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Jurassic evolution of the Arabian carbonate platform edge in the central Oman Mountains

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Abstract: The Jurassic Sahtan Group exposed in northern Oman was deposited in shallow marine environments at the edge of the Arabian Platform facing the Neo-Tethys (Hamrat Duru Basin). The upper Sahtan Group is made up of a mixed siliciclastic–carbonate unit overlain by pure carbonate deposits, assigned to a Bathonian and Early Callovian age on the basis of brachiopods and foraminifers. These carbonate depositional systems were composed of outer oolitic shoals that underwent subaerial exposure, and a deeper, somewhat restricted, gently dipping shelf interior. Oolitic material was shed off the platform edge into the deep-sea depositional complex of the Guweyza Formation. The Sahtan Group is affected by an important thickness reduction towards northeastern Jabal Akhdar. The angular unconformity (0.2%) at the top of the Sahtan Group is shown to result from tilting and top truncation of genetic sequences. This unconformity is overlain by the Rayda Formation, a veneer that shows an onlap pattern including a gradual deepening upwards facies evolution. The minimal time span of the stratigraphic hiatus is Mid-Callovian–Kimmeridgian. Oxfordian and Kimmeridgian sequences were probably never deposited in this area because of lack of accommodation space and/or because of subaerial exposure. It is proposed herein that the unconformity was shaped by subaerial carbonate dissolution during a steady, tectonically driven exhumation of the platform edge. During the Tithonian, a major eustatic sea-level rise caused transgression of the Rayda Formation upon the platform edge and normal shelf marine conditions resumed in the eastern Arabian Peninsula.

Keywords: Jurassic, Arabian Peninsula, Tethys, facies, carbonate platform.

The Jurassic section of the Arabian Platform is one of the major hydrocarbon-producing intervals of the Middle East. This period of widespread carbonate deposition resulted in a vertical and lateral mosaic of shallow-water facies, adjacent to deep-water, coarse-grained calcareous deposits, which were subsequently incorporated into tectonic slices thrust onto the eastern margin of the Arabian Platform (Bernoulli & Weissert 1987). The large anticlinal structure of Jabal Akhdar in northern Oman (Fig. 1) exposes excellent outcrops of the seaward edge of the Jurassic platform (Sahtan Group) (Fig. 2), and allows restoration of the depositional history of this continental margin, which recorded syndepositional tectonics, sea-level fluctuations and changes in the regional marine hydrographic regime.

The aims of this paper are two-fold: (1) to address the origin of the Jurassic–Cretaceous unconformity that is conspicuous over the platform edge (Rabu *et al.* 1990); (2) to document the transfer of carbonate platform products to the deep-sea depositional fan of the Guweyza Formation (Cooper 1990; Rabu *et al.* 1990; Guillocheau *et al.* 2001). Accordingly, the study involves description of the depositional facies and systems, reconstruction of the stratal termination pattern associated with the thinning of the Jurassic series towards the edge of the platform, and identification of the stratigraphic gap between the Sahtan Group and the Rayda Formation.

Stratigraphic setting

The first stratigraphic synthesis and nomenclature of the Mesozoic autochthonous terrain in Oman was produced by Glennie *et al.* (1974) (Fig. 2). A significant reduction in thickness of the Jurassic platform series in association with the development of the Jurassic–Cretaceous unconformity was subsequently documented across Jabal Akhdar by Rabu *et al.* (1990). The shallow-water Jurassic carbonate rocks of the Sahtan Group are about 400 m thick in western Jabal Akhdar (e.g. wadi Sahtan, Fig. 1), but only 30 m thick in the northeastern area (e.g. wadi Qarah, Fig. 1). According to Rabu *et al.* (1990), the porcellaneous limestones of the Rayda Formation rest directly upon the *Lithiotis*-bearing limestones (Pliensbachian) in the NE part of Jabal Akhdar. Little else has been published about the stratigraphic organization and age of the Sahtan Group, which is abruptly overlain by the Kahmah Group limestones. The basal unit, the Rayda Formation (‘Porcellanite’ of Glennie *et al.* (1974), or Awabi Formation of Béchenec *et al.* (1988) and Rabu *et al.* (1990)), is a light-coloured, fine-grained limestone corresponding to the Jurassic to Cretaceous transition (Connally & Scott 1985; Simmons & Hart 1987; Scott *et al.* 1988; Pratt & Smewing 1990; Rabu *et al.* 1990; Scott 1990).

The Jurassic Sahtan Group of Jabal Akhdar (Fig. 1) is composed of two main lithological units (Rabu 1987; Le Métour

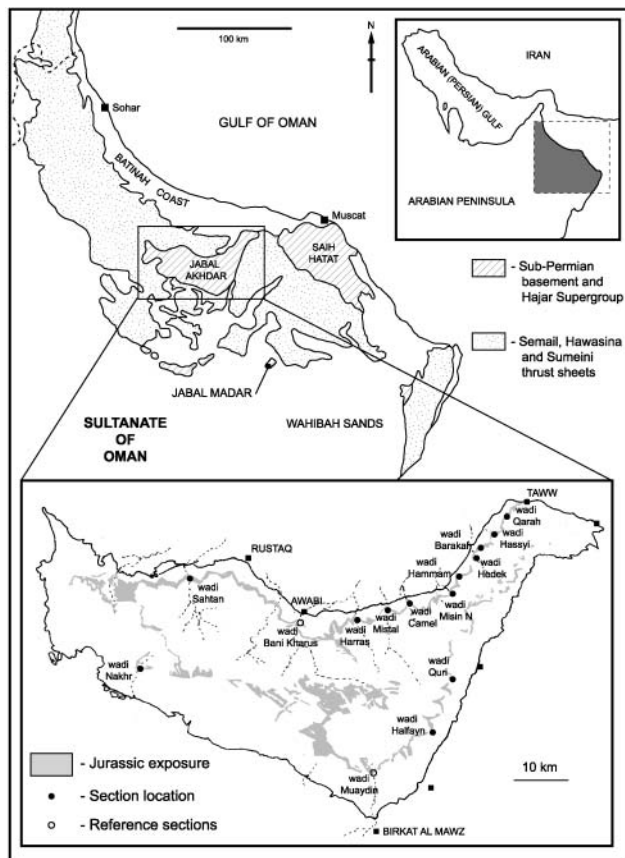


Fig. 1. Map of Oman showing simplified geology of the Oman Mountains and locations of sections, wadis and jabsals referred to in the text.

M.a.	GEOLOGICAL AGE		SAUDI ARABIA (Enay <i>et al.</i> , 1987)	INTERIOR OMAN (Hughes Clarke, 1988)	OMAN MOUNTAINS (this study)
140	CRET.	BERRIASIAN	Sulay Fm	Rayda Fm	KHAMAH GP Rayda Fm
150		TITHONIAN	Hilh Anhydrite + Arab Fm	Jubaila Fm	
	MALM	KIMMERIDGIAN	Jubaila Fm	Hanifa Fm	HIATUS
160		OXFORDIAN	Hanifa Fm	Tuwaiq Mt. Fm	
170	DOGGER	CALLOVIAN	Tuwaiq Mt. Fm	Dhruma Fm	Oolite member
180		BATHONIAN	Dhruma Fm		Terrigenous member
		BAJOCIAN			
190	LIAS	AALENIAN	Marrat Fm	Mafraq Fm	Lithiotis Limestone
		TOARCIAN			
		PLIENSCHACHIAN			

Fig. 2. Stratigraphic nomenclature for the Jurassic and Lower Cretaceous sequences of the Oman Mountains, Interior Oman (Hughes Clarke 1988) and Central Arabia (Enay *et al.* 1987).

1988): (1) a Lower Jurassic, mixed siliciclastic–carbonate unit referred to as *Lithiotis* limestones; (2) a Middle to Upper Jurassic massive carbonate upper unit. Because the *Lithiotis* limestones are minimally affected by the thickness reduction, sections for this study have been measured from the top of these limestones

to the Sahtan Group–Rayda Formation contact. Two informal lithological units have been distinguished: a lower Terrigenous member and an upper Oolite member (Fig. 3).

