in Galilee and the Golan Heights, and unfaulted successions occur only in the northernmost areas. Thus, only the Har Ramim section (Galilee; Fig. 2) and the Ein Quniya section (Golan Heights) comprise the entire marine Lower Cretaceous succession (Upper Barremian–Upper Albian), whereas the other two sections only contain the lower part (Upper Barremian–Lower Aptian). The thicknesses of the sections are between 80 and 390 m. The sections were described in the field, including the weathering profile, bedding surfaces, sedimentary structures and facies. They were sampled in detail within the carbonate-dominated parts, with sample spacing of often $<1$ m, including most of the beds containing orbitolinids. The sample spacing is larger in marly and sandstone-dominated intervals.

Two hundred and nineteen samples were analysed in approximately 300 thin-sections. All thin-sections were analysed under the microscope for stratigraphically relevant fauna (benthic foraminifers and calcareous algae) and for facies composition. Since the taxonomy of the orbitolinids is largely based upon the internal structures, especially the embryonic apparatus (e.g., Schroeder, 1975; Simmons et al., 2000), the analyses concentrated on specimens in which embryonic apparatus was


Fig. 2. The Har Ramim section, Galilee, comprising the entire Lower Aptian–Middle Albian succession.

cross-cut in axial section. If orbitolinids were present but not cross-cut in an accurate section, more thin-sections of the sample were prepared. Differences in the test shape of orbitolinids (discoidal or conical), depending on the environment (e.g., Vilas et al., 1995; Pittet et al., 2002), were involved in the facies interpretation. The biostratigraphic information is summarised in the definition of six larger foraminifer biozones (LFBs), based on the first occurrence (FO) and/or last occurrence (LO) of different species, ranging from Upper Barremian to Upper Albian (Section 4.1, below).

Detailed facies analysis under the microscope allowed determination of the ratio between matrix and components, and the composition and grain-size of the skeletal and non-skeletal components, and differentiation between ‘‘abundant’’, ‘‘common’’ and ‘‘rare’’ relative frequencies. These analyses are summarised in the definition of facies zones, which include a set of microfacies types.

Further steps of interpretation followed the biostratigraphic and microfacies analyses: the sections were correlated according to biostratigraphic parameters. Interpretations of the depositional environment, drawn on the basis of sedimentary structures and microfacies analyses, resulted in the development of a platform model for the mid-Cretaceous. On the basis of facies changes, an interpretation of different-order depositional cycles in the individual sections, and correlation of those cycles between the sections, was drawn and adjusted within the biostratigraphic framework. Here, we first consider changes in depositional depths. Even if facies-zone distribution patterns on carbonate platforms are controlled by several parameters, the determination of vertical variations allows the recognition of water-depth changes. The lateral variations of those changes observed in the correlation of the sections enabled us to draw conclusions on progradation and retrogradation of the facies belts. Lateral and vertical variations allowed the determination of the accommodation patterns.

All of these methods led to the development of a chart of the local cyclic development on a fine scale. On the basis of the biostratigraphic framework, we compare these third- and second-order depositional cycles with patterns from different regions (e.g., Hardenbol et al., 1998; Röhl and Ogg, 1998; Sharland et al., 2001) and discuss the controlling factors in terms of local and regional sea-level changes, climate and tectonic influence.

## 3. Geological framework

### 3.1. Tectonic framework

Mesozoic tectonic processes in the eastern Levant region were related to the opening and closure of the Neotethys (Keeley, 1994; Hirsch et al., 1995) and may be subdivided into three main phases: (1) Permian–earliest Cretaceous extensional tectonics related to widening of the Neotethys and development of subsiding areas. Succeeding the abortion of a Triassic deep under Galilee, a Jurassic embayment developed (Hirsch, 1996), framed by heights in Galilee and southern Israel. From the Late Jurassic onwards, the development of the Levant Basin (Fig. 1A), and a swell bordering this basin in the east, characterised the region, leading to the development of an African/Arabian passive continental margin during the Early Cretaceous (Garfunkel, 1998). (2) An Early–mid-Cretaceous phase of subsidence and transgression. This generated shallow-marine platform conditions in a relatively narrow strip, subparallel to the Mediterranean coastline, from Lebanon and Syria across Israel to northern Sinai and Egypt (Fig. 1B). (3) Late Coniacian–Palaeogene compressive tectonics triggered by the initial closure of the Neotethys (Guiraud, 1998). This resulted in the development of the Syrian Arc system (Krenkel, 1924; Shahar, 1994; Walley, 1998), extending from northern Sinai to Lebanon and Syria (Fig. 1A). Post-Oligocene separation of the Sinai Subplate from the African Plate, and its rotation, resulted in the formation of the Gulf of Suez, the post-Miocene transform fault along the Dead Sea, and a complex system of faults and half-grabens (Knott et al., 1995; Badawy and Horvath, 1999). The area studied is cross-cut by the Dead Sea Transform Fault, resulting in the left-lateral displacement of Galilee against the Golan Heights (Garfunkel and Ben-Avraham, 1996); the restored position of the Golan exposures is located 105 km south of its present position (Fig. 1B).

*3.2. Platform geometry and depositional environment*

During the Early Cretaceous, the depositional geometry of the region studied was characterised by the shallow eastern Levant Platform (Fig. 1B). Roughly 100 km separate the platform rim, located close to the present coastline, from the landward proximal border of the platform, characterised by a transition to terrestrial environments in the Negev, Jordan (Lewy, 1989), and southern Sinai (Bartov and Steinitz, 1977). A steep shelf-break is described from northern Israel (Carmel area; Fig. 1B) (Garfunkel, 1998). Here, rudist reefs developed during Albian–Cenomanian times (Bein, 1971; Sass and Bein, 1982; Ross, 1992). Basinal sediments occur close to these bioherms (Bein and Weiler, 1976), indicating a steep slope. From areas further south, a gradual shallow–deep transition has been described (Rosenfeld et al., 1998), until the geometry of a distally-steepened ramp is reached in the northern Sinai (Bachmann and Kuss, 1998) (Fig. 1B).

The platform itself comprised a wide area with interfingering, shallow, open-marine, lagoonal and brackish to freshwater environments (Rosenfeld et al., 1998). A landward-thinning wedge of Barremian–Cenomanian shallow-marine sediments accumulated in Galilee and the Golan Heights (Braun and Hirsch, 1994; Rosenfeld et al., 1998) as well as in adjacent regions (Negev: Lewy, 1989; Lebanon and Syria: Powell, 1989; Best et al., 1993; Sinai: Bachmann and Kuss, 1998). Progradation and retrogradation of these facies belts were interpreted as reflecting second-order sea-level changes (Braun and Hirsch, 1994).

*3.3. Stratigraphical concepts for Galilee and the Golan Heights*

The Lower Cretaceous strata consist of 400–700 m of continental and shallow-marine sediments (Rosenberg, 1960; Eliezri, 1965; Rosenfeld et al., 1995, 1998). The Late Barremian transition from terrestrial to marine sedimentation is rarely exposed, and its interpretation relies mainly on a few descriptions from the subsurface (e.g., Rosenfeld et al., 1995, 1998) and on rather poorly exposed sections at Mount Hermon, Golan Heights (Hirsch, 1996). For this reason, we start at the well-exposed, marine Upper Barremian strata.

The Lower Cretaceous lithostratigraphy in the study area compares well with that in Lebanon (Heybroek, 1942), from which the earlier subdivisions used in Galilee were adopted (Rosenberg, 1960; Reiss, 1961). We have broadly followed the formal subdivision of Eliezri (1965) and Rosenfeld et al. (1995) (Fig. 3) that applies to both Galilee and the Golan Heights.

The terrestrial deposits of the base of the succession are known as the Hatira Formation. They consist mainly of sandstones and occur in northern Israel only in the subsurface (Rosenfeld et al., 1998). They are overlain by a sedimentary succession about 440 m thick that is subdivided into five formations: Nabi Said, Ein el Assad, Hidra, Rama and Yagur (Fig. 3).

Although some ammonites occur in the upper part of this succession (Hirsch, 1996), biostratigraphic subdivisions have been based on various benthic foraminifers and calcareous algae (Rosenberg, 1960; Reiss, 1961; Saint-Marc, 1974), as well as ostracods (Rosenfeld and Raab, 1984; Rosenfeld et al., 1995, 1998). The latter allowed a certain regional correlation to stage and substage level. The adoption of newer concepts (e.g., Hardenbol et al., 1998) has led to a more detailed biostratigraphic subdivision of the strata.

## 4. Stratigraphy

*4.1. Determination of larger foraminifer biozones (LFBs)*

The prevailing shallow-marine conditions of the Late Aptian–Middle Cenomanian in the study region were favourable for the development of larger benthic foraminifers (mainly orbitolinids). A biostratigraphic subdivision into six larger foraminifer biozones (LFBs) is based on the FOs and/or LOs of different species, ranging from the Late Barremian to Late Albian (Fig. 4). As a stratigraphic guide, we have compared our biostratigraphic data with references on Early Cretaceous benthic organisms of the Tethyan Realm (Schroeder and Neumann, 1985; Arnaud-Vanneau, 1998; Arnaud et al., 1998; Conrad et al., 2004) and the Middle East (Saint-Marc, 1974; Simmons and Hart, 1987; Kennedy and Simmons, 1991; Simmons, 1994; Simmons et al., 2000) as well as with the chronostratigraphy of Hardenbol et al. (1998).

Orbitolinids are abundant in a wide range of mid-Cretaceous Tethyan platform habitats, from lagoonal to the deeper platform areas (e.g., Pittet et al., 2002), and are therefore important for the biostratigraphic interpretation of such platforms. The division into LFBs allows us to subdivide the succession analysed into well-defined stratigraphic intervals, which is very useful for the interpretation of the platform environment and its development in a regional context. The lower part of the succession especially is characterised by a continuous distribution of orbitolinids, thus their LOs and FOs at specific levels indicate well-defined biostratigraphic intervals.

Next to orbitolinids, consisting of *Palorbitolina* (one species), *Eopalorbitolina* (one species), *Praeorbitolina* (two species) and *Orbitolina* (*Mesorbitolina*) (three species), the taxa *Choffatella decipiens* and *Praechrysalidina infracretacea* are additionally used for biostratigraphic subdivision. Other common benthic foraminifers are the long-ranging *Buccicrenata hedbergii*, *Charentia cuvillieri*, *Vercorsella*, *Cuneolina*, *Glomospira urgonia*, *Quinqueloculina*, *Triloculina* and *Debarina*, which do not contribute to the subdivision. Green algae contribute little to age determination. They are generally uncommon and have long ranges. *Cylindroporella sugdeni* indicates the entire Barremian–Albian. *Actinoporella podolica* may have occurred from the Late Barremian onwards. The LO of *Hensonella dinarica* is in the lowermost Late Aptian in the

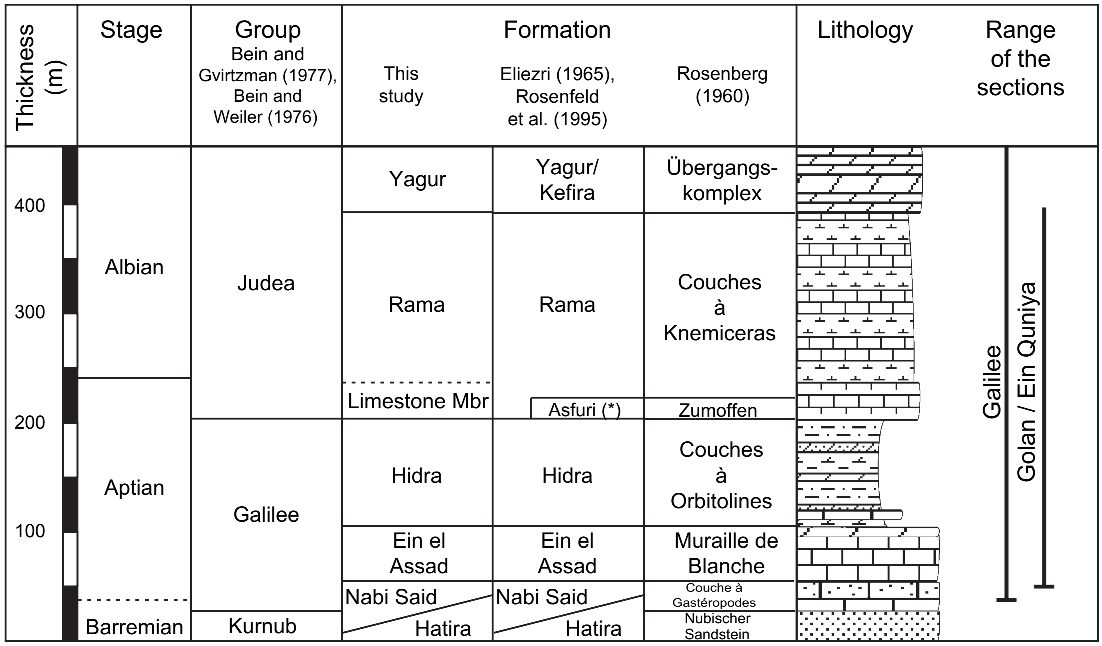


Fig. 3. Lower Cretaceous lithostratigraphy of Galilee and the Golan Heights. We have used a modified version of the subdivision of Eliezri (1965) in our paper. * Asfuri Limestones according to Eliezri (1965). See also: Bein and Gvirtzman, 1977; Bein and Weiler, 1976; Rosenfeld et al., 1995; Rosenberg, 1960.

Periadriatic (Masse, 1998). *Triploporella marsicana* indicates the Lower Aptian (Masse, 1998).