Methods and materials

Sequence analysis methods

In this study depositional sequences were used to unravel the stratigraphic architecture of the sedimentary system. This approach has found widespread application in shallow-water carbonates. Sequences are the stratigraphic record of changes in the ratio between accommodation space (A) and sediment flux (S). Two orders of sequences (large and medium scale) are of relevance for this study, and fall into the second order (3–50 Ma) and third order (0.5–3 Ma) as defined by Vail *et al.* (1991).

Outcrop and petrographic description and interpretation is followed by 1D sequence analysis in which the trends of increase or decrease in the accommodation/sediment-supply ratio are based on the palaeobathymetric evaluation of depositional environments, the preservation of sedimentary structures (e.g. amalgamation, reworking), and the special surfaces (e.g. submarine ravinement, subaerial exposure). Then, a time stratigraphic correlation scheme is established using, in particular, the maximum flooding surface (MFS) of sequences. Third-order sequences can be mapped for tens to hundreds of kilometres in some Jurassic carbonate systems, for example, the Anglo-Paris Basin (Garcia *et al.* 1996; Garcia & Dromart 1997). The main constraint for these correlations is provided by an independent time control given by particular faunal and lithological marker beds.

The ultimate step is the biochronological dating and the description of the successive depositional systems, which are 3D assemblages of geomorphological elements (i.e. palaeogeographical models).

Materials

Our study is based on 15 sedimentological outcrop sections in Jabal Akhdar (Fig. 1). The fieldwork was carried out in February 2000 and 2001. The outcrop sections are located in wadis cutting the flanks of Jabal Akhdar, and have been named after local geographical features. The most distant sections are 85 km apart and the two closest are only 1.5 km apart. The thickest measured section, in the wadi Nakhr (western part of the Jabal), is 180 m, and the thinnest section, measuring only 1 m, is in the wadi Qarah (NE of the Jabal). Sections of wadi Nakhr, wadi Bani Kharus and wadi Muaydin have been completed using microfacies analysis of about 100 thin sections.

The macrofossils collected in the field have been identified by B. Laurin (brachiopods) and F. Atrops (ammonites). The microfossil assemblages have been identified from thin sections by J.-P. Bassoullet, P. Bernier (large foraminifers), F. Atrops (calpionellids) and S. Gorican (radiolarians).

Facies and sequence description

Detailed description of the main depositional facies of the Middle–Upper Jurassic carbonate series comes from two well-exposed sections at wadi Bani Kharus and wadi Muaydin. These reference sections have a similar thickness and composition, and are 33 km apart on the northern and southern flanks of Jabal Akhdar (Fig. 3).

A stack of 11 medium-scale genetic sequences have been identified through the uppermost Lias–Middle Jurassic interval (Fig. 3). These sequences have been grouped into three major, large-scale sequences referred to as sequences I, II, and III. They are presented below in a stratigraphic ascending order.

Lower sequence (S I)

This sequence overlies the *Lithiotis* limestones with apparent conformity. The surface that bounds the two units shows

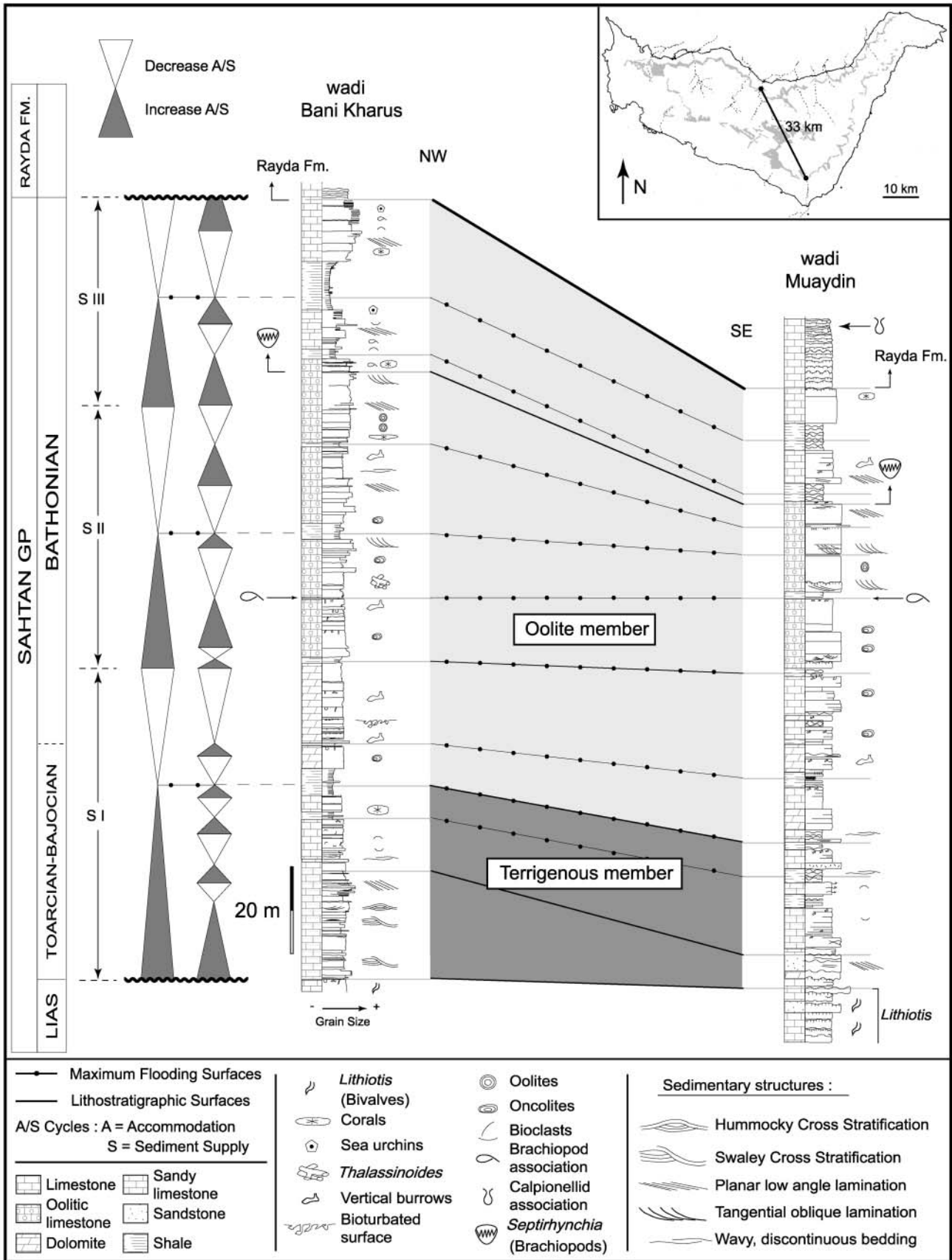


Fig. 3. Reference sections of wadi Bani Kharus and wadi Muaydin with sequence analysis (two orders of cycles). Datum is the brachiopod association of *Daghanirhynchia daghaniensis*, *D. subversalibis* and *Cererithyris bihinensis*.

evidence of microkarstification, and is capped by a thin, ferruginous crust. The increasing accommodation hemi-cycle of sequence I consists of three medium-scale sequences and is characterized by a succession of two depositional facies.

At the base of sequence I, the hummocky-cross-stratified (HCS) facies occurs. This is a dolomitic sandstone showing typical amalgamated hummocky cross-beds and, occasionally, laterally accreted hummocky cross-beds, swaley cross-beds (Fig. 4) and single bioclastic storm layers with graded bedding. The lamination is underlined by ferruginous grains and tiny mollusc shells consisting mainly of tiny bivalves such as fragmented small oysters and often gastropods, mostly concentrated into storm layers. Quartz grains are fine to medium sand sized. The typical rust colour of weathered surfaces is due to the presence of the ferruginous grains along with scattered development of dolomitic cement.

The Bivalves facies, overlying the HCS facies, consists of a fine-grained, variegated limestone, showing wavy, discontinuous bedding as the argillaceous content increases. Most bivalves are *Trichites* but small oysters and gastropods are concentrated in lenses and thin storm layers. Upper bounding surface of beds are sometimes ferruginous, and generally show a complex amalgamation of *Thalassinoides* and *Glossifungites*-type galleries. The fine-grained matrix contains small (i.e. 0.1–0.5 mm) ferruginous ooids. The ooids consist of hardly visible, concentric micritic laminae and an iron-stained nucleus. These ooids belong to type 1 of Strasser (1986).

The HCS facies assemblage is characteristic of an (upper) shoreface environment. Above, the Bivalves facies corresponds to an (upper) offshore depositional environment. The maximum flooding surface of sequence I consists of black, foetid, dolomitic and fissile shales with some thin, bioclastic storm layers with subplanar, undulatory lamination.

The regressive hemi-cycle of sequence I is composed of two medium-scale sequences (Fig. 3), and is characterized by the development of a number of resistant, dolomitic levels through the dark-coloured micritic unit, together with the profusion of dolomitic filled burrows (i.e. Dolomite facies). The dolomitic fraction is subordinate in the lower hemi-cycle, and increases upwards to yield genuine dolomitic levels. Automorphous dolomitic crystals with dark nuclei can be assigned to the CCCR dolomite type (i.e. cloudy centre clear rimmed dolomite) (Sibley 1980) (Fig. 4). The nucleus may consist of an unaltered piece of the original facies (i.e. dark mudstone). This dolomite type is considered typical of very early dolomitization. Traces of later dolomitization can be found as saddle dolomite in pores. This regressive hemi-cycle records the successive appearance of oncolites and genuine oolites. At the base, oncolites are small (about 1 mm). Upwards, they become larger (1–3 mm), and display an irregular micritic cortex, resembling ooids of type 2 of Strasser (1986). Oolites can be found a few metres above the first oncolite occurrence, and remain subordinate in abundance.

The uppermost interval of sequence I is a massive, up to 1 m thick, dolomitic level with typical orange-weathered surface.

Middle sequence (S II)

Sequence II is composed of massive, resistant carbonate units of several metres thickness separated by thin, shaly horizons that are interpreted to be the maximum flooding surfaces of medium-scale genetic sequences (Fig. 3). Sequence II at wadi Bani Kharus shows a stacking of four medium-scale sequences that display a relative symmetrical pattern in terms of hemi-cycle thickness and facies composition (Fig. 3).

Depositional facies mostly consist of an oolitic packstone–grainstone with depositional structures such as dunes (showing top truncation and internal reactivation), planar lamination, trough and swaley cross-stratified beds, and variably amalgamated bioclastic storm layers. Oolites represent the dominant grain component, with subordinate oncolites, intraclasts and bioclasts. Oolites in general are well rounded and sorted (Fig. 4). The cortex is made of micrite and is vaguely distinctive from the nucleus by a finely concentric lamination. Nucleus-to-cortex ratios are highly variable. Those oolites correspond to type 1 of Strasser (1986). Oncolites are several millimetres in diameter with a clearly ovoid shape. Cortex laminations are poorly visible under the microscope. Generally, the nucleus is large compared with the thickness of the cortex. Bioclasts are composed of fragmented oyster shells and tiny gastropods. The skeletal macrofauna includes clypeid echinoderms, brachiopods and corals.

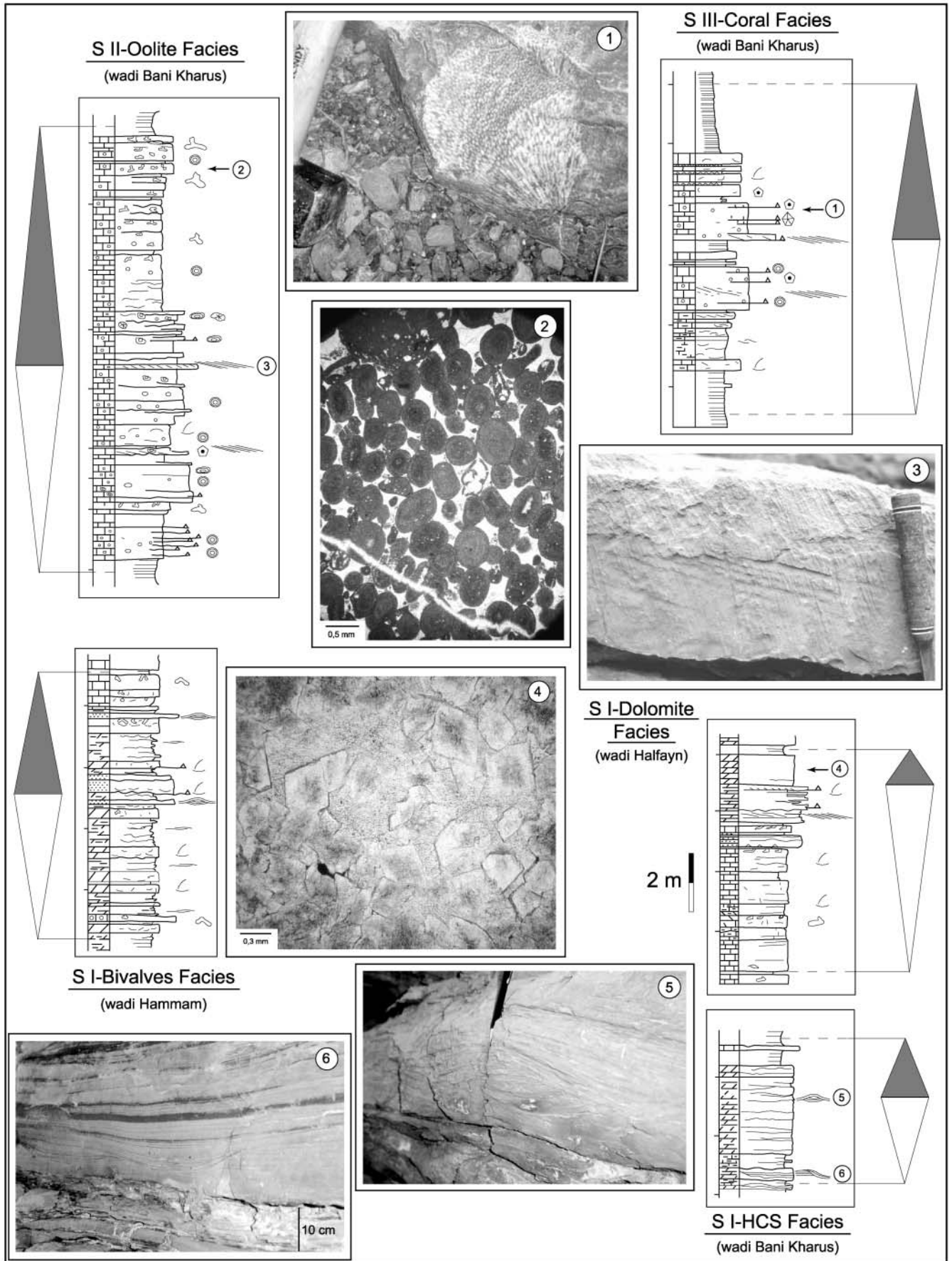
At wadi Muaydin, the textural fabrics and depositional structures are indicative of an overall shallowing trend throughout sequence II. The regressive part of the lowermost sequence yields amalgamated, thin bioclastic storm layers intercalated within a peloidal, dark mudstone. Conversely, grainstone fabrics of the upper sequences show the development of bladed and equant calcite cement around oolites, indicative of a primary cementation in a freshwater phreatic environment. Additional evidence for a meteoric influence is provided by the occurrence of dissolved mollusc shells partially filled by drusy calcite spar (uppermost sequence at wadi Muaydin). It is thus apparent that the upper oolitic shoals were temporarily subaerially exposed, receiving meteoric water and probably allowing the formation of a lens of fresh water in the subsurface.

The top boundary of sequence II is a decrease-to-increase accommodation–sediment-supply turnaround surface between two medium-scale sequences. This bounding surface of large-scale sequences does not show any remarkable sedimentological and petrographic feature. It basically marks a vertical change in the facies assemblage.