#### 4.1.1. LFB Pl-Cd (Palorbitolina lenticularis-Choffatella decipiens): middle Upper Barremian–lowermost Aptian

The base of this LFB is defined by the FO of *Palorbitolina lenticularis*. The biozone is characterised by the co-occurrence of *P. lenticularis* (Fig. 5A) and *Choffatella decipiens*. Of the accompanying fauna, *Triploporella marsicana*, *Actinoporella podolica* and *Eopalorbitolina charollaisi* are of greater importance for the age definition of the zone. However, only a single specimen of *E. charollaisi* was found in the lowermost part of the Nabi Said locality (Fig. 6). *T. marsicana* and *A. podolica* occur in the Ein Quniya section in the uppermost part of the LFB (Fig. 7).

The age of the zone is indicated by the FO of *P. lenticularis*. This occurs in middle Late Barremian deposits in the Tethyan realm, whereas in the Adriatic area, it does not occur in beds older than Early Aptian (Arnaud-Vanneau, 1998). Studies on the Arabian Plate indicate a middle Late Barremian FO for *P. lenticularis* (Simmons, 1994; Witt and Gökdağ, 1994; Simmons et al., 2000). The occurrence of *E. charollaisi* also indicates a Late Barremian age for the lower part of the *Pl-Cd* LFB. However, the range of *E. charollaisi* is controversial: Clavel et al. (1995); Conrad et al. (2004) indicated a middle Early Barremian age, whereas Arnaud et al. (1998) described its occurrence extensively through the Late Barremian. The co-occurrence of *E. charollaisi* with *P. lenticularis* in the section studied thus indicates that the LO of *E. charollaisi* must be at least middle Late Barremian or younger (as indicated by Arnaud et al., 1998) and that the lower part of the *Pl-Cd* LFB is definitely not younger than Late Barremian. The occurrence of *T. marsicana* indicates an Aptian age for the uppermost part of the *Pl-Cd* LFB (Masse, 1998).

Altogether, the local range of the *Pl-Cd* LFB is uppermost Barremian–lowermost Aptian. The described parameters indicate the position of the Barremian/Aptian boundary in the uppermost *Pl-Cd* LFB. A Barremian age for the lowermost part of the succession, indicated by Rosenfeld et al. (1995) on the basis of ostracods, somewhat confirms our stratigraphic determinations for the lower part of the succession.

#### 4.1.2. LFB Pl (Palorbitolina lenticularis): lower Lower Aptian

The base of this LFB is defined by the FO of *Praechrysalidina infracretacea* and is characterised by the beginning of a local temporary absence of *Choffatella decipiens* just above. The biozone overall is characterised by the occurrence of *P. lenticularis*. The following calcareous algae are present in some samples: *Cylindroporella sugdeni*, *Actinoporella podolica*, *Hensonella dinarica* and *Triploporella marsicana*.

*P. infracretacea* indicates an Early Aptian or younger age (Schroeder and Neumann, 1985). *C. decipiens* has a long range, from Hauterivian to Lower Aptian (middle Lower Aptian in Simmons, 1994; lower Upper Aptian in Witt and Gökdağ, 1994), but its local temporary absence from the lower LFB *Pl* is typical in all sections analysed (Fig. 7). This absence starts synchronously within the different sections and is very useful as a local time-line. Similar eclipses in the Lower Aptian occur in Oman (southern Tethys: Witt and Gökdağ, 1994) and in the Prebetic Zone (Spain, northern Tethys: Castro and Ruiz-Ortiz, 1995). *C. decipiens* remains scarce in

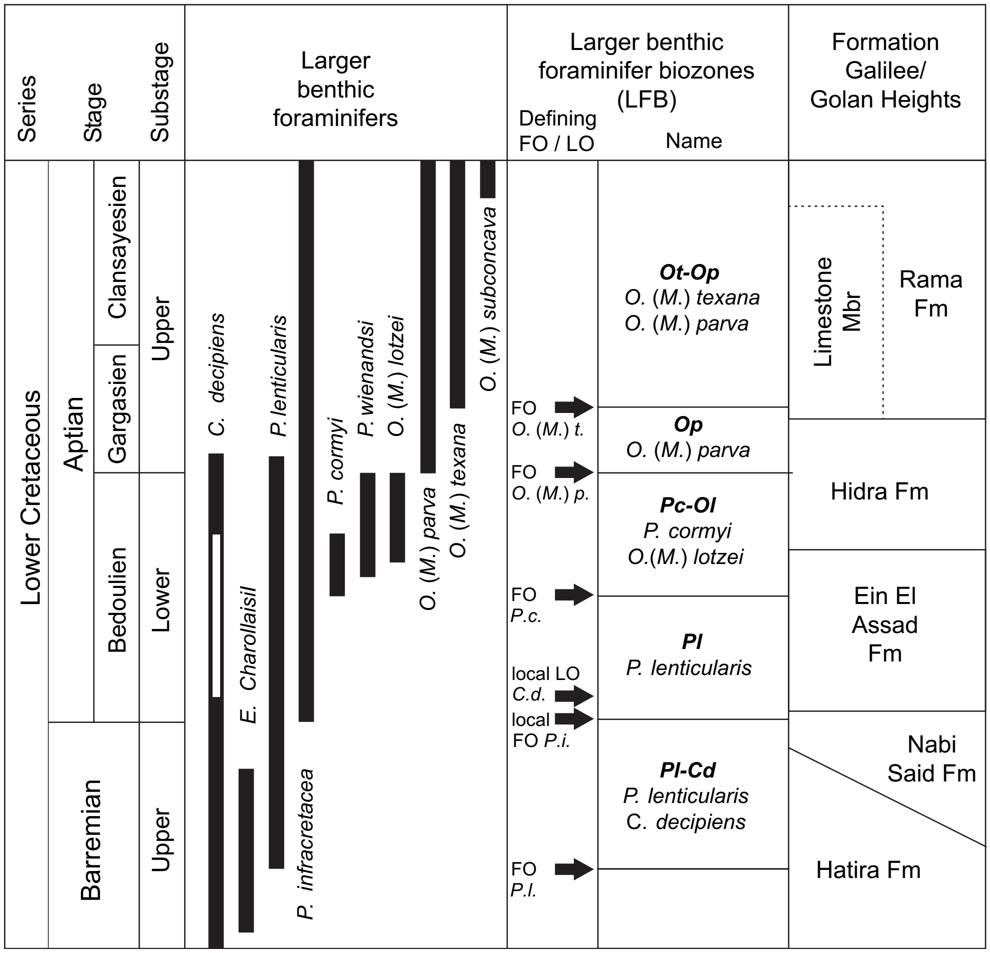


Fig. 4. Biostratigraphic subdivision of the Upper Barremian–Aptian and ranges of the larger foraminifer biozones. The ranges of the most important benthic foraminifers were compiled from several authors (see text) and arranged in the chronostratigraphic framework of Hardenbol et al. (1998).

the upper part of this LFB (Fig. 7). The Early Aptian age of the biozone is further confirmed by the presence of *T. marsicana*.

#### 4.1.3. LFB Pc-Ol (*Praeorbitolina cormyi* – *Orbitolina (Mesorbitolina) lotzei*): upper Lower Aptian

The base of this LFB is defined by the FO of *P. cormyi* (Fig. 5B). Relevant for the definition of this biozone are also the FO and total range of *Praeorbitolina wienandsi* (Fig. 5C) and *O.* (*M.*) *lotzei*.

The age of the base is defined by the FO of *P. cormyi* in the early Early Aptian (according to Arnaud-Vanneau, 1998). *P. wienandsi* and *O.* (*M.*) *lotzei* have somewhat younger FOs in the upper Lower Aptian and LOs around the Lower/Upper Aptian boundary, according to Simmons et al. (2000). Schroeder (1975) gave a younger LO for *O.* (*M.*) *lotzei* (earliest Late Aptian) and an older one for *P. wienandsi* (below the Early/Late Aptian boundary).

Within the sections studied, *P. cormyi*, *P. wienandsi* and *O.* (*M.*) *lotzei* have similar ranges. Hence, according to the available stratigraphic information, the LFB represents the upper Lower Aptian.

#### 4.1.4. LFB Op (*Orbitolina (M.) parva*): lowermost Upper Aptian

The base of this LFB is defined by the FO of *O.* (*M.*) *parva* (Figs. 4, 5D). Described by Schroeder (1975) only from the Upper Aptian, *O.* (*M.*) *parva* was reported by Velic (1988) to have a range of Upper Aptian–Lower Albian; and Arnaud-Vanneau (1998) indicated an Upper Aptian–Middle Albian range in the Adriatic and Tethyan realms. In some mid-Cretaceous successions of Oman, *O.* (*M.*) *parva* is regarded as no younger than Late Aptian (Witt and Gökdağ, 1994).

The local FO of *O.* (*M.*) *parva* in beds with transitional forms of *O.* (*M.*) *lotzei-parva* gr. suggests that the local FO of *O. (M.) parva* coincides with its evolutionary appearance, at approximately the Early/Late Aptian boundary.

#### 4.1.5. LFB Ot-Op (*Orbitolina (M.) texana* – *Orbitolina (M.) parva*): middle Upper Aptian

The base of this LFB is defined by the FO of *O.* (*M.*) *texana*. The biozone is characterised by the concurrent ranges of *O.* (*M.*) *parva* and *O.* (*M.*) *texana*.

An uppermost Aptian–Upper Albian range of *O.* (*M.*) *texana* is given by Arnaud-Vanneau (1998) for the Tethyan and Adriatic realms. In the study area, the FO of *O.* (*M.*) *texana*

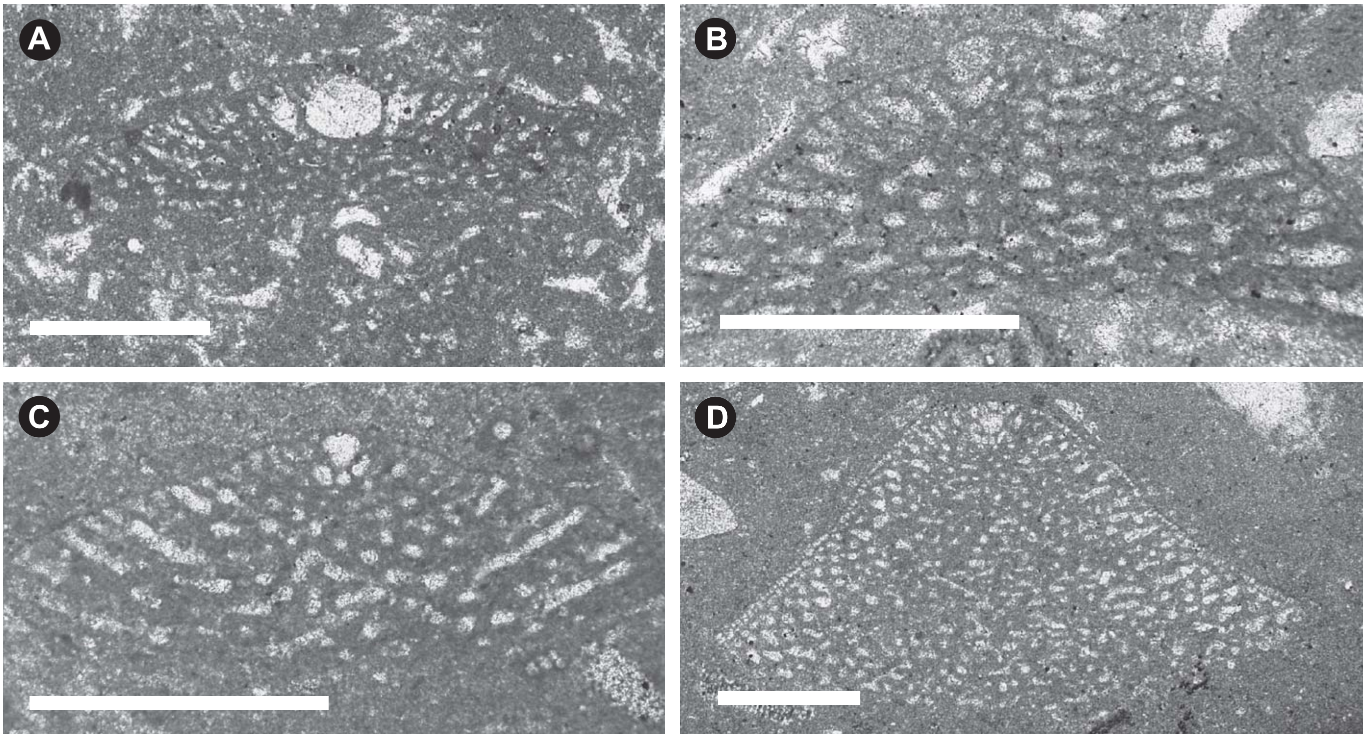


Fig. 5. Some orbitolinids characterising the larger foraminiferal biozones. A, *Palorbitolina lenticularis*, Har Ramim section, base Ein el Assad Formation (28 m, thin-section C I 10, photograph CI10-10x-1), B, *Praeorbitolina cormyi*, Har Ramim section, top Ein el Assad Formation (55 m, C I 20-1, CI20-1-10x-1), C, *Praeorbitolina wienandsi*, Ein Quniya section, top Ein el Assad Formation (42 m, B I 28, BI28-10x-HQ-2), D, *Orbitolina (Mesorbitolina) parva*, Ein Quniya section, top Hidra Formation (105 m, B II 9, BII9-4x-1). Scale-bars represent 0.5 mm.

nears the local LO of orbitolinids, which disappeared as a result of shoaling. Thus, a younger LFB, and an upper boundary for the *Ot-Op* LFB, are not defined. Rosenfeld et al. (1995, 1998) suggested a Middle–Upper Albian age for the overlying succession, which would include the LO of *O*. (*M*.) *parva*.

### 4.2. Stratigraphy of the sections and ages of the formations

The LFBs allow a fairly detailed dating of the Lower Cretaceous carbonate platform successions, from Galilee to the Golan Heights, as well as correlation between the sections, suggesting a synchronous deposition of most of the formations (Figs. 6, 7). This contrasts with the laterally interfingering formations in other areas, for example, southern Israel (Rosenfeld et al., 1995, 1998).

#### 4.2.1. Nabi Said Formation

About 45 m of limestones and marlstones are well exposed in Galilee but only a few metres are present on the Golan Heights (Hirsch et al., 1994). The Nabi Said Formation falls entirely within the *Pl–Cd* LFB and is latest Barremian–earliest Aptian in age (Fig. 7A). The top of the formation is only a few metres below the top of the *Pl-Cd* LFB (Fig. 7A). The lateral correlation of this biozone boundary, from Galilee to the Golan Heights, indicates the almost synchronous facies change from the Nabi Said Formation into the Ein el Assad Formation over the entire platform.

#### 4.2.2. Ein el Assad Formation

This prominent landmark is a 55-m-thick ledge of limestones, marlstones and dolomites, well developed in Galilee (Fig. 2) and on the Golan Heights. The base of the Ein el Assad Formation comprises the uppermost *Pl-Cd* LFB, while the top is within the lower part of the *Pc–Ol* LFB (Figs. 6, 7). Thus, the Ein el Assad Formation is entirely Lower Aptian. The lateral correlation of the base of the *Pc–Ol* LFB, from Galilee to the Golan Heights, again indicates a synchronous onset of the overlying Hidra Formation, which begins in all sections 8–10 m above (Fig. 6).

#### 4.2.3. Hidra Formation

Sandstone, marlstone and limestone alternations, well documented on the Golan Heights, reach a total thickness of about 95 m. In Galilee, the rare outcrops are strongly weathered. Rosenfeld et al. (1998) mention a thickness of 90 m in wells in the Har Ramim region (Fig. 2) and 120 m from the Rami region (close to Wadi Nabi Said). The lower part of the Hidra Formation does not contain orbitolinids, while its middle part contains the boundary between the *Pc-Ol* and *Op* LFBs, indicating proximity to the Lower/Upper Aptian boundary (Fig. 6). A Late Aptian age for the formation was determined by Rosenfeld et al. (1995) on the basis of ostracods.

#### 4.2.4. Rama Formation

The ca. 150-m-thick Rama Formation comprises nodular limestones and marlstones in northern Galilee and the Golan

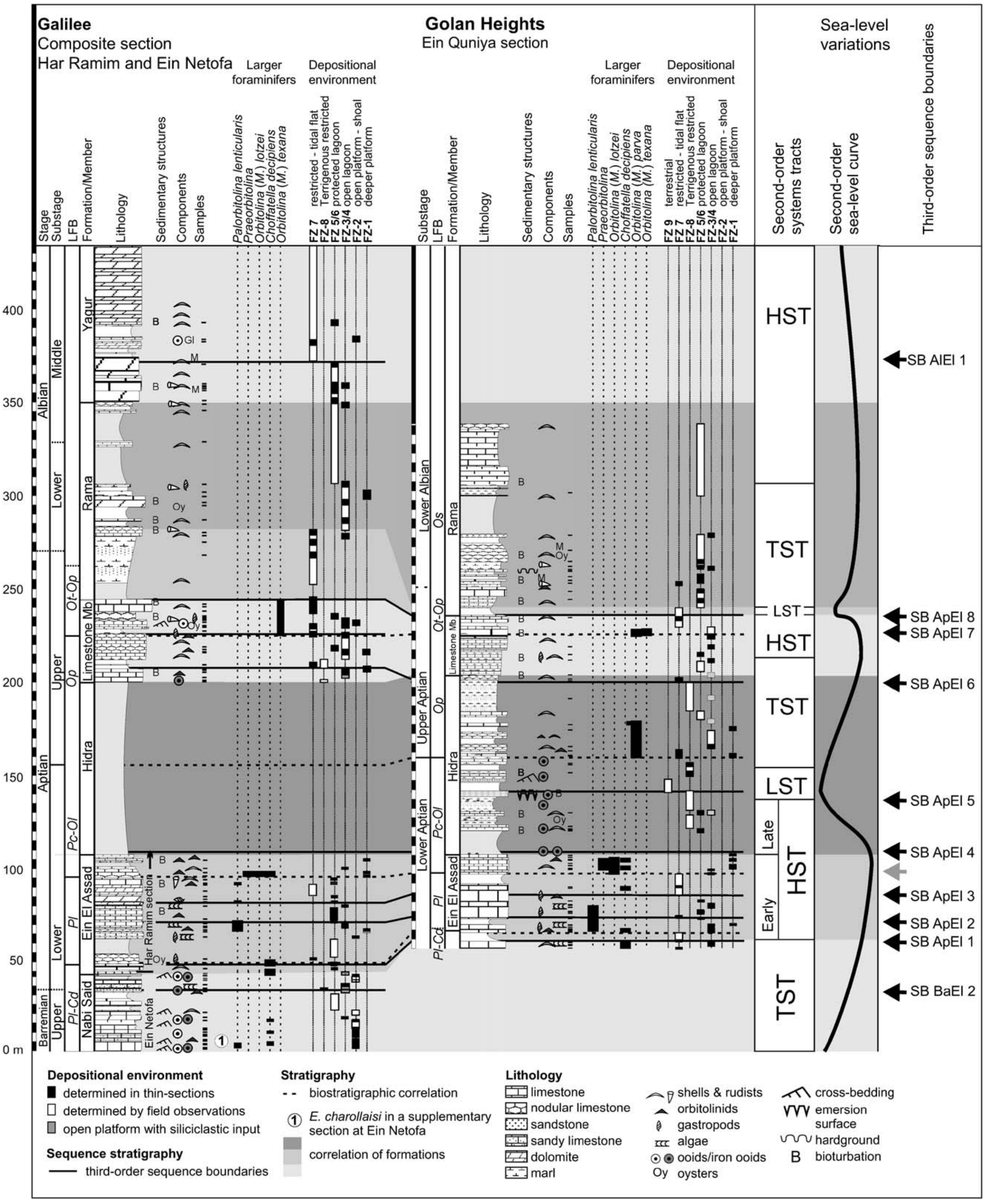


Fig. 6. Correlation of the Upper Barremian–Middle Albian successions of Galilee and the Golan Heights. Galilee is represented by a composite section (Ein Netofa section in the lowermost part and the Har Ramim section in the upper part). The graph indicates the most important sedimentary structures and components, the larger foraminifers, the larger foraminiferal biozones (LFBs) and the depositional environment determined (facies zones). Besides the second-order systems tracts and the respective sea-level variations, third-order sequence boundaries are shown by black arrows. A significant deepening event in the Early Aptian is marked by a grey arrow. For complete legend, see Fig. 9.

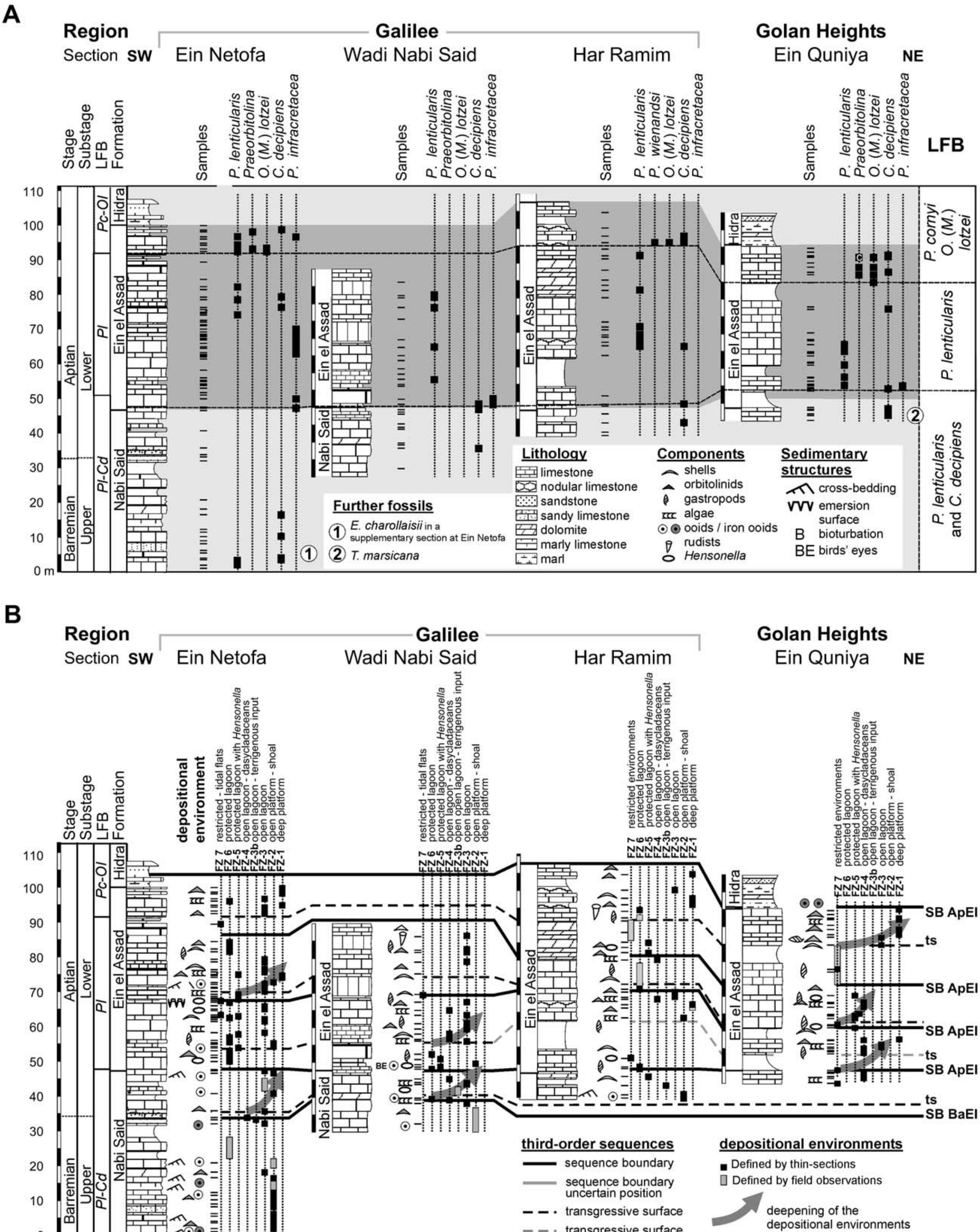


Fig. 7. Detailed biostratigraphic subdivision (A), and facies zone distribution and sequence stratigraphical interpretation (B) of the Upper Barremian–Lower Aptian succession in Galilee and the Golan Heights. A, the biostratigraphic correlation indicates a proximal thinning of the biozones (stippled lines) and formations (grey intervals). B, a distinct proximal–distal trend from east to west is visible in the distribution of components and sedimentary structures. Facies zone distribution allows the identification of shoaling–deepening cycles, which are well correlated between the sections and interpreted as third-order sequences. Sequence boundaries are characterised by significant shoaling or by emergence horizons. Deepening, and a trend towards more open-marine platform environments, mark transgressive surfaces.

Heights. At the base of the formation, a 35–40-m-thick Limestone Member is discriminated from the more marly middle and upper Rama Formation (Fig. 3). The Limestone Member straddles the *Op*/*Ot*-*Op* LFB boundary, still within the lower Upper Aptian, in the Har Ramim (Galilee) and Ein Quniya (Golan Heights) sections (Fig. 6). Orbitolinids are missing from the upper part of the sections. However, Rosenfeld et al. (1995) described Albian ostracods from the lower part of the formation (30 m above the base of the Har Ramim section) and Upper Albian ostracods from the upper part. Rosenberg (1960) mentioned finding different specimens of *Knemiceras* ammonites from the middle and upper Rama Formation in the Har Ramim area, also suggesting an Albian age.

*4.2.5. Yagur Formation*

Mainly composed of dolomitic marlstones and dolomites, the Yagur Formation was studied in the Har Ramim/Galilee section. An age determination is not possible on the basis of the available data, because age-diagnostic fossils are not present. We follow Rosenfeld et al. (1995), who indicated a Middle–Late Albian age for the formation based on the observed interfingering of the formation with limestones rich in Albian ostracod assemblages in the adjacent Judean area. This dating allows us to infer a major reduction in sediment accumulation rate during the latest Aptian. In particular, the lower (Limestone Member) and middle Rama Formation encompass a long time-interval, represented by thin successions.

## 5. Platform environment

### *5.1. Carbonate platform facies zones*

Few microfacies studies in central Galilee (Reiss, 1961; Eliezri, 1965), the northern part of the Jordan Valley (Rosenberg, 1960), and southern Lebanon (Saint-Marc, 1974) have preceded our study. An analysis of macro-, meso- and microfacies characteristics allow interpretations of lateral and vertical shifts in facies zones that reflect major and minor variations in environmental patterns, such as climate, water circulation, and siliciclastic input or sea-level.

Facies analysis of this Upper Barremian–Albian succession has resulted in the definition of nine facies zones (FZs; Table 1), characterising platform development. They range from terrestrial and siliciclastic-influenced restricted-platform environments to deeper, open-platform environments, all characterised by typical skeletal and non-skeletal components, textures and sedimentary structures. Some FZs only occur in one or two formations, whereas others are typical of the entire succession studied (Table 1). Some differences between the FZs are expressed by sedimentological variation, such as lithology, bedding patterns or components, and were observed in the field. The study of the thin-sections allowed description of the FZs in more detail and the characterisation of their skeletal and non-skeletal components, especially within the carbonate dominated intervals.

Facies zones represent the depositional environment. However, although their definition is independent of stratigraphic aspects of their biotic variation, their fossil components still may express evolutionary trends over a longer time-span. For example, the abundance of calcareous green algae within the Ein el Assad Formation, or the increasing abundance of rudist debris through the Rama Formation, may reflect not only environmental and ecological, but also evolutionary, trends.

The classification of the FZs according to matrix, texture and components is shown in Table 1. The general environmental interpretation and the distribution of the FZs are discussed in the following paragraphs. The lateral and vertical distribution of the FZs in the Galilee and Golan sections is shown in Figs. 6 and 7B. The interpretation used here conforms with several facies interpretations of mid-Cretaceous carbonate platforms around the Tethyan Sea (e.g., Masse, 1993; Masse et al., 2003; Sandulli, 2004).