Upper sequence (S III)

The upper sequence (S III) consists typically of an alternation of recessive clayey mudstone and resistant grain-supported limestone that corresponds to small-scale deepening–shallowing cycles. At wadi Bani Kharus, the resistant level of the lower cycle shows parallel and oblique (low-angle) lamination and thin

Fig. 4. Sahtan Group facies associated with typical depositional sequences (symbols as in Fig. 3). 1, outcrop of dark mudstone containing whole corals, Coral facies, wadi Bani Kharus. 2, thin-section photomicrograph of oolitic grainstone, Oolite facies, wadi Bani Kharus. 3, outcrop of oolitic grainstone affected by planar cross-bed sets, Oolite facies, wadi Bani Kharus. 4, thin-section photomicrograph of dolomitic crystals assigned to the CCCR dolomite type (i.e. cloudy centre clear rimmed dolomite), Dolomite facies, wadi Halfayn. 5, outcrop of hummocky cross-beds, HCS facies, wadi Bani Kharus. 6, outcrop of swaley cross-beds underlain by ferruginous grains, HCS facies, wadi Bani Kharus.



storm layers with normal grading (Fig. 4). Grains are composed of bioclasts (bivalves, gastropods, corals), foraminifers, oolites and intraclasts. Oolites are similar to those of the underlying subunit. The resistant level of the upper cycle shows stacked thick beds of low-angle cross-laminated oolitic, foraminiferal grainstones, and rudstones bearing large rhynchonellid brachiopods and coral heads.

Transitional beds beneath and above the grain-supported deposits are composed of a peloidal wacke–packstone containing variably sized debris of thin- and thick-shelled molluscs, gastropods and clypeid echinoderms.

Depositional facies encountered throughout sequence III suggest vertical alternation between a storm-agitated environment (i.e. grainy shoal), and a deeper and quieter depositional setting.

At wadi Bani Kharus, the upper boundary of sequence III is an erosional surface cutting in the increasing accommodation–sediment-supply hemi-cycle of a medium-scale sequence (Fig. 3).

Rayda Formation

The Rayda Formation is a conspicuous, light grey limestone that ranges from 30 to 83 m in thickness (Pratt & Smewing 1990). The Rayda overlies the Sahtan sharply and conformably in most of the sections of Jabal Akhdar. Locally, onlap of the Rayda upon the Sahtan limestone can be observed in the wadi Barakah. The Rayda typically consists of wavy-bedded, cherty lime mudstone to wackestone containing peloids and pelagic fossils: calpionellids, radiolarians, ‘filaments’ (tiny bivalves), belemnites and small ammonites. Packstone interbeds composed of echinoderm debris occur in the lower Rayda at wadi Bani Kharus. The lower Rayda at wadi Muaydin consists of amalgamated, wave-ripple cross-beds (Fig. 5). The lower Rayda in wadis Halfayn and Quri (SE Jabal Akhdar) is made up of coarse sand-sized crinoid ossicle grainstone (i.e. encrinite), directly overlying the Sahtan Group, and grading upwards to the typical fine-grained limestone of the Rayda (Fig. 5). In both wadis, true encrinite is 5 m thick and contains cephalopods (frequent belemnites and sparse ammonites at wadi Quri). Sedimentary structures within this coarse grainstone are planar cross-bed sets and scours (Fig. 5), suggesting intermittent storm events in a permanently wave-agitated environment (i.e. shoreface setting). It is thus inferred that the Rayda at wadi Quri records a very gradual increase of depositional water depths, from shoreface to lower offshore environments.

Stratal termination pattern

The Middle Jurassic sequences have been correlated across Jabal Akhdar to reveal the stratal organization associated with the Jurassic unconformity. Two transects parallel to the southern and

northern flanks have been reconstructed (Fig. 6) by correlating the maximum flooding surface (MFS) of medium-scale genetic sequences. The transects are oriented according to the main direction of thickness reduction of the Sahtan Group. In the northern area of Jabal Akhdar, a conspicuous yellow dolomitic level, 1 m thick, common to many sections of Jabal Akhdar has been selected as a datum surface. A maximum flooding surface has been used as a datum plane for the southern transect. The transects have then been linked by the correlation of wadi Muaydin and wadi Bani Kharus sections, which are 33 km apart (Fig. 3). The sequences of these sections have been correlated on the basis of the occurrence of a brachiopod marker bed in the middle part of the sections (see below), and of the appearance of the brachiopod *Septirhynchia* in the upper part of sections.

The reduction in thickness of the Middle Jurassic units in the northern flank of Jabal Akhdar is mainly due to a top truncation (Fig. 6). Above the datum plane, six medium-scale genetic sequences are successively removed from the top to bottom towards the northeastern edge of the platform. The general gradient of erosion is about 0.2%, the Sahtan Group losing 200 m in thickness over a length of almost 100 km.

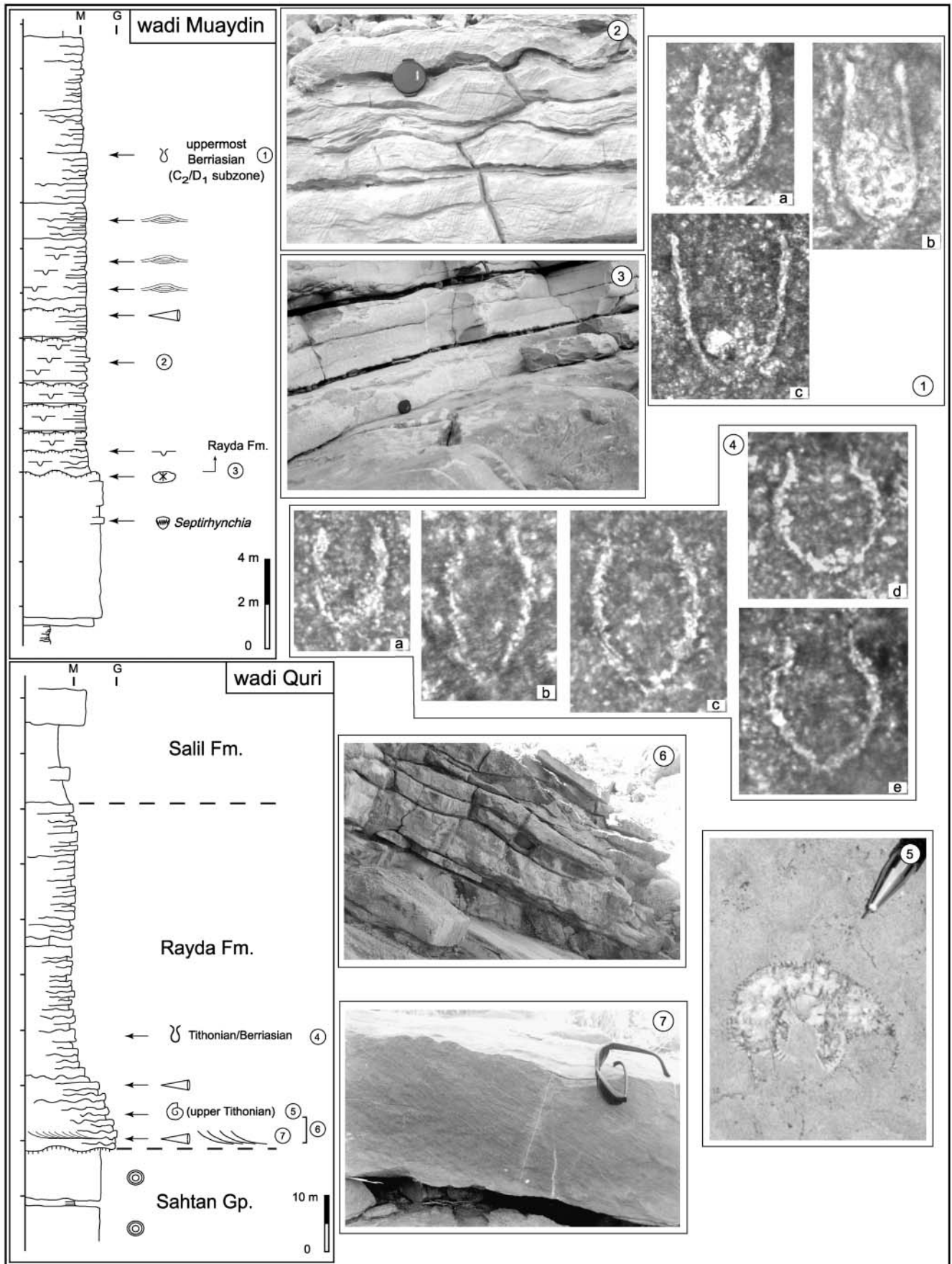
The southern cross-section shows both progressive pinching out (e.g. S II between wadi Nakhr and wadi Muaydin) and top truncation eastward of medium-scale genetic sequences (Fig. 6). This architectural pattern suggests possible syndepositional and certain post-depositional removal of sediments. Similarly to the northern flank, the gradient of top truncation is 0.2% (the uppermost Jurassic series loses 120 m in thickness over a length of 70 km).

The stratal termination pattern of the Jurassic carbonate platform across Jabal Akhdar reveals that the Middle Jurassic series was affected possibly by syndepositional export (southern flank), and unmistakably by post-depositional top truncation (northern flank). The top truncation surface is widespread, planar and shows a gentle slope of about 0.1°. A volume-based approach to calculation of the total amount of sediment removed after deposition over Jabal Akhdar has been applied according to the procedure described by Dromart *et al.* (2002). The calculation yields an average depth of erosion of 43 m (total volume divided by the total surface). Above the unconformity, biostratigraphic and sedimentological data together suggest that the Rayda Formation is transgressive, and overlaps this major hiatal surface towards the west (Fig. 6).

Biostratigraphic data and geochronological assignments

The lower and upper Sahtan Group have been assigned, on the basis of foraminiferal occurrences, to the Early and Mid–Late Jurassic, respectively. A series of new findings are now available, which permit the general Jurassic stratigraphy of Jabal Akhdar to be significantly refined.

Fig. 5. Rayda Formation facies associated with wadi Muaydin and wadi Quri sections (symbols as in Fig. 3). 1, thin-section photomicrographs of calpionellid association of the D₂ subzone (uppermost Berriasian), wadi Muaydin. a, *Calpionellopsis simplex* (Colom) (×300); b, *Calpionellopsis oblonga* (Colom) (×300); c, *Remaniella cadischiana* (Colom) (×300). 2, outcrop of amalgamated wave-ripple cross-beds in lime mudstone of the lower Rayda, wadi Muaydin. 3, outcrop at wadi Muaydin showing the sharp contact between Sahtan Group and Rayda Formation (massive dark mudstone of the Coral facies in the lower part of the photograph is overlain by thin-bedded lime mudstone of the Rayda Formation). 4, thin-section photomicrographs of calpionellid association of the B₁ subzone (lowermost Berriasian), wadi Quri. a, *Crassicollaria parvula* (Remane) (×300); b, *Crassicollaria brevis* (Remane) (×300); c, *Calpionella* aff. *alpina* (Lorenz) (×300); d and e, *Calpionella alpina* (Lorenz) (×300). 5, bedding plane view of poorly preserved perisphinctid ammonite, wadi Quri. 6, outcrop at wadi Quri showing undulating stratification with scours of the lower Rayda Formation. 7, planar cross-bed sets, wadi Quri.



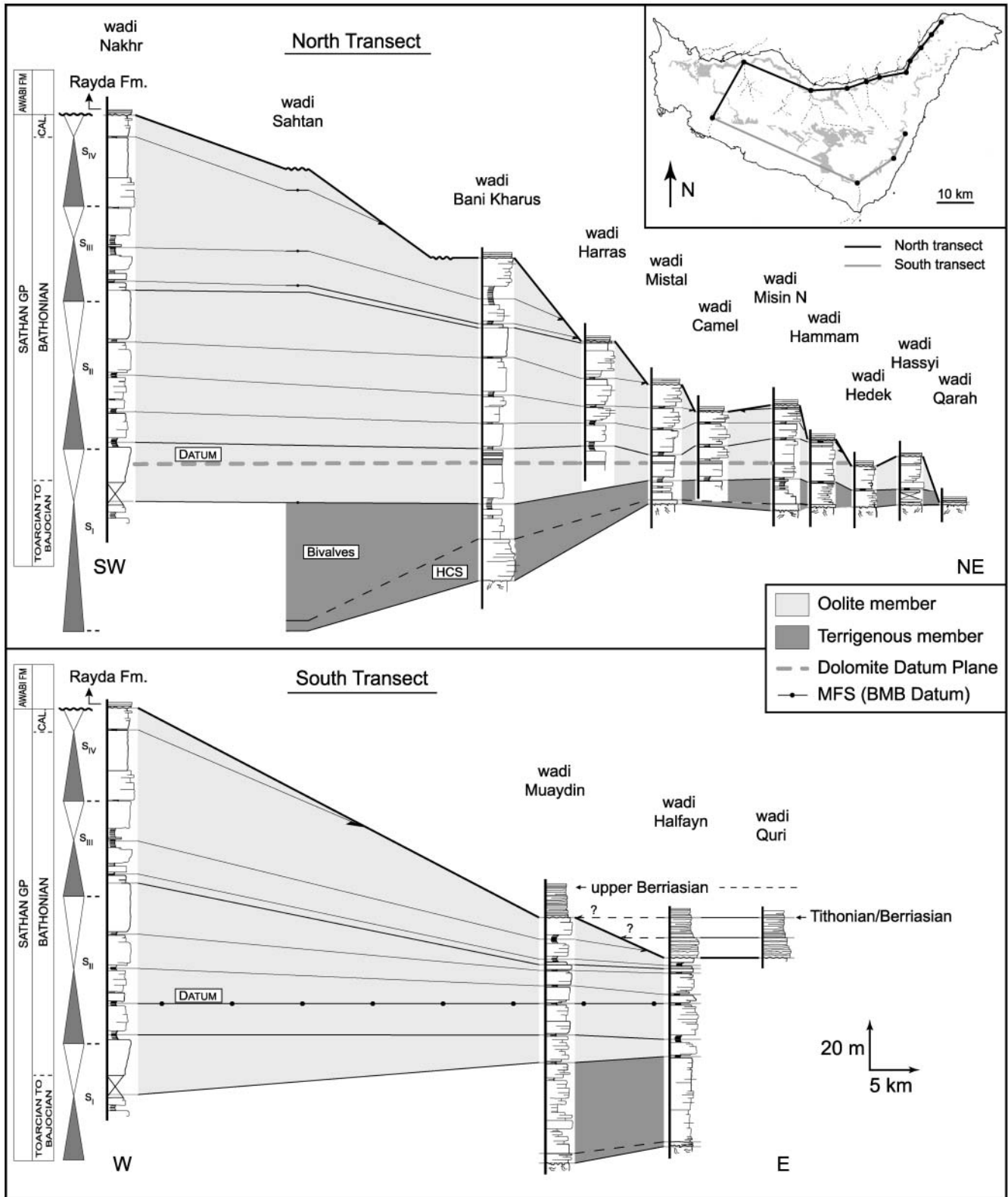
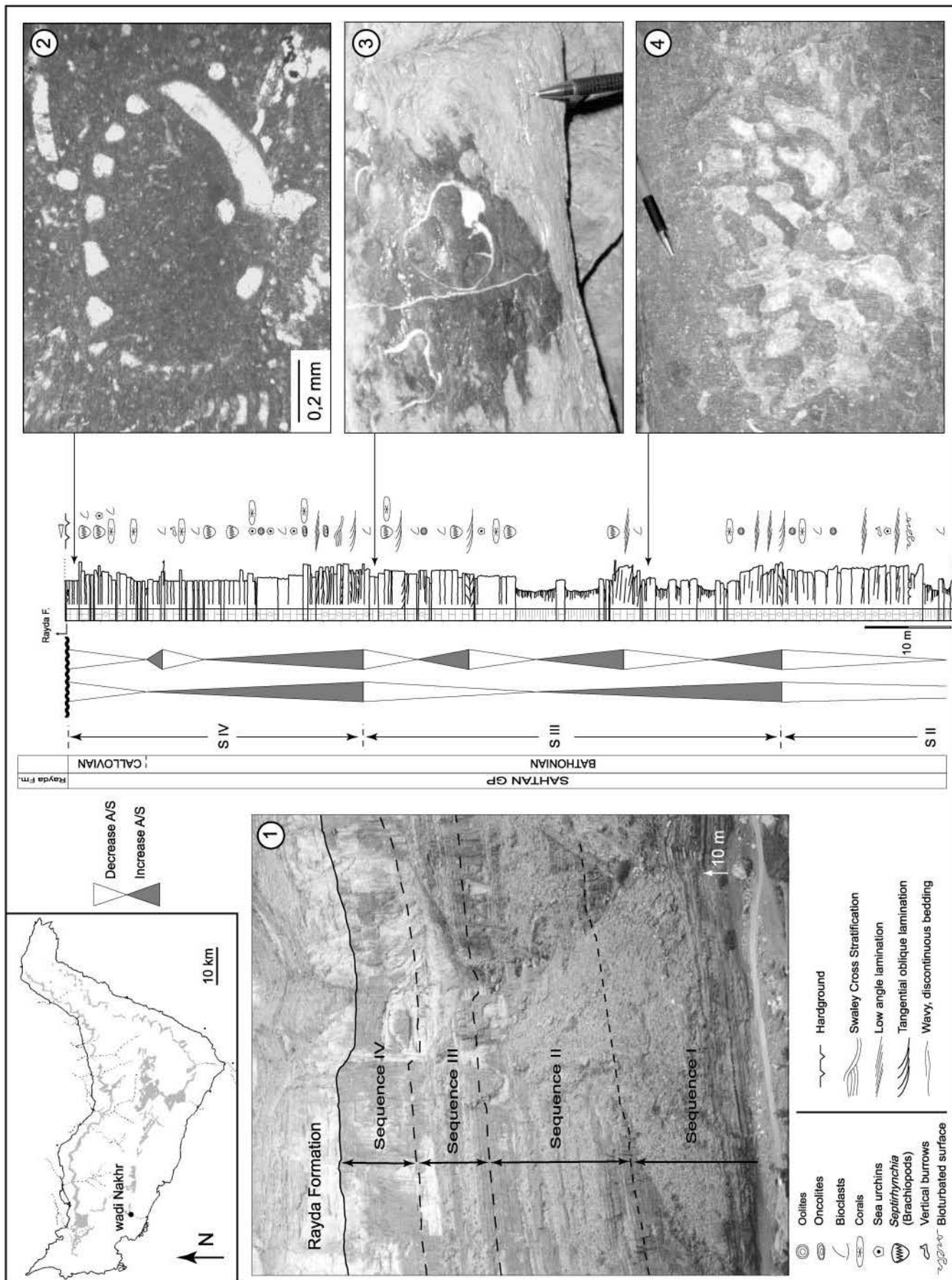