Each FZ is characterised by typical skeletal and non-skeletal components, textures and sedimentary structures. One or more FZs compose the depositional environments reflecting the lateral and local variations of the platform, which in our study area range from deeper subtidal open-platform to terrestrial.

*5.1.1. FZ-1 (subtidal open platform)*

FZ-1 is characterised by a diverse fossil assemblage, frequently abundant in flat-growing forms of *Palorbitolina*, *Praeorbitolina* or *Orbitolina* (*Mesorbitolina*) (Table 1 and Fig. 8A). Intercalated are beds with a low-diversity orbitolinid-echinoderm-dominated fauna. The depositional depth of Barremian–Aptian discoidal orbitolinid-rich environments, and the influence of the environment on orbitolinid-shape, have been discussed in several papers (e.g., Vilas et al., 1995; Simmons et al., 2000; Pittet et al., 2002). Pittet et al. (2002) summerized the controversy over the influence of light-dependent symbiotic algae or nutrient input on orbitolinid growth-forms. They presume an intertidal to very shallow platform, mesotrophic environment for orbitolinid-rich deposits in Oman, influenced by detrital and nutrient input. Although we found a similar faunal association of orbitolinids, *Permocalculus* (gymnocodiacean red algae) and echinoderm debris, and often a muddy and marly texture, we have to assume a different depositional environment. In general, the observed higher faunal diversity and the associated benthic foraminifers (diverse textulariids, rare miliolids, *Choffatella decipiens*, common *Lenticulina*, complex lituolids and *Buccicrenata*) and planktonic foraminifers (Table 1), as well as bioclasts, indicate open-marine platform conditions. The occurrence of planktonic foraminifers especially distinguishes this FZ as the deepest and most open-marine of the succession analysed. Sedimentary structures, such as nodular bedding and an often poorly-washed matrix, suggest environments below wave-base influenced by bottom-currents. Input of detritus and nutrients may be relatively high, as suggested by the alternation of beds of marly texture, rare planktonic foraminifers and low orbitolinid-echinoderm diversity, and beds of higher assemblage diversity. On the other hand, van Buchem et al. (2002) suggested normal marine conditions in the deep

Table 1
Facies zone descriptions

| | Facies zone | Microfacies | Diagnostic components | Subordinate components | Sedimentary structures | Depositional environment/ energy conditions | Occurrence |
|---|---|---|---|---|---|---|---|
| Subtidal open platform | FZ-1 | bioclastic to intraclastic wackestones to packstones often rich in orbitolinids, orbitolinid marlstones | Diverse bioclasts, discoidal orbitolinids (*Palorbitolina*, *Praeorbitolina*, *Orbitolina*), intraclasts, smaller and larger benthic foraminifers (textulariids, miliolids, *C. decipiens*, *Lenticulina*, complex lituolids, *Buccicrenata*), frequently planktonic foraminifers | often abundant echinoderms, sponge spicules, calcareous red algae (*Permocalculus*), mud peloids and cortoids, +/− gastropods, rudist debris, ostracods | thin-bedded or nodular-bedded marlstone−limestone alternation or limestone couplets components poorly sorted | deep inner to outer platform/low energy | Top of Ein el Assad Fm: at all locations; Rama Fm: all locations |
| High-energy open platform | **FZ-2** | oolithic to bioclastic grainstones, few packstones both partly with quartz and/or ferruginous ooids | ooids, bioclasts, intraclasts, bivalves, echinoderm debris, cortoids, partly ferriginous ooids, quartz grains, groundmass: sparitc | bryozoans, rare and diverse benthic foraminifers (orbitolinids, cuneolinids, complex lituolaceans, *Buccicrenata hedbergii*, *Choffatella decipiens*, *Charentia cuvillieri*), dasycladaceans, udoteaceans, *Marinella* (red algae), rudist debris, gastropods | cross-bedding, channels, up to 5-m-thick limestone couplets | shallow outer platform/ high-energy shoals | Nabi Said Fm (Galillee region), Ein el Assad Fm: rare |
| Open lagoon - shallow subtidal | **FZ-3** | bioclastic to intraclastic packstones and wackestones with diverse bioclasts | diverse bioclasts and/or intraclasts, echinoderm debris, bivalves (shells), calcareous green algae, mud peloids +/− oncoids and cortoids, groundmass: micritic or partly poorly washed | common gastropods, rare diverse benthic foraminifers (cuneolinids, textulariids, miliolids, larger agglutinated foraminifers, *B. hedbergii, C. decipiens*, *Praechrysalidina*, *C. cuvillieri*), oysters, rudists, sponge spicules | well-bedded, poorly sorted and commonly bioturbated sediments | shallow subtidal, low energy open lagoon optimal conditions with regard to salinity, water circulation, nutrient transport, siliciclastic input | Nabi Said Fm: with cortoids, Ein el Assad Fm: typically highly diverse, with calcareous algae Limestone Mbr, Rama Fm: less diverse, often rich in rudist debris and lithoclasts; poor in calcareous algae |
| | **FZ-3b** | **3b** with quartz and/or ferruginous ooids | **3b** +quartz and ferruginous ooids | | | **3b** shallow subtidal influenced by siliciclastic input | **3b:** Nabi Said Fm, Hidra Fm |
| | **FZ-4** | bioclastic packstones and wackestones rich in calcareous green algae | calcareous green algae (dasycladaceans and udoteaceans: *Cylindroporella*, *Pseudoactinoporella*, *Neomeris*, *H. dinarica*, *Acicularia*), abundant and diverse foraminifers (miliolids, textulariids, cuneolinids, larger agglutinated foraminifers) | gastropods, echinoderm debris, bivalves, rare sponge spicules and ostracods, few *Permocalculus* | well-bedded, poorly sorted and commonly bioturbated sediments | open lagoon shallow subtidal characterised by calcareous algae | Lower Aptian only, Ein el Assad Fm: common, Nabi Said Fm: rare |

(*continued on next page*)

Table 1 (*continued*)

| | Facies zone | Microfacies | Diagnostic components | Subordinate components | Sedimentary structures | Depositional environment/ energy conditions | Occurrence |
|---|---|---|---|---|---|---|---|
| Protected lagoon | **FZ-5** | wackestones to mudstones, rarely packstones with *H. dinarica* | calcareous green algae (mostly *H. dinarica*), shells, echinoderm debris | Common benthic foraminifers (mostly cuneolinids, less abundant miliolinids, orbitolinids, textulariids), calcareous debris, ostracods and sponge spicules, mud peloids | nodular- or planar-bedded, poorly sorted and commonly bioturbated sediments | protected lagoon characterised by *H. dinarica* | Nabi Seid Fm: top only, Ein el Assad, Fm Rama Fm: rare all sections |
| | **FZ-6** | mudstones to wackestones, rarely packstones with foraminifers and wackestones to floatstones with rudists | benthic foraminifers (diverse miliolids, textulariids and cuneolinids) rudists | shells, echinoderm debris, sponge spicules, gastropods, *H. dinarica, Acicularia,* ostracods, mud peloids, rudists (in situ or as large rudist debris) | lamination or nodular bedding | protected lagoon | Nabi Said, Ein el Assad (most common), Rama Yagur Fms. proximal and distal locations; wackestones to floatstones with rudists occur only in Rama Fm |
| Restricted carbonate lagoon and tidal flats | **FZ-7** | mudstones and wackestones often characterised by microbial laminae, birds'-eyes or mud-cracks | microbial mats, ostracods, or gastropods, spicules (monaxons of siliceous sponges) | calcareous debris, few foraminifers (miliolids), mud peloids, bivalve shells | lamination, mud-cracks, birds'-eyes | restricted lagoon and peritidal environment | Ein el Assad Fm, Rama Fm Yagur Fm: abundant associated with dolomite in Ein el Assad and Yagur Fms |
| Protected, with high siliciclastic input | **FZ-8** | laminated, cross-bedded or bioturbated sandstones, claystones, marlstones, sandy mudstone and wackestones or dolomites | quartz and/or ferruginous ooids | few bivalves, oysters, echinoderm debris, gastropods, ostracods, bioclasts, iron crust at top of some beds | lamination or cross-bedding, bioturbation | protected to restricted lagoon with high siliciclastic input | Hidra Fm |
| Siliciclastic supratidal and fluvial | **FZ-9** | cross-bedded sandstones | quartz, ferruginous crusts | | trough cross-bedding, unsorted | siliciclastic supratidal to fluvial | Hidra Fm |

subtidal range above storm wave-base in the open lagoon of a platform environment for an association of orbitolinids, *Chofatella* and lenticulinids, in contrast to the restricted environment of the orbitolinid/calcareous algae association. It is obvious that we have both facies types in one FZ (Table 1) and, thus, we suggest deeper environments for both associations.

To summarise, this FZ represents a low-energy environment that displays the deepest environment recorded in the Galilee-Golan sections. Lateral distribution patterns of FZ-1, and its synchronous occurrence in proximal and distal platform areas (e.g., Ein el Assad Formation; Fig. 7), record deepening events more than lateral shallow-deep variations. This observation coincides with that of Vilas et al. (1995), who described orbitolinid-accumulations or *Orbitolina*-beds from transgressive phases.

### 5.1.2. FZ-2 (open platform, high energy)

This FZ (Table 1; Fig. 8B) is characterised by oolithic grainstones and washed packstones representing deposition under high-energy conditions, which are also well reflected by the often cross-bedded limestones and channels, and by the non-skeletal components, such as ooids, oncoids, cortoids and intraclasts, and mostly sparitic, or at least partly sparitic, groundmass. The diverse skeletal components, such as bryozoans, larger and smaller benthic foraminifers and calcareous algae (Table 1) indicate normal marine, well-oxygenated conditions.

Such high-energy deposits are typically associated with carbonate shoals or bars on carbonate platforms (e.g., in van Buchem et al., 2002). A synchronous lateral occurrence in nearly all sections (uppermost Nabi Said Formation) indicates an occasional wide extension of this FZ. Its composition indicates proximity to the low-energy FZs of the shallow subtidal platform (FZ-3 and 4; Fig. 9). The considerable siliciclastic input, and the ferruginous ooids, indicate freshwater influence in coastal environments (e.g., Mücke, 2000).

### 5.1.3. FZ-3 (open lagoon with diverse components, shallow subtidal)

Both FZ-3 and FZ-4 represent low-energy, open lagoon, shallow subtidal environments, but differ from each other by their skeletal grain composition (Table 1). They often occur in the same interval and their differentiation is only possible in thin-section on the basis of typical component composition.

The bioclastic and intraclastic packstones and wackestones of FZ-3 are characterised by diverse skeletal grains and/or the presence of oncoids or coated grains (Table 1; Fig. 8C). Greater amounts of quartz or ferruginous components may occur (FZ-3b; Table 1).

Some differences are seen between occurrences of FZ-3, in that diversities are higher and intraclasts fewer in the Nabi Said and Ein el Assad formations than in the Hidra and Rama formations. The high-diversity type is more common in the most distal section (Ein Netofa) than in the proximal section (Golan Heights). The high-diversity association of skeletal and non-skeletal components represents a shallow subtidal environment, with optimal conditions with regard to salinity, water circulation, nutrient transport and siliciclastic input. The occurrence of pseudopeloids and poorly washed packstones indicate the presence of bottom currents. The lower diversity of associations of the Hidra and Rama formations indicates more protected environments than those of the Ein el Assad and Nabi Said formations. Its more frequent occurrence in the more distal section (Fig. 7B) reflects a typical proximal-distal platform zoning. A high input of quartz and ferruginous components is typical in the Nabi Said and Hidra formations.

Similar facies types were described from the Dinarids (Sandulli, 2004) and the Oman (Pittet et al., 2002; van Buchem et al., 2002). Here, the authors interpreted the facies as open lagoonal sediments with normal marine conditions and water circulation.

### 5.1.4. FZ-4 (open lagoon with calcareous green algae, shallow subtidal)

The bioclastic wackestones and packstones of FZ-4 (Table 1) are abundant in diverse and often fragmented calcareous algae (*Cylindroporella*, *Pseudoactinoporella*, *Neomeris*, *Hensonella dinarica*, *Acicularia*, udoteaceans and *Permocalculus*), among which the dasycladaceans are mostly dominant. Associated skeletal grains, though similar to those of the open lagoon (FZ-3), are less abundant. The partly reworked micritic groundmass indicates moderate bottom-currents. The foraminiferal assemblage resembles that one of the protected lagoon environments (FZ-5/6) and suggests an intermediate position between the open and the more protected lagoon.

This FZ indicates the presence of a low-energy open lagoon environment, creating optimal conditions for the development of calcareous algae typical of the Ein el Assad Formation and rarely of the Nabi Said Formation. Better protected platform environments, as well as evolutionary trends, may possibly explain the lack of FZ-4 in the younger formations.

### 5.1.5. FZ-5 (protected lagoon with Hensonella)

FZ-5 and FZ-6 both represent protected environments, with restricted interchange with the open lagoon. They differ in skeletal grain composition observed in thin-sections.

Mudstones and bioclastic wackestones to packstones rich in *Hensonella dinarica* (Table 1; Fig. 8D) were grouped in FZ-5. The components are similar to those of FZ-4, but associated skeletal grains are less diverse and not as abundant (Table 1). Lower diversity of green algae and other skeletal components, combined with fewer components, indicates increasing protection of the platform environment by comparison with FZ-4.