Fig. 6. Stratigraphic cross-sections showing correlation of principal measured sections. Datum for the north transect is an orange dolomitic level of the Dolomite facies, and for the south transect, the brachiopod marker bed (BMB) in the Oolite facies.



Sahtan Group, Terrigenous member

The lower upper Sahtan of Jabal Akhdar, referred to as the Terrigenous member, has not yielded any diagnostic faunal element. This unit directly overlies the *Lithiotis* limestone, which has been recently assigned to the Carixian (Early Jurassic) in Algeria (Elmi *et al.* 2003). The Terrigenous member shares a number of similarities with the upper Mafraq Formation defined in the Haushi–Huqf area (SE Oman). The Mafraq Formation consists of shallow-marine deposits affected by terrigenous inputs, and has been dated as Late Bajocian on the basis of ammonite moulds (*Thambites* cf. *planus*) (Dubreuilh *et al.* 1992). Accordingly, the Terrigenous member of Jabal Akhdar can be tentatively assigned to the Toarcian–Bajocian interval.

Sahtan Group, Oolite member

A brachiopod-rich level in the middle of sequence II (Fig. 3) has yielded *Daghanirhynchia daghaniensis*, *D. subversalibis* and *Cererithyris bihinensis*. On the basis of the range of these species established by Alméras (1987) for the Middle Jurassic sequence of Saudi Arabia, this assemblage provides an Early Bathonian to Mid-Callovian age.

Above, sequence III is characterized by the very common occurrence of a large, thick-shelled form that belongs to *Septirhynchia* (Fig. 7). This genus is common over the South Tethyan margin, from Tunisia to the Arabian Peninsula including Lebanon and Syria, and has been broadly dated as Mid-Bathonian to Mid-Callovian (Mancenido & Walley 1979). Particularly, *S. budulcaenensis* has been documented in the Middle–Upper Dhurma Formation (Bathonian–Callovian) of Jabal Tuwaiq (Saudi Arabia) (Nazer 1970), and *S. numidiensis* has been reported from the Beni Oussid II Member (of latest Bathonian–Early Callovian age) of the Fom Tataouine Formation in southern Tunisia (Ben Ismail *et al.* 1989).

The mud-rich facies bearing corals of sequence IV of the wadi Nakhr contain a prolific assemblage of benthic foraminifers including *Pfenderina* (*P. trochoidea* or *P. salernitana*) (Fig. 7), possible *Alzonella cuvillieri*, *Pseudocyclammina* and small *Trocholina*. The foraminiferal association is typical of the cenozoone that corresponds to the Atash Member of the Upper Dhurma Formation in Saudi Arabia. The Atash Member marks the Bathonian–Callovian transition on the western Arabian Platform (Enay *et al.* 1987). In addition, it should be noted that sequence IV of the wadi Nakhr has very similar facies attributes and foraminiferal assemblages to the *Pfenderina* Zone VIII defined by Gollesstaneh (1965) in South Fars of Iran, and placed at the Bathonian–Callovian transition. Biostratigraphic data from brachiopods and Foraminifera are in accordance, indicating that the uppermost Sahtan in Jabal Akhdar (i.e. sequence IV of the Oolite member) is of latest Bathonian to earliest Callovian age (Fig. 8).

Sharland *et al.* (2001) have proposed a sequence stratigraphic framework for the Mesozoic of the Arabian plate on the basis of identification of several eustatic sea-level maxima that were correlated through the Middle East. The MFS of Sequence I, which is correlative to the marine incursion recognized in the Haushi–Huqf area (Dubreuilh *et al.* 1992), is probably Late Bajocian in age, and has no counterpart in the MFS chart of Sharland *et al.* (2001). The MFS of Sequence II may correspond

to the Early Bathonian MFS (J30). Neither sequence III MFS, nor sequence IV MFS fits in age with the Mid-Callovian MFS (J40). Sequence I and sequence III MFS, which are the prominent MFS in Jabal Akhdar, correlate better in age with flooding surfaces of units D3 and D6, respectively, of the Dhurma Formation in central Arabia (Enay *et al.* 1987). It is thus apparent that there is no good agreement between the ages of MFS of the large-scale sequences defined in Jabal Akhdar and the relevant MFS of Sharland *et al.* (2001) for the interval studied here. This difficulty probably stems from the fact that Middle Jurassic reference sections of Sharland *et al.* (2001) are located in Saudi Arabia, about 1000 km west of Jabal Akhdar. It is suspected that the hierarchical organization of genetic sequences is variable through the Arabian plate because of differential subsidence and carbonate sediment production.

Lowermost Rayda Formation

Only very fine-grained facies referred to as porcellaneous have provided biostratigraphically indicative fauna, i.e. calpionellids. In wadi Muaydin, 14 m above the unconformity (Fig. 5), calpionellid association are dominated by *Calpionellopsis oblonga* (Cadish) associated with rare *C. simplex* (Colom) and very rare *Remaniella cadishiana* (Colom). This fauna marks the *Calpionellopsis* standard zone (*oblonga* subzone), the lower part of which is equivalent to the D₂ subzone of Remane *et al.* (1986). Parallel standard ammonite zonation (Le Hégarat & Remane 1968) indicates the Upper Berriasian *boissieri* zone (*picteti* subzone). In wadi Quri (Fig. 5), levels containing calpionellids are 20 m above the Sahtan Group–Rayda Formation contact. The association is dominated by spherical forms of *Calpionella alpina* (Lorenz) (more than 90%). Rare elongated forms, such as *C. aff. alpina* (Lorenz), can be observed in association with frequent *Crassicolaria parvula* (Remane) and very rare *C. brevis* (Remane). This association marks the base of the *Calpionella* standard zone (*alpina* subzone equivalent to zone B of Remane *et al.* (1986)). The lack of *Crassicolaria intermedia* rather suggests basal zone B (B₁ subzone) (Benzaggagh & Atrops 1995). Clearly, the calpionellid association of these levels corresponds to the lowermost Berriasian *euxinus* zone (*jacobi* subzone), according to the standard zonation of ammonites (Le Hégarat & Remane 1968). Small ammonites found in wadi Quri, 5 m above the contact and 15 m below the calpionellid levels (Fig. 5), belong to Perisphictidae (uppermost Tithonian) and not Berriassellidae (lowermost Cretaceous). The wadi Quri section reveals that the base of the Rayda Formation is of Tithonian age in Oman and not Early Berriasian as stated by Simmons & Hart (1987) and Simmons (1994).