### 5.1.6. FZ-6 (protected lagoon)

The wackestones and mudstones in FZ-6 are rich in foraminiferal associations dominated by diverse miliolids and/or by textulariids, as well as cuneolinids (Table 1; Fig. 8E). They typically represent protected lagoonal environments (e.g., Pittet et al., 2002; Masse et al., 2003; Sandulli, 2004). Additionally, rare rudist floatstones and wackestones, associated with

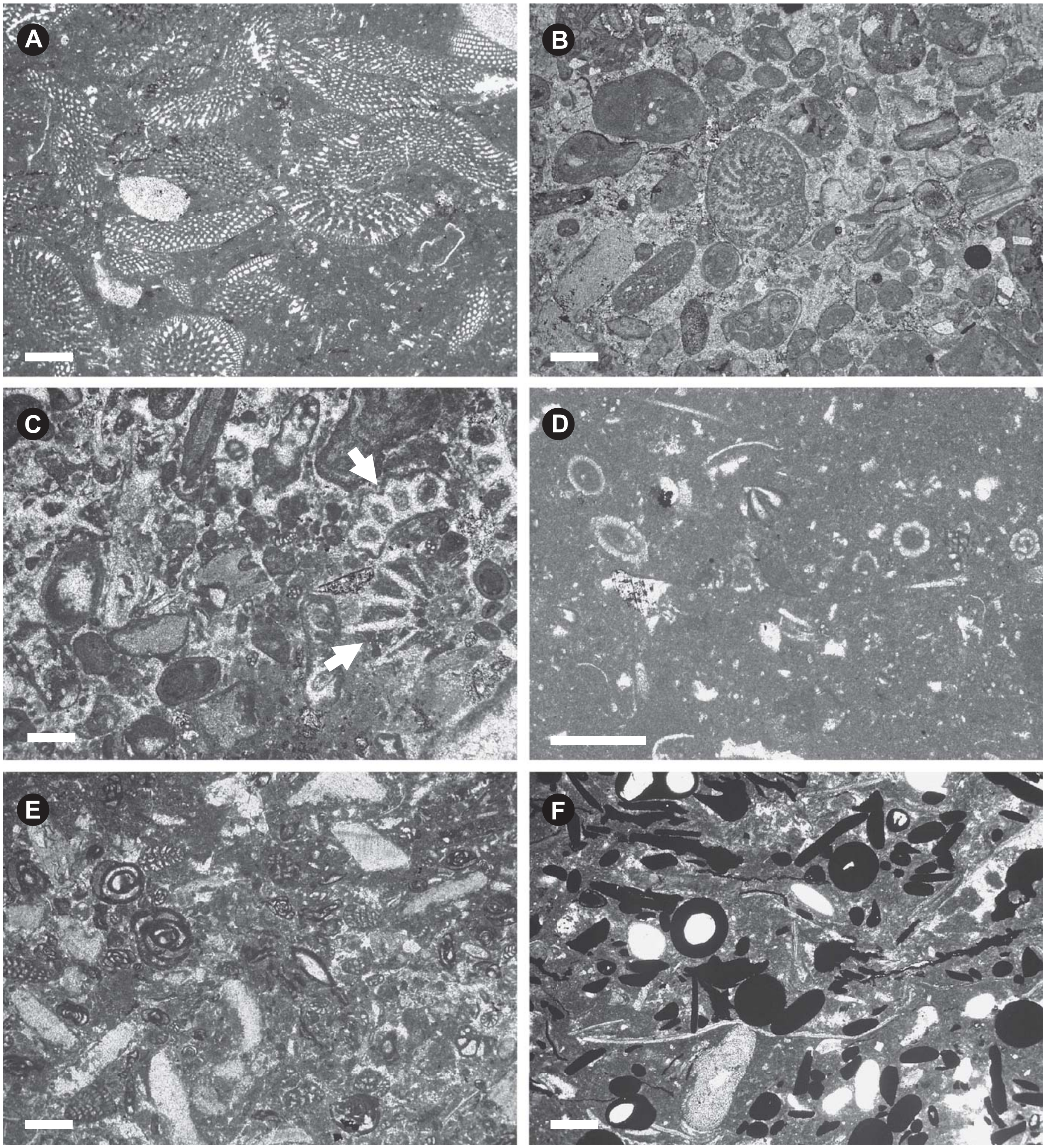


Fig. 8. Microfacies of some significant facies zones. A, packstone rich in orbitolinids (FZ-1) representing deepening at the top of the Ein el Assad Formation, Ein Quniya section (44 m, thin-section B I 30-1, photograph BI30-1-2x-1.2-2). B, high-energy platform environment (FZ-2) grainstone with diverse bioclasts and *C. decipiens*, base of Ein Netofa section, (1.5 m, L I 3, LI3-2x-2). C, open platform, shallow subtidal environment (FZ-3) with diverse bioclasts, dasycladecean algae (arrows), oncoids and echinoderm debris, Ein Quniya section, Ein el Assad Formation (10 m, B I 11-1, BI11-1-2x-3.3). D, protected platform with *H. dinarica* (FZ-5), Ein Quniya section, Ein el Assad Formation (20 m, B I 20-3, BI20-3-4x-5.1). E, protected platform–lagoon (FZ-6) packstone with smaller and larger miliolids and cuneolinids, Ein Quniya section, Rama Formation (195 m, B III 16, BIII16-2x-6.1). F, protected platform with siliciclastic input, quartz sand and ferruginous ooids (FZ-8), Ein Quniya section, lower Hidra Formation (62 m, B II 1, BII1-4x-8.1). Scale-bars represent 0.5 mm.

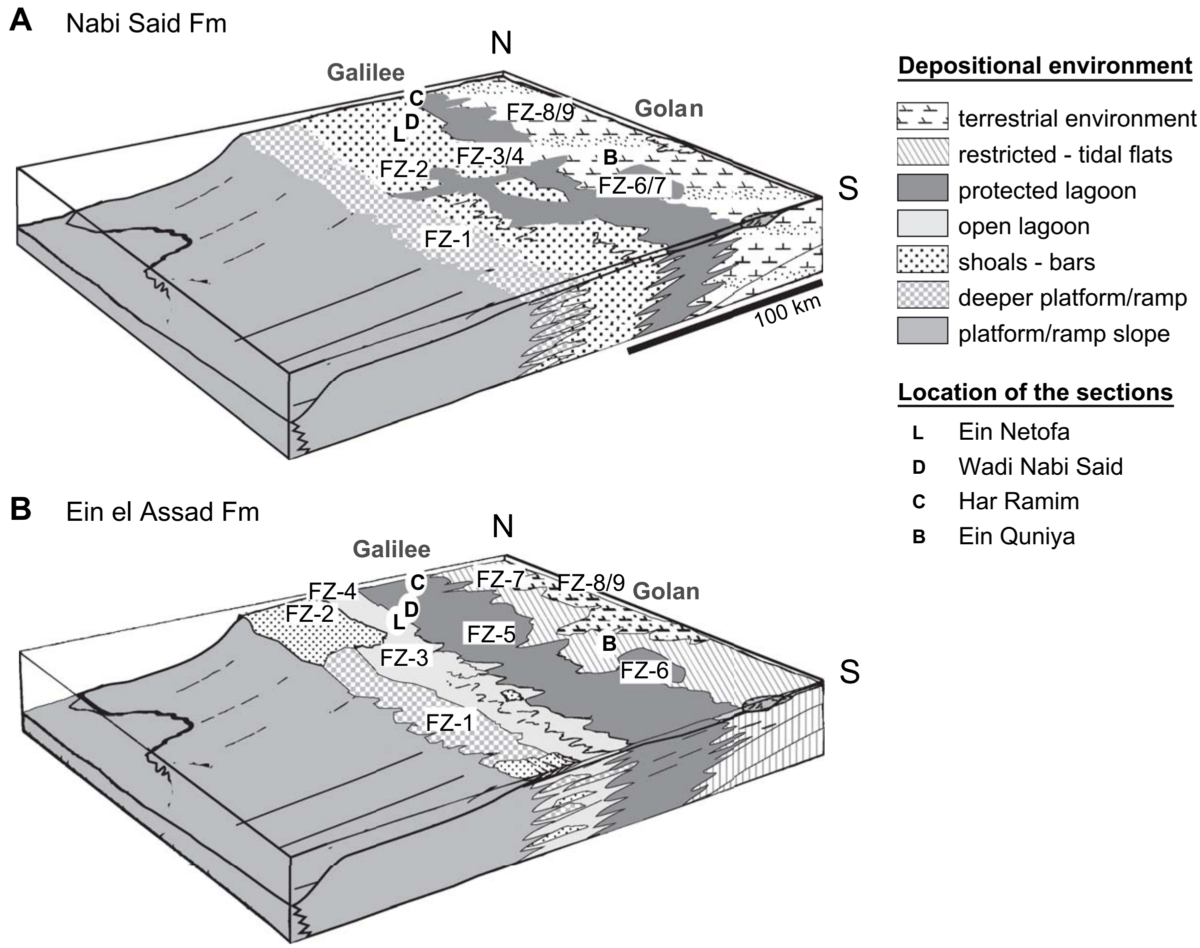


Fig. 9. A, ramp model showing distribution of depositional environments indicated by different facies zones (FZ) during deposition of the Upper Barremian–Lower Aptian Nabi Said Formation. B, facies distribution modelled for the Ein el Assad Formation indicates a flat-layered platform geometry characterising the younger formations. The deeper platform facies is shown in the most distal part of the platform, but may also extend to more proximal parts of the ramp during third-order transgressions.

only a few other fossils, were also grouped in this facies zone. Their micritic matrix and lower diversity indicate a protected environment. Alternation of this protected environment with intertidal flats is witnessed by the occasional presence of mud-cracks. Rudist floatstones and wackestones typically occur within the Rama Formation. A large lateral extension of the FZ (e.g., Ein el Assad Formation) reflects a temporary wide extension of protected environments over the entire platform.

### 5.1.7. *FZ-7 (restricted carbonate lagoon and tidal flats)*

FZ-7 consists of mudstones and wackestones characterised by microbial laminates, birds'-eyes or gastropod associations (field observations), as well as mudstones and wackestones with ostracods, siliceous sponge spicules and/or gastropods and/or calcareous debris (Table 1). Flat bedding-patterns are more common than nodular ones.

The low-diversity, partly monospecific skeletal grain associations of these mudstones and wackestones reflect restricted environments. Microbial laminates represent carbonate tidal flat environments. The FZ distribution pattern over the entire region studied indicates the enlargement of a restricted environment during several periods.

### 5.1.8. *FZ-8 (protected lagoon with high siliciclastic input)*

The laminated, cross-bedded or bioturbated sandstones, marlstones, claystones and limestones representing this FZ are often abundant in ferruginous ooids. Mudstones to wackestones associated with this FZ contain a skeletal component composition that indicates a protected subtidal to intertidal restricted depositional environment, influenced by detrital input (Table 1, Fig. 8F). Formation of the ferruginous ooids results from freshwater influence in the nearshore environments (Mücke, 2000). Iron crusts at the top of some beds indicate interfingering with FZ-9. These FZs typically alternate with beds of open or restricted lagoonal environments (FZ-4 and 6), as well as with terrestrial sediments, indicating a very shallow environment between open lagoon and terrestrial. Sediments of FZ-8 occur exclusively in the Hidra Formation and are only well represented in outcrops of the Golan Heights (Fig. 6).

#### 5.1.9. FZ-9 (siliciclastic supratidal and fluvial environment)

Cross-bedded, poorly-sorted quartz sandstones with ferruginous crusts dominate in FZ-9 (Fig. 8). The matrix may be carbonate or dolomite. This FZ is restricted to the Hidra Formation (Fig. 6). Sedimentary structures, e.g., cross-bedding, indicate fluvial to supratidal deposition.

### 5.2. The carbonate platform

All sections analysed represent developments of platform facies during the Late Barremian-Albian. Our study includes sections from both sides of the Rift Valley, along which a sinistral strike-slip has moved the East Bank at least 100 km north of its original position (Fig. 1B). The depositional environment varies from emerged platform with fluvial deposition to deeper platform (Table 1; Fig. 8). Facies variation is more intense in vertical than in lateral direction (Fig. 8). A certain uniform inner platform environment characterises each time-interval, and lateral changes are merely expressed by finer FZ variations. This is well illustrated in the proximal-distal trend from the Golan Heights (Ein Quniya) to northern Galilee (Har Ramim) and central Galilee (Ein Netofa-Wadi Nabi Said; Fig. 9). As such, the Galilee sections always represent the more open-marine environment, compared to the Golan Heights (Fig. 6). This is visible in the upper part of the Nabi Said Formation (Table 1), where high-energy FZ-2 characterises the formation in western Galilee, becoming less common in north-east Galilee, and completely absent in the south-eastern Golan area. The same proximal-distal trend is obvious in the Rama Formation. Open-lagoon facies (FZ-3/4) is concentrated in the Galilee area, whereas sediments of the protected lagoon (FZ-5/6) were deposited synchronously in the Golan area (Fig. 7). The platform rim, characterised by rudist reefs (Sass and Bein, 1982; Ross, 1992), was located about 40 km west of our most distal section (Ein Netofa section) and 100 km north-east of the most proximal Golan section (due to the later tectonic movements).

#### 5.2.1. Uppermost Barremian–lowermost Aptian: Nabi Said Formation

The entire Nabi Said Formation is exposed in the more distal Ein Netofa section (Fig. 7B). Rosenfeld et al. (1995) signalled lateral interfingering of these marine sediments, with terrestrial deposits in the area between Galilee and the Golan Heights. In western Galilee, the lower Nabi Said Formation is characterised by cross-bedded limestones of the open-platform, high-energy environment (FZ-2). High-amounts of ferruginous ooids and quartz reflect the proximity of coastal environments. A greater variety of depositional environments characterises the upper part of the formation, comprising protected areas that had a high siliciclastic input as well as open-marine environments (FZ-8, 5, 6, 4 and 3). Towards the top of the Nabi Said Formation open-marine conditions are indicated in all sections in Galilee, while a lateral trend towards more protected environments is apparent in the proximal eastern sections.

#### 5.2.2. Middle Lower Aptian: Ein el Assad Formation

Shallow platform deposits (Fig. 7B) are dominant in the Ein el Assad Formation, ranging from open-lagoon (FZ-3) to protected lagoon (FZ-6). While the siliciclastic input of quartz and ferruginous ooids decreased over the entire region, packstones and wackestones, containing diverse platform components (FZ-3) and locally rich in calcareous algae (FZ-4), characterise the typical features of the Ein el Assad Formation. The comparison between synchronous sections reveals only slight lateral facies variations, indicating the establishment of a homogeneous shallow-platform environment over the entire region. The appearance of planktonic foraminifers in orbitolinid beds (FZ-1; lowermost part of the *Pc-Ol* LFB) in the uppermost Ein el Assad Formation signals an important deepening event, suggesting the synchronous establishment of deeper platform environments over the entire region.

#### 5.2.3. Upper Lower Aptian to lower Upper Aptian: Hidra Formation

The exposures of the Hidra Formation make lateral correlations difficult. The comparison of descriptions from northern (Rosenberg, 1960) and central (Reiss, 1961; Eliezri, 1965) Galilee with our observations of the Golan Heights suggests that similar sediments characterise this region. Some different facies variations may reflect the more proximal platform development on the Golan Heights, where the lower part of the formation consists of ferruginous-ooid-rich, mixed siliciclastic–carbonatic sediments deposited in protected (FZ-5,6) and restricted (FZ-7,8) lagoons (Fig. 7). In the middle part of the formation, 10 m of repeated intercalations of fluvial sandstones and ferruginous crusts (FZ-9) signal emergence of the platform across the Early/Late Aptian boundary, with the base of the event being latest Early Aptian. The upper part of the formation is composed of carbonates and mixed siliciclastic–carbonatic sediments from several shallow subtidal environments. Outer platform environments were only reached temporarily. Stabilisation of protected and restricted environments, with siliciclastic input mainly represented by quartz-silt, characterises the uppermost part of the formation.

#### 5.2.4. Middle Upper Aptian: Limestone Member (lower Rama Formation)

The Limestone Member represents, in its lower part, open platform conditions. The more distal Har Ramim section shows greater variance and deeper environments (FZ-7, 6, 3, 2, 1) than the more proximal Ein Quniya section. Here, the open-platform environment is characterised by lower diversity compared to the older formations.

In the upper Limestone Member (lowermost *Ot-Op* LFB), sediments from restricted or protected environments (FZ-6 and 7) become dominant, characterised by increased amounts of rudist debris. The sediment accumulation rate of the member is substantially lower than that of the older formations, representing less than a quarter of the total thickness of Aptian sediments in the region, while its duration is one third of the Aptian time span (Fig. 10).

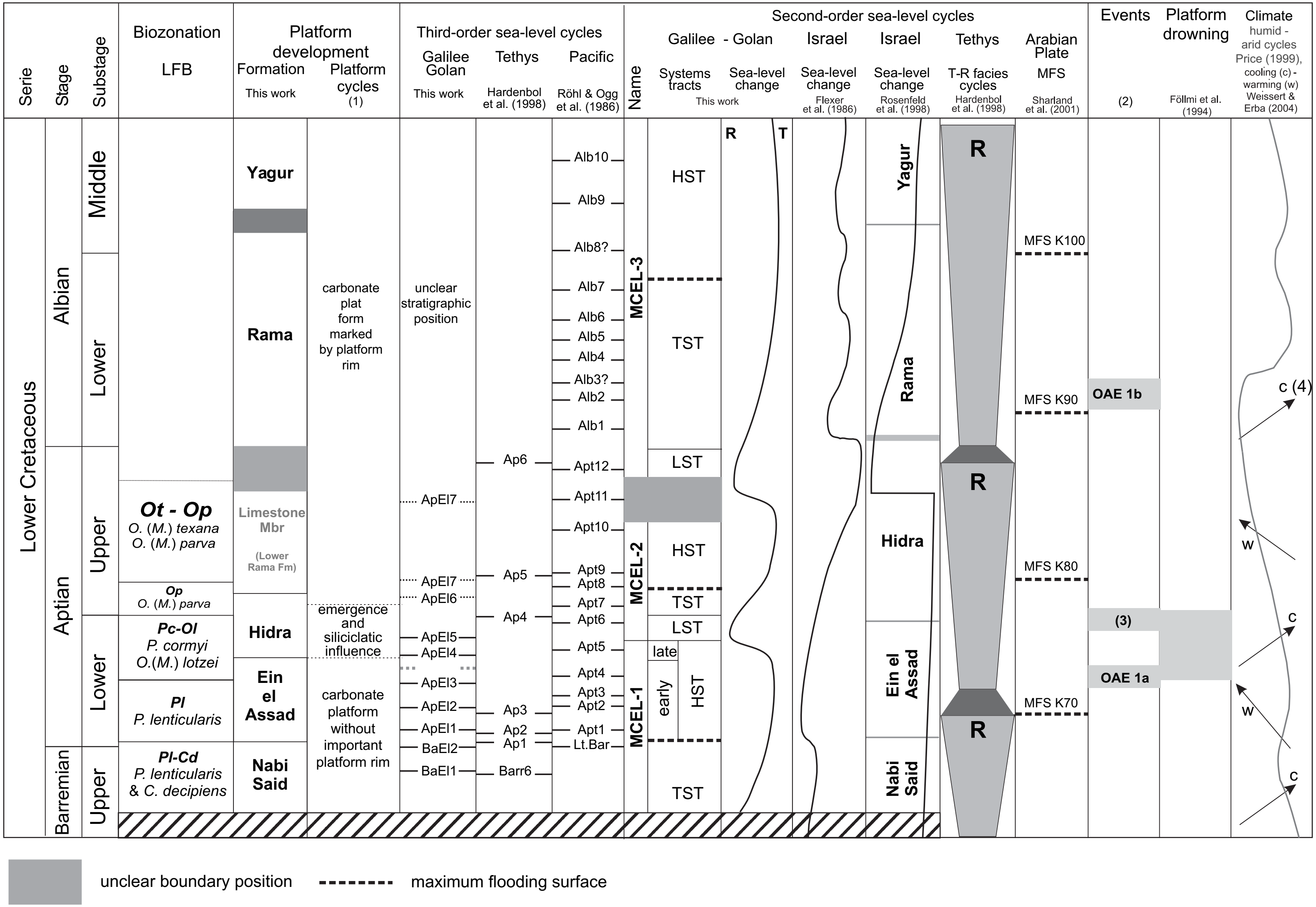


Fig. 10. Diagram summarising the chronostratigraphic interpretation of the formations, calibration of the third- and second-order sea-level changes in Galilee and the Golan Heights, and correlation with local and regional sea-level variations (chronostratigraphy according to Hardenbol et al., 1998). The platform cycles (1) are compiled from results of this work and platform rim descriptions from Bein (1971); Sass and Bein (1982); Ross (1992) and Rosenfeld et al. (1998). The Events (2) column indicates the location of oceanic anoxic events according to Weissert and Erba (2004), and a major biological crisis (3) located around the Lower/Upper Aptian boundary according Castro and Ruiz-Ortiz (1995) and Skelton (2000). The platform drowning in relation to the Selli Level is shown by several authors (Masse, 1989; Föllmi et al., 1994; Weissert et al., 1998). The cooling−warming trends of the Climate column are after Weissert and Erba (2004), who summarised the results from several studies. We add an Early Albian cooling event (4) indicated by Pirrie et al. (2004).

*5.2.5. Uppermost Aptian–Middle Albian: middle–upper Rama Formation*

The lateral correlation of the middle Rama Formation (Har Ramim and Ein Quniya sections) indicates greater sediment thicknesses and a higher ratio of detrital input (FZ-7 and 8) in northern Galilee compared to the Golan Heights (FZ-7). These patterns reflect higher sediment accumulation rates in the more distal northern Galilee area, as well as occasional non-deposition in the proximal Golan Heights. In the younger part of the succession, a distal-proximal shallowing trend is indicated by deposition in open-lagoon environments (FZ-3) in northern Galilee and in protected lagoons (FZ-6) on the Golan Heights (Ein Quniya section). In the upper Rama Formation, sediments from protected lagoons (FZ-6) extend over the entire region. The recurrence of a low sediment accumulation rate during the Early Albian, similar to that for the Late Aptian Limestone Member, seems to characterise the upper part of the Rama Formation.

*5.2.6. Upper Albian: Yagur Formation*

The limestones and dolomites of the Yagur Formation represent protected lagoonal environments. Foraminiferal wackestones (FZ-6) occur in the lower part, and mudstone associations (FZ-7) of restricted platform environments in the upper part (Fig. 7).

*5.3. Sequence stratigraphic interpretation*

Lateral and vertical facies distribution patterns (FZs) reveal variations of high frequency and low frequency. Short-term facies changes are often indicated by only slight displacements of the facies zones and are interpreted as third-order variations, while more drastic facies changes encompassing longer time-intervals are treated as second-order variations in the sense of Vail et al. (1991). Lateral correlation of the sections result in the interpretation of the platform depositional architecture as a function of accommodation and sediment supply and production (summarised in Fig. 11). Lateral and vertical facies changes reflect water-depth and palaeoenvironmental variations, which are interpreted in connection with relative sea-level changes. Sequence stratigraphic terminology is used herein for both third- and second-order depositional cycles (according to Vail et al., 1991; Emery and Myers, 1996). In addition, the second-order cycles were prefixed MC (mid-Cretaceous), EL (eastern Levant), and numbered (e.g., MCEL-1), allowing differentiation from third-order sequences. The latter are labelled with stage (e.g., Ap), locality (El), and number (e.g., ApEl 1). Each cycle (second- and third-order), and the respective systems tracts, are named after the sequence boundary (SB) at their bases. Their interpretation results in the development of a second- and third-order relative sea-level curve. Comparison with published data from surrounding areas results in the interpretation of the regional platform development.

*5.3.1. Second-order cycles*

Lying above the continental deposits of the Lower Cretaceous Hatira Formation, the mostly marine Upper Barremian–Albian succession in Galilee and the Golan Heights is characterised by three second-order sea-level cycles, with major lowstands around the Lower/Upper Aptian boundary and within the Upper Aptian. The sedimentation patterns of second-order systems tracts vary from mixed siliciclastic to pure carbonate systems. The changeover from terrestrial sediments of the Hatira Formation to marine sediments of the Nabi Said Formation, reflecting the transgressive boundary (ts) of the first marine second-order cycle (Figs. 7B, 11) is not included in the analysed sections.

*MCEL-1*. Our analysis starts at the base of the Upper Barremian–lowermost Aptian Nabi Said Formation reflecting the transgressive systems tract (TST) of the MCEL-1. The lower part of the formation is characterised by a slightly dipping relief, causing marine deposition in the eastern environments (Nabi Said section, Galilee; Fig. 6) and terrestrial depositional environments in the western proximal zones (Ein Quniya section, Golan). Successive retrogradation resulted in marine sediments overlying terrestrial deposits also in proximal areas (upper Nabi Said Formation; Figs. 7B and 9A). Increasing accommodation space, resulting from the transgression, is recorded by the successive submergence of the western platform during this time (Rosenfeld et al., 1995), and by the deposition of high-energy sediments during long time-intervals with high accumulation rates. At the end of the Nabi Said time-interval, a carbonate platform without major relief was created by a higher sedimentation rate in the distal marine environments (Fig. 9B). The creation of accommodation space slowed down slightly, allowing temporary progradation of the protected lagoon facies as part of a third-order sea-level change.

The maximum flooding surface (mfs) coincides with the boundary between the Nabi Said and Ein el Assad formations in the lowermost Aptian, representing the transition from retrogradational to aggradational sedimentation patterns.

The highstand systems tract (HST) comprises the entire Ein el Assad Formation and the lower Hidra Formation. A long period of low-energy lagoonal conditions, reflecting a balanced situation between accommodation and sedimentation, characterises the Ein el Assad Formation. This aggradational depositional pattern represents the early HST, whereas the progradation of siliciclastics, and shoaling of the depositional environment, in the lower Hidra Formation reflects decreasing accommodation of the late HST.