The biostratigraphic findings for the uppermost Sahtan and lowermost Rayda indicate that the Jurassic stratigraphic hiatus over Jabal Akhdar ranges at least from somewhere in the lowermost Callovian to somewhere in the Tithonian (Fig. 8), corresponding to a lack of depositional record of 18 ± 2 Ma (Gradstein *et al.* 1994).

The basal beds of the Rayda Formation, currently interpreted as equivalent to the lower Habshan Formation (de Matos 1994), should be now considered to be the distal, and not deep, marine equivalent of the uppermost Hith Formation, i.e. Manifa Reservoir in Abu Dhabi (de Matos 1994).

Fig. 7. Coral facies and top of Oolite facies in wadi Nakhr section with sequence analysis. 1, view of wall of wadi Nakhr, showing the upper part of the Sahtan Group and sharp contact with the overlying Rayda Formation. 2, thin-section photomicrograph of small *Pfenderina*, typical of the *Pfenderina trochoidea* Cenozoone. 3, view of *Septirhynchia* sp. 4, coral at the top of the Oolite facies.

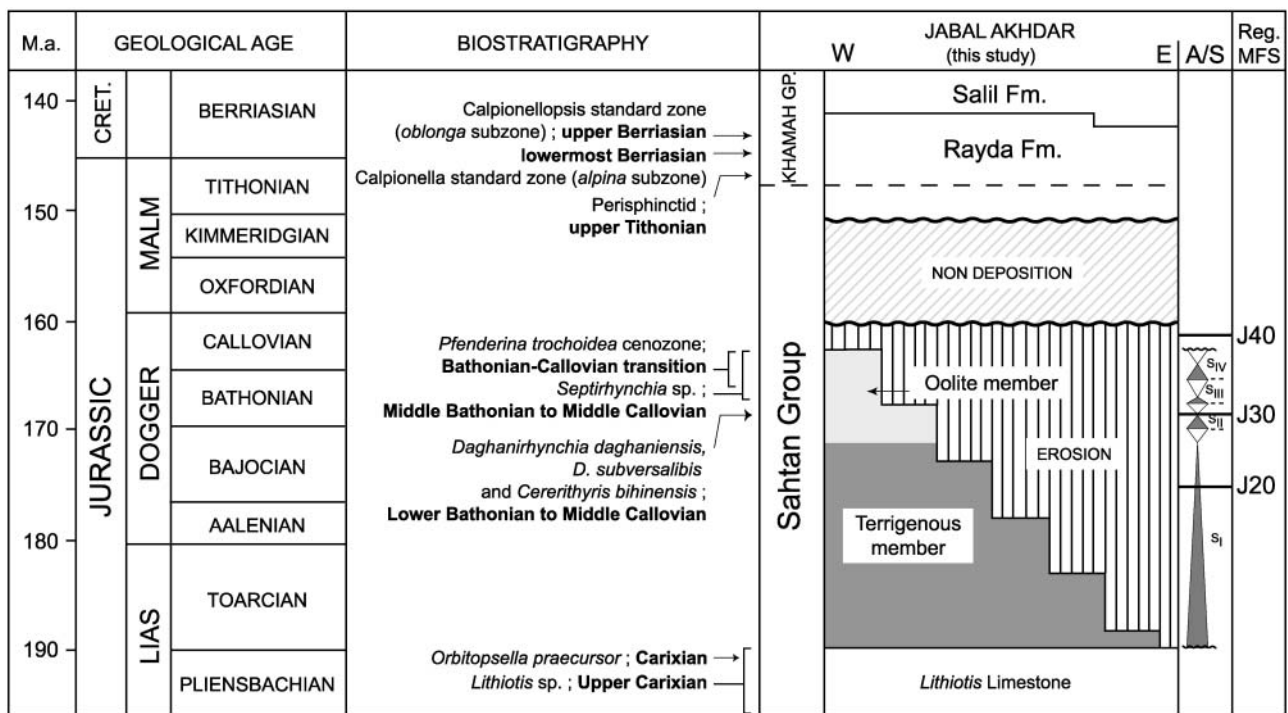


Fig. 8. Synthetic chart for the stratigraphy of the Jurassic and Lower Cretaceous units of the Oman Mountains. Sequence analysis in Jabal Akhdar is compared with the regional MFS (Reg. MFS) from Sharland *et al.* (2001).

Correlation with deep-water sequences (Guweyza Formation)

The Guweyza Formation in wadi Muaydin at Birkat al Mauz is currently thrust upon the SE flank of Jabal Akhdar. The Guweyza Formation was deposited in the deep Hamrat Duru basin, which stretched out in front of the Omanese section of the Arabian Platform (Béchenec 1987) (i.e. in the position of the present-day Oman Gulf). This 300 m thick formation is made up of three lithological units. The lowest unit overlies radiolarian chert layers, and consists of interbedded shale and quartz-rich sandstone arranged in typical Bouma sequences. The intermediate unit is composed of three stacked massive, resistant carbonate units showing large trough cross-beds. The carbonate products are made up of oolitic grains, oolitic gravels, benthic foraminifers and crinoid ossicles, in decreasing order of abundance. The uppermost unit is decidedly heterolithic in nature, containing deposits of highly variable grain size: (1) thin beds of shale and fine-grained, grey limestone; (2) medium-thickness, planar cross-beds of grainstone; (3) several metres thick, clast-supported carbonate conglomerates. The conglomerate levels show common evidence of amalgamation and reworking in association with pure bedload clast transport and prograding depositional sheets. These lithoclasts are subangular, sometimes perforated, forms and dominantly derive from the Triassic Mahil Formation (orange, dolomitic). Clasts also include elements removed from the Jurassic Sahtan Group (dark, oncolite-bearing and *Lithotis*-bearing lime mudstone, oolitic grainstone, sandstone), and from the Permian Saiq Formation (fusulinid- and coral-bearing large clasts).

Diagnostic radiolarian assemblages from the wadi Muaydin area indicate a Toarcian age for the basal radiolaritic unit, and a latest Bajocian (to earliest Bathonian) age for the lowest to

intermediate unit transition within the Guweyza Formation. The uppermost Guweyza, overlain by the Sid'r Formation (Béchenec *et al.* 1990), has yielded Oxfordian radiolarians in a more distal section (i.e. Jabal Dhera). On the basis of lithological and biostratigraphical data, it is proposed that the lowest and intermediate units of the Guweyza Formation correlate with the Terrigenous and Oolite members of the Sahtan Group, respectively. The heterolithic upper unit of the Guweyza Formation is apparently correlative to the major unconformity that developed over the platform.

Discussion: the Jurassic platform edge evolution

A general Mesozoic configuration and evolution of the platform margin has been proposed by Pratt & Smewing (1990, 1993). This paper adds details to the Jurassic history of the carbonate platform edge.

The platform edge palaeogeography

On the basis of the correlations and facies tract descriptions given above, four types of depositional systems have been distinguished in the Middle Jurassic section of Jabal Akhdar. The systems differ in lithological composition, facies assemblages and faunal content. The reconstruction of the systems is variable because the top erosional surface cuts into Jurassic sequences.