*MCEL-2*. The second-order SB, MCEL-2, is very clearly developed in the Ein Quniya section, as the boundary between marine and terrestrial sediments, indicating emergence of the platform (Figs. 6, 11). This SB, dated fairly well as latest Early Aptian (upper *Pc-Ol* LFB), set off a lowstand systems tract (LST) formed by terrestrial sediments and ferruginous crusts alternating with a few shallow-marine siliciclastics, thus indicating the repeated emergence of the platform during middle Hidra Formation times. The TST comprises the marine sediments of the upper Hidra Formation and of the lower Limestone Member (Rama Formation). It is the reduction of the detrital input and the deepening of the depositional area that mark the ts and the setting in of retrogradational sedimentation patterns. As the ts coincides with the base of the *Op* LFB, it

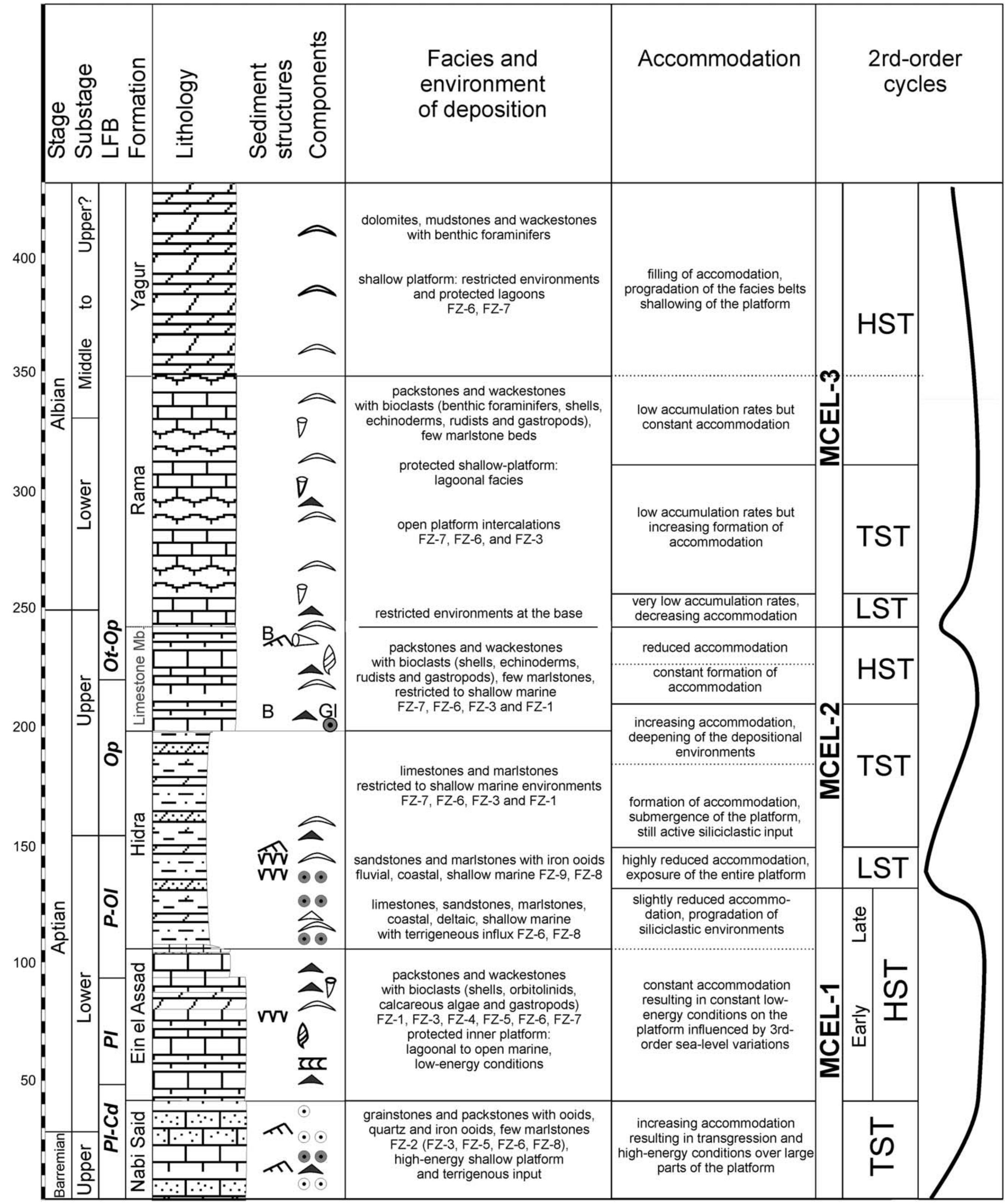


Fig. 11. Idealised section indicating the main characteristics of the formations, larger foraminiferal biozones, age determination, depositional architecture and development of the accommodation as well as the respective interpretations of second-order sea-level change. For legend, see Fig. 6.

occurred around the Early/Late Aptian transition. Overall increasing accommodation is reflected by deepening of the environment and establishment of subtidal lagoons in the lower Limestone Member during the early Late Aptian (Fig. 10). The reduction of detrital input may reflect retrogradation.

The mfs falls within the lower Limestone Member, indicating shoaling of the environments by reduced formation of accommodation space. It is dated as early Late Aptian (Fig. 10). The early HST was characterised by constant subtidal, open-lagoonal environmental conditions (FZ-3 and 4), representing constant accommodation in the middle part of the Limestone Member. The late HST again shows a trend to more protected sediments (FZ-5 and 7), expressing filling of the accommodation and shoaling of the environment in the upper Limestone Member. At this time, the decrease in sediment accumulation rate supposedly began, characteristic of the uppermost Aptian–Albian succession.

*MCEL-3*. The SB of the MCEL-3 cycle coincides with the top of the Limestone Member (lower Rama Formation; Figs. 6, 11). A Late Aptian age can be presumed from the SB location shortly above the FO of *O*. (*M*.) *texana* (Fig. 6). The subsequent succession of marlstones and sediments from restricted environments characterises the LST sediments in Galilee. The reduced thickness of this interval on the Golan Heights may be due to non-deposition or slow accumulation, resulting from emergence or less incremented accommodation in the proximal parts of the platform. The increasing accommodation space above was combined with a low sediment accumulation rate, resulting in slow deepening of the environments and the establishment of open-lagoonal conditions in Galilee (FZ-3 and 4), whereas protected lagoonal conditions prevailed in the Golan Heights area. A trend to more protected environments over the entire region marks the mfs. The HST comprises the upper Rama Formation and the Yagur Formation, both characterised by re-establishment of protected lagoonal environments indicating filling of accommodation space.

In summary, the Aptian LST (MCEL-2) had the highest siliciclastic input of the entire succession, pointing to clear emergence of the platform; the Albian LST (MCEL-3) was much more modest. The Aptian TSTs (MCEL-1 and MCEL-2) are characterised by siliciclastic input and remarkably increasing accommodation space, whereas the Albian TST (MCEL-3) is dominated by carbonates and contains only a few marlstones. The HSTs are characterised by more or less stable carbonate production during the entire interval. Progradation of siliciclastics occured during the Aptian late HST only.

Although the sediment accumulation rate of MCEL-3 was low, the platform environment, commonly characterised by open lagoonal conditions, was not subject to significant deepening, which may imply that the rise of relative sea-level during the MCEL-3 cycle was lower compared to the earlier ones.

*5.3.2. Third-order sequences*

The second-order sequences are composed of smaller-scale sequences. Stacking and facies patterns of the latter vary according to their position in the larger-scale sequences and in relation to climate and local detrital input. They are well developed when the second-order sequence development forces open platform and open lagoon environments, as typical of the lower part of the succession (Fig. 7B). However, they are less well-developed when facies variations are reduced, owing to second-order development or when the outcrop situation prevents correlation of those sequences.

Smaller-scale sequences of the Nabi Said and Ein el Assad formations are characterised by typical sedimentation patterns (Fig. 7B). The thickness of the sequences are in the range of 15–20 m and their duration was about 0.5 myr, according to our stratigraphic framework and following the age calculation in the sense of Hardenbol et al. (1998). We interpret these as third-order sequences in the sense of Vail et al. (1991).

The correlation of the third-order sequences is shown in Fig. 7B for the Ein el Assad and Nabi Said formations and in Fig. 6 for the younger formations. The older formations allow a very detailed correlation of the SBs. The correlation of SBs BaEl 1, ApEl 1 and 2 is close to the upper boundary of the *Pl-Cd* LFB, and that of the SBs ApEl 3 and ApEl 4 is supported by their position below and above the *Pl*/*Pc-Ol* LFB boundary, respectively. In the upper part of the succession, correlation of third-order sequence boundaries is impaired due to insufficient biostratigraphic control. However, SBs ApEl 6 and ApEl 8 can be correlated between Galilee and the Golan Heights.

Upper Barremian and Lower Aptian SBs are characterised by abrupt facies changes from open-marine to more protected environments. Such changes from open-lagoonal FZs to protected lagoons or tidal flat environments reflect significant decreases in water-depth. Only SB ApEl 3 and SB ApEl 5 are characterised by emergence of the platform, recorded as stacked rhizolithic horizons (Figs. 6, 7B). The latter is characterised by the co-occurrence of third- and second-order SBs. Upper Aptian and Albian SBs (ApEl 6, 7 and 8 and AlEl 1) are indicated by the establishment of restricted environments or tidal flats (FZ-7) above open lagoon environments (FZ-3) in Galilee, and above protected lagoons (FZ-5/6) on the Golan Heights.

During LSTs, the depositional area remained in very shallow and tidal flat environments (FZ-7), and restricted or protected lagoons (FZ-5 and 6) developed on the platform in all locations. The TSTs of the small-scale sequences are basically indicated by successive deepening of the environment and the establishment of open lagoon (FZ-3 and 4) or deeper platform environments (FZ-1) in Galilee, while open and protected lagoonal conditions (FZ-3, 4 and 5) prevailed in the proximal area of the Golan Heights. High-energy conditions (FZ-2) mark the TSTs BaEl 1 and BaEl 2 (Nabi Said Formation) in Galilee. Here, the third-order TSTs overlie the second-order one (MCEL-1), indicating stronger transgression and the creation of open-marine, high-energy conditions in wide areas of the Galilee. TST ApEl 3 (upper part of Ein el Assad Formation) reflects a strong third-order relative sea-level increase at the end of a second-order early HST (MCEL-1). This significant middle Early Aptian deepening (Lower *Pc-Ol* LFB) caused the deep platform FZ-1 to extend over the entire region, from Galilee to the Golan Heights. An important transgressive event is suggested to overprint the trend to more proximal conditions in the second-order HST.

Third-order mfss are not shown in the sections because their positions are not always clear. Generally, a trend to more protected environments marks the third-order HSTs and deposits of the protected lagoons (FZ-5 and 6) prevail in all locations.

## 6. Discussion

The precession of the biochronostratigraphic control of the Barremian–Albian succession, factors that monitor the development of the eastern Levant depositional sequences, as well as the depositional architecture of the eastern Levant carbonate platform, are discussed below. Considered are local factors, such as changing platform geometry with respect to global trends in climate, sea-level change and ecology.

### *6.1. Global framework: climate and sea-level*

The Early Cretaceous was characterised by climate changing towards a greenhouse acme, and the Late Barremian–Albian interval especially was subject to significant oceanic, climatic and biotic variation (e.g., Weissert et al., 1998; Larson and Erba, 1999). After the cooler Valanginian–Hauterivian climate, the Barremian–Early Albian interval was marked by a change towards the hot mid-Cretaceous greenhouse world. Within this general climatic trend, the Late Barremian–Early Aptian interval was characterised by unstable conditions (Weissert and Erba, 2004).

The formation of OAEs (Selli Level/OAE 1a, 1b) is an important characteristic of Tethyan basins. A global biocalcification crisis in Early Aptian pelagic and neritic environments, and a major carbonate platform drowning event, were possibly linked to the formation of OAE 1a (Föllmi et al., 1994; Weissert et al., 1998; Larson and Erba, 1999; Wissler et al., 2003). Those shoal-water platforms overgrowing this event are characterised by major ecological changes in the faunal associations and extinction of several organisms (e.g., Skelton, 2003; Immenhauser et al., 2005). Further changes in the benthic community were observed at the Barremian/Aptian boundary (Hillgärtner et al., 2003) and at the Lower/Upper Aptian boundary (Masse, 1989; Skelton, 2000). Both ecological changes and the development of OAE 1a have been discussed as being results of changing climate, nutrient levels, and/or variations in ocean geochemistry, all controlled by increased carbon dioxide concentration in the oceans and atmosphere, related to enhanced volcanic activity in the Early Cretaceous (Weissert et al., 1998; Larson and Erba, 1999; Leckie et al., 2002; Wissler et al., 2003; Weissert and Erba, 2004). An Early Aptian cooling event preceding OAE 1a was postulated by Pucéat et al. (2003). Weissert and Erba (2004) suggested an earliest Aptian warming phase and a cooling event succeeding OAE 1a. They defined temperature as subordinate, but increasing carbon dioxide concentration as important, factors triggering the Early Aptian biocalcification crisis. Furthermore, increasing carbon dioxide concentration was suggested as enhancing the weathering rate resulting in higher quartz input in the Tethyan basins and in higher nutrient availability in the coastal areas (Wortmann et al., 2004).

In the frame of the general Early Cretaceous sea-level rise, the Late Barremian–Early Aptian represents an interval of generally low sea-level, with a major rise in sea-level beginning in the Late Aptian. This sea-level change is superimposed by several second- and third-order transgressive–regressive facies and sea-level cycles (Hardenbol et al., 1998) affecting carbonate platform development. The large number of regional studies have painted an inconsistent picture for the interval studied: the adjacent Arabian Plate (Sharland et al., 2001) and examples from the Alpine Tethys (Strasser et al., 2001) exhibit several second-order sea-level changes not in conformity with those described by Hardenbol et al. (1998). Furthermore, third-order sequences described from the Pacific (Röhl and Ogg, 1998) and from the Arabian Plate (van Buchem et al., 2002) coincide only in part with those of Hardenbol et al. (1998; Fig. 10).

### *6.2. Stratigraphy*

While the early data of Rosenberg (1960) and Eliezri (1965), and the more recent data of Rosenfeld et al. (1995, 1998), were based on a few megafaunas and mostly on ostracod biostratigraphy, respectively, our new stratigraphic data allow a relatively more detailed subdivision of the platform strata and a comparison with the biochronostratigraphic framework of Hardenbol et al. (1998). Orbitolinid biostratigraphy is often employed on carbonate platforms, and there exist correlations with well-dated pelagic successions (Arnaud-Vanneau, 1998; Arnaud et al., 1998; Simmons et al., 2000). Thus, our biostratigraphic interpretation of the platform succession allows the estimation of the timing of local sedimentation and sea-level variations (Fig. 10) and their comparison with regional and global interpretations of the factors controlling third- and second-order sea-level changes.

Our new stratigraphic interpretations result in variations in the local relative second-order sea-level curve in comparison to the earlier concepts of Flexer et al. (1986, 1999) and Rosenfeld et al. (1998; Fig. 10). A major lowstand around the Lower/Upper Aptian boundary (MCEL-2) was also indicated from the same part of the succession by Rosenfeld et al. (1998) but dated as Late Aptian. A major sea-level drop in central Israel from around the Aptian/Albian boundary (Braun and Hirsch, 1994) may also correspond to the MCEL-2 sequence boundary. Our second-order sea-level chart thus differs from that of Flexer et al. (1986, 1999) in timing rather than in cycle interpretation, but these differences are important.

Furthermore, the stratigraphic framework results in the estimation of timing of the third-order SBs. We distinguished one SB in the uppermost Barremian, five in the Lower Aptian, three in the Upper Aptian and one in the Albian. A relatively precise dating was possible for SBs BaEl 2 and ApEl 1, 3, 4 and 7 because they are located close to LFB boundaries (Figs. 6, 10). The smaller-scale sequences are interpreted as third-order sequences, because their duration was similar to those described for Aptian third-order sequences by Hardenbol et al. (1998) and Röhl and Ogg (1998) (Fig. 10).

A relatively precise dating was possible of the most prominent short-term sea-level rise, characterised by the orbitolinid beds in the upper Ein el Assad Formation. Its onset shortly above the base of the *Pc-Ol* LFB indicates a middle Early Aptian age, which corresponds with the timing of the extended drowning of the Tethyan carbonate platform (Masse et al., 1995), correlating with the Selli Level (Castro and Ruiz-Ortiz, 1995; Moullade et al., 1998; Weissert et al., 1998).

### 6.3. Palaeogeography and platform geometry

The observed facies patterns reflect the platform geometry of Galilee and the Golan Heights as part of a larger-scale palaeogeographic development. Firstly, there is an overall trend towards more proximal environments in the regions further south and east (Lewy, 1989; Braun and Hirsch, 1994; Rosenfeld et al., 1998). This trend is particularly distinct in the lowermost marine succession (Nabi Said Formation), which was deposited synchronously with terrestrial sediments further east and south. This facies pattern reflects, on the one hand, the retrograding Late Barremian–Early Aptian transgression (MCEL-1, Figs. 10, 11), as also indicated by Braun and Hirsch (1994) and Rosenfeld et al. (1995, 1998), and on the other hand, slightly inclining ramp geometry is obvious. This latter interpretation ties in with the open-marine, high-energy conditions that existed during the Late Barremian–earliest Aptian, occurring over wide areas when the platform was submerged (top Nabi Said Formation; Table 1), as well as with the seismic profiles of Garfunkel (1998) and the transitional zone between platform and slope, recorded in central Israel by Rosenfeld et al. (1998; Fig. 2). The steep slope recorded in the western Carmel area (Sass and Bein, 1982) may represent a distal steepening of this ramp.

Around the Aptian/Barremian boundary (uppermost Nabi Said Formation), the ramp inclination was reduced by the filling of available accommodation space with more sediment in Galilee than in the more proximal Golan Heights, resulting in a flat-topped platform. The Lower Aptian Ein el Assad Formation was deposited at a uniform depth and is of similar thickness throughout (Figs.7B, 9). Lateral facies variation mainly concerns proximal-distal trends within the inner platform area. Little remaining inclination resulted in less sediment accumulation on the Golan Heights. In the late Early Aptian, while open-marine depositional conditions still prevailed over large areas of the platform, the onset of deposition of the siliciclastic Hidra Formation began earlier in proximal areas, as several authors have indicated (Braun and Hirsch, 1994; Rosenfeld et al., 1998). The Upper Aptian–Albian succession is characterised by laterally very similar, although less open, marine deposits. Less variation and lower diversity of the skeletal and non-skeletal components characterise the prevailing protected platform facies of transgressive systems tracts and highstand systems tracts of the MCEL-2 and 3 cycles, compared to the MCEL-1 cycle. This pattern coincides with development of the rudist barrier reefs at the western edge of the platform (Bein, 1971; Sass and Bein, 1982; Ross, 1992), forming effective barriers against wave action and open-marine circulation.

### 6.4. Depositional sequences: correlation and controlling patterns

Biostratigraphy allows detailed comparisons between the successions analysed and local and regional interpretations (Fig. 10). Local correlations of second-order sea-level curves were drawn for the northern Sinai carbonate ramp (Bachmann et al., 2003) and the Galielee/Golan Platform (Fig. 10). Important similarities in sedimentation patterns and second-order sea-level change are apparent, although their Upper Aptian–Albian geometry is different. Both regions were subjected to a major sea-level fall around the Early/Late Aptian transition, as indicated by the deposition of terrestrial siliciclastics. However, in Sinai, marine siliciclastic deposition persisted until the Middle Albian, whereas in Galilee and Golan it lasted only until the Late Aptian, these differences being mainly due to different platform configurations.

Correlation with mfss determined for the Arabian Plate (Sharland et al., 2001) highlights major similarities. Three (MFS K70, 80 and 100) of four mfss on the Arabian Plate match well those recorded in the successions studied, with good stratigraphic correspondence. Pittet et al. (2002) and van Buchem et al. (2002) described two major sequence boundaries, characterising the eastern Arabian Platform margin, but both are dated as older than their correlatives (SBs MCEL-2 and 3) in eastern Levant. These differences may result from uncertainties in stratigraphy. Regarding the Tethyan transgressive–regressive cycles (Hardenbol et al., 1998), similarities are not obvious, and the only shared trend is the concurrence of the MCEL-3 LST with a maximum regression in the Tethyan area.

The prominent sea-level rise characterised by the orbitolinid-beds in the upper Ein el Assad Formation correlates well with the extended drowning event of several Tethyan carbonate platforms (Masse et al., 1995; Skelton, 2003), coinciding with the Selli Level (Föllmi et al., 1994; Castro and Ruiz-Ortiz, 1995; Moullade et al., 1998). The subsequent LST (MCEL-2) indicates the converse trend, like many Tethyan carbonate platforms that are characterised by prolonged drowning and later re-establishment of carbonate platform production (e.g., Castro and Ruiz-Ortiz, 1995; Moullade et al., 1998; Bosellini et al., 1999; Graziano, 1999). However, a similar Lower Aptian relative sea-level lowstand has been recorded from platforms of different Tethyan regions (e.g., Oman: Immenhauser et al., 2001; the French Alps: Strasser et al., 2001). The Late Aptian–Middle Albian second-order sea-level trend correlates well with trends on the Arabian Plate (Immenhauser et al., 1999; Sharland et al., 2001; van Buchem et al., 2002; Hillgärtner et al., 2003) and Tethys (Hardenbol et al., 1998), and also with sea-level changes recorded in the French Alps (Strasser et al., 2001) with respect to the lowstand during the earliest Albian (MCEL-3) and the subsequent long-term transgression.

This combination of similarities and differences results from eustatic sea-level changes and tectonic evolution of the Tethyan region. Reorganisation of the Tethyan rift-system characterised the Late Barremian–Early Aptian, resulting in different subsidence regimes within the individual plates and subplates (e.g., Dercourt et al., 1986; Stampfli et al., 2001). Relative sea-level changes in the eastern Levant are linked to the tectonic relationship of this region with the Arabian Plate and central Tethyan platforms, resulting in similar responses to regional subsidence and global eustasy.

The comparison of the third-order sequence boundaries with regional and global concepts concentrates on those of the Lower Aptian, because the stratigraphic control is better there than in the upper part of the succession. The Lower Aptian sequences reflect about 0.5 myr of deposition, whereas the Upper Aptian–Lower Albian sequences encompass longer time spans (Fig. 10). Their correlation with third-order sequences, indicated by Hardenbol et al. (1998) for the Tethys, yields no significant correspondence. Better agreements in frequency and age are apparent when comparing with sequence boundaries described from the Pacific guyots (Röhl and Ogg, 1998) or by van Buchem et al. (2002) for the eastern part of the Arabian Plate, suggesting an influence of regional Tethyan sea-level changes on the deposition of third-order sequences.

### 6.5. Climate

Further aspects to be considered in the interpretation of depositional sequence development are climate and ecological changes. Climate may be an important factor in controlling the depositional architecture, especially those reflecting the interplay of siliciclastic input and carbonate production. The two intervals characterised by siliciclastic input represent different parts of the second-order sea-level curve. The first (Nabi Said Formation, Upper Barremian–lower Lower Aptian) is interpreted as a second-order TST. At the time of deposition, a humid climate prevailed over the entire region. This is reflected by fluvial sediments in Jordan (Amireh and Abed, 2000), freshwater and brackish ostracods in northern Israel (Rosenfeld et al., 1998), and the formation of ferruginous ooids, indicating the global trend of Barremian-earliest Aptian warmth and humidity (Price, 1999). Siliciclastic input (including the deposition of ferruginous ooids) decreased at the mfs. This atypical phenomenon (Vail et al., 1991; Emery and Myers, 1996) may represent reduced erosion or reduced formation of ferruginous ooids, connected with a change from a humid to a more arid climate. Reduced humidity in the Early Aptian ties in with the aridity-humidity cycles demonstrated by Price (1999) and a trend towards a cooler climate (Pucéat et al., 2003).

The second siliciclastic interval begins in the Hidra Formation, a little above the orbitolinid beds in the upper part of the Ein el Assad Formation, possibly correlating with OAE 1a, and representing a second-order HST. It continues through the subsequent second-order lowstand and the following TST (Hidra Formation, MCEL-2, Upper Aptian; Figs. 7, 10).

Weissert and Erba (2004) suggested that elevated nutrient supply and increasing suspension loads from weathering affected Barremian–Aptian carbonate platforms, in connection with increasing carbon dioxide content around OAE 1a. This would have resulted in mesotrophic or eutrophic conditions on the shallow platform and created perfect conditions for orbitolinids (Simmons et al., 2000; Pittet et al., 2002). Thus, the orbitolinid beds may represent both deepening and elevated nutrient supply as a result of Early Aptian climate change.

More humid conditions have to be presumed to explain the formation of the ferruginous ooids deposited in Galilee/Golan and Sinai in the Hidra formation, as well as for the development of a delta system in the northern Sinai during Late Aptian–Middle Albian times (Bachmann and Kuss, 1998). Increasing humidity in the late Early Aptian correlates with similar features observed in the western Tethys (Hochuli et al., 1999). Wortmann et al. (2004) presumed altered weathering and erosion rates accompanying and following the global increase in carbon dioxide. They proved this for the period up to the Late Aptian. However, a further decrease in humidity around the Aptian/Albian boundary to explain the further reduced siliciclastic input to the Upper Aptian/Albian Rama Formation, is unlikely because of clearly documented humid conditions during the Late Aptian–Middle Albian in northern Sinai. A change to more arid conditions around the Middle/Late Albian boundary is suspected for northern Sinai (Bachmann and Kuss, 1998), and may be indicated by the predominance of dolomitic facies in the Middle–Upper Albian Yagur Formation in Galilee and Golan. Decreasing humidity in the Middle Albian fits well into global climatic patterns (Larson and Erba, 1999; Price, 1999), but the obvious middle Early Aptian and Late Aptian decrease in siliciclastic input may also have resulted from variations in platform configuration.

### 6.6. Ecological change

The eastern Levant platform facies is characterised by obvious differences between the Upper Barremian–Lower Aptian and Upper Aptian–Albian successions, as reflected in the open platform facies. The former contains low number of calcareous green algae of limited diversity, but the occurrence of rudist fragments increases up to the Late Aptian–Albian platform facies, reflecting the development of a platform rim at this time (Sass and Bein, 1982). A similar record of orbitolinid-calcareous algae associations has been documented from the Upper Barremian–Lower Aptian of Oman (Pittet et al., 2002), and a major change in the ecology of the carbonate platform in connection with OAE 1a was considered by Immenhauser et al. (2005). However, changes in the eastern Levant Platform association around the Lower/Upper Aptian boundary correlate with ecological changes observed on Tethyan carbonate platforms by Masse (1989); Castro and Ruiz-Ortiz (1995) and Skelton (2000, 2003; Fig. 10). A clear correlation of the ecological events that took place between the middle Early Aptian and Early/Late Aptian boundary is not possible because of the major change of facies during this interval. However, they may be the biological answer to intensified greenhouse conditions and the global change in ocean chemistry (see Wissler et al., 2003; Weissert and Erba, 2004).

## 7. Conclusions

Correlation of the Upper Barremian–Middle Albian carbonate platform succession of northern Israel (Galilee) and the Golan Heights has provided a basis from which to study the record of mid-Cretaceous sedimentation in a location between the Arabian Plate and central Tethyan Sea. The biostratigraphy is based on orbitolinids, and has resulted in the definition of six larger foraminiferal biozones that were correlated with the international chronostratigraphic concept of Hardenbol et al. (1998). This allowed us to date the platform succession.

Analysis of the sedimentary development has provided an interpretation of major sedimentary events, and third- and second-order depositional cyclicity of the eastern Levant Inner Platform. The biostratigraphy allows calibration of the second-order cycles and the sequence boundaries, as well as of a significant Late Aptian drowning event. The observed sedimentation patterns reflect regional platform evolution from a probable distally-steepened ramp geometry during the Late Barremian–Early Aptian to a rimmed platform that was established during the Late Aptian–Albian (Sass and Bein, 1982; Ross, 1992).

Eight third-order sequences were observed in facies changes in Galilee and on the Golan Heights. The Upper Barremian–Lower Aptian sequence boundaries correlate well with those recorded on Pacific guyots (Röhl and Ogg, 1998) and may represent the imprint of regional sea-level changes on the eastern Levant Platform.

Three second-order depositional cycles were also recorded. The facies patterns clearly indicate their origin in relative sea-level variations.

Second-order sequence boundaries and maximum flooding surfaces basically correlate with sea-level variations that have been recorded on the Arabian Plate, and are interpreted here as resulting from eustatic sea-level variations enhanced by subsidence (Sharland et al., 2001; van Buchem et al., 2002). Tethyan signals may be recorded around the Aptian/Albian boundary. A notable deepening during the late Early Aptian correlates with the extensive platform drowning (Masse et al., 1995) that is linked to the Selli Level/Oceanic Anoxic Event 1a (Föllmi et al., 1994; Weissert et al., 1998). The associated orbitolinid-rich facies is suggested to reflect this deepening and possibly also nutrient enrichment. This may have been triggered by increased amounts of carbon dioxide in the atmosphere and ocean basins as a result of volcanic activity (Larson and Erba, 1999; Weissert and Erba, 2004). The subsequent lowstand represents a signal different from the drowning of many Tethyan platforms, but a similar one has been recorded from some other parts of the Tethyan region. Middle Aptian variations in the benthic open-platform community are interpreted as reflecting ecological changes, which have been observed on several Tethyan carbonate platforms (Masse, 1989; Skelton, 2003).

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