The lower depositional system has been referred to as the Terrigenous system, and corresponds to the transgressive part of the large-scale sequence I. It is a mixed carbonate-siliciclastic system, composed of two facies tracts: a shoreface (i.e. HCS facies) and an offshore (i.e. Bivalves facies) facies tract. The lack of HCS facies in the NE part of Jabal Akhdar (Fig. 6) as well as

the underlying ferruginous surface at the top of the *Lithiotis* unit together suggest that this area was emergent at that time. The offshore facies tract is transgressive throughout Jabal Akhdar. Its thickness, however, varies from 10 m on the northern flank to 30–40 m on the southern flank of Jabal Akhdar. This variation is thought to be due to the fact that the lower Bivalves facies of the eastern part of Jabal Akhdar could be the lateral, outer equivalent of the HCS facies. To sum up, the Terrigenous depositional system is viewed as a storm-dominated shelf, dipping towards the SE, with a shoreface belt rimming an emerged carbonate plateau.

The second depositional system has been referred to as the Dolomite system, and corresponds to the regressive part of the large-scale sequence I. The topography of this system was fairly flat. In general, the eastern area of Jabal Akhdar shows evidence of extensive and early dolomitization, and, at least sporadically, a high level of the hydrodynamic regime: a well-sorted quartz-rich cross-bedded sandstone (wadi Hassyi), and type 1 oolites composing planar cross-bed sets (wadi Mistal), or arranged as low-angle, oblique laminae (wadi Halfayn). Westwards (e.g. wadi Nakhr), the dolomitization is not so pervasive and facies show mud-supported fabrics, suggesting deeper and quieter submarine environments. Type 2 oncolites and solitary corals within these facies are indicative of protected environments. Sparse oolites found here may have been swept from shoals of the eastern area. The Dolomite depositional system as a whole is considered to be composed of a very superficial plateau with shoals and ponds, limiting a submerged and protected inner shelf environment in the western area.

The third and fourth systems are carbonate-dominated ramps. Both include typical oolitic shoal facies tracts, and basically differ in their faunal content. They have been referred to as Oolite and Coral systems, and, respectively, correspond to sequence II and sequences III–IV. Facies changes occur mostly in a vertical sense, showing an alternation of carbonate-dominated and clay-dominated sedimentation that reflects high-frequency variations in relative sea level. The carbonate/clay ratio of sequences decreases westwards, towards the deeper shelf interior.

The Mid-Jurassic history of the Arabian Platform edge can be summed up as follows. After the Early Jurassic (?Early Pliensbachian) deposition of the *Lithiotis* limestone complex, an episode of subaerial exposure affected the platform edge in eastern Oman. Storm-influenced, shallow-water, marginal marine conditions resumed, presumably during the latest Early Jurassic (?Toarcian) with a regional Middle East transgression (Arkell 1956; Enay *et al.* 1987). This aggradational regime of mixed siliciclastic–carbonate sediments, i.e. the Terrigenous system, lasted more or less until the Late Bajocian. Sedimentation then switched to pure carbonate, and shallow-water conditions persisted over the platform edge throughout the Bathonian–Early Callovian interval. Depositional environments were those of a typical carbonate-ramp not facing the (palaeo)ocean but gently dipping westwards to an intrashelf depression. Tectonically induced differential accommodation caused by general basement tilting may have created a topographic high over the platform edge itself. Correlation of the medium-scale sequences suggests that the Bathonian–Early Callovian platform edge may have been subjected to high-frequency, eustatically controlled sea-level fluctuations.

Development of the Jurassic unconformity

There are no Middle–Upper Callovian, Oxfordian or Kimmeridgian sequences preserved on the Jurassic carbonate platform edge in the Oman Mountains. This major stratigraphic hiatus is

associated with a widespread angular unconformity (*c.* 0.1°) that consists of a planar truncation of Middle Jurassic sequences. This surface is sealed by the coastal onlap of the Rayda Formation that developed throughout the Tithonian, showing vertically a gradual transition from a coarse-grained, shallow-water to a fine-grained, pelagic limestone.

The Jurassic unconformity in Jabal Akhdar actually is a composite feature, including the widespread Middle–Upper Jurassic unconformity that has been recognized all over the Arabian peninsula (Murriss 1980). There is no record of the uppermost Callovian–Lower Oxfordian between the Tuwaiq and Hanifa Formations in Saudi Arabia (Enay *et al.* 1987; Hirsch *et al.* 1998). This major hiatus has been recently related to a general sea-level lowstand in association with the formation of high-latitude continental ice sheets (Dromart *et al.* 2003). Whereas marine conditions resumed during the Mid-Oxfordian over most of the Arabian peninsula, subaerial exposure of the Sahtan Group of the Oman Mountains continued throughout the Oxfordian–Kimmeridgian. Necessarily, this relative high elevation would have been tectonically created because the Late Jurassic was a time of high global sea level (Hallam 1988). The general planar topography of the top-truncation surface of the Sahtan Group suggests that erosion mainly involved subaerial dissolution, in association with a gentle uplift of the carbonate platform edge. This view is supported by the fact that the deep-sea temporal equivalent depositional unit (i.e. upper Guweyza) is volumetrically limited, and is composed of a mixture of pelagic sediments and carbonate clasts eroded from the platform. In Jabal Akhdar, the dominance of the clasts that derived from the underlying Triassic Malih Formation indicates that the Jurassic emerged plateau was probably incised by deep canyons. Furthermore, the presence of Permian-sourced clasts within the upper Guweyza suggests that the cumulative incision into the plateau by the successive sea-level falls may have attained 500 m, taking account of the thickness of the platform series (Béchenneq *et al.* 1990).

A possible mechanism for the uplift of the platform edge could be some salt mobilization in the Infracambrian to Cambrian Ara Formation of the Huqf Group, because of the relative proximity of the Fayud salt basin (Murriss 1980). However, Mount *et al.* (1998) suggested that there is no salt lithology beneath the Jabal Akhdar anticline. Moreover, the evidence that the relative elevation of the platform edge lasted throughout the Jurassic is not supportive of any halokinetic movement, which generally operates over much shorter periods of time. A possible mechanism responsible for such a long-term resistance, to gentle exhumation, of the platform edge would better lie in some isostatic re-equilibrium as a result of a former regional thickening of the crust, which is still detectable beneath the Oman Mountains: 42–55 km according to Al-Lazki *et al.* (2002) against a typical value of 30–40 km for Palaeozoic and Mesozoic regions (Tanimoto 1995; Mooney *et al.* 1998). An alternative mechanism is a compressive buckling of the lithosphere. Such a view is supported by the fact that the exhumation described for the Late Jurassic is conspicuous over the entire eastern edge of the Arabian Plate (e.g. Fars Province of Iran, Gollesstaneh 1965).

The interpretation of this regional truncation as a post-rift unconformity as observed in Atlantic-type continental margins, as proposed by Rabu *et al.* (1990), is not favoured here. The Jabal Akhdar block is 70 km, much larger than the traditional tilted block width of about 20 km. This would imply the presence of a décollement level deep into the upper mantle, for which there is no evidence.

Flooding of the platform edge

In the central Oman Mountains, the Jurassic unconformity is sealed by the onlap of the Rayda Formation (Tithonian in age), which shows a deepening-upward sequence. During the Tithonian, the eroded Jurassic strata were transgressed by the Rayda, and the platform edge retreated, and evolved into an ocean-facing, storm-influenced ramp. This physiographic change of the margin has previously been related to downwarping caused by compression offshore (Pratt & Smewing 1993). A similar reset of marine conditions can be documented in the Interior Fars province of Iran (Gollesstaneh 1965). In outermost shelf sections of the High Zagros (e.g. Khaneh Kat and Kuh-e Gadvan sections), fine-grained and thin-bedded limestones, bearing latest Kimmeridgian–Early Tithonian ammonites (i.e. *Lithoceras* and *Torquatisphinctes*), directly overlie Middle Jurassic strata. It should be stressed that the Latest Kimmeridgian–Tithonian was a time of general transgression over the western Tethys carbonate platforms including the Dinarides and the Jura (eastern France) (Strohmenger *et al.* 1991), northern Algeria and Morocco (Atrops & Benest 1984; Cattaneo 1991). This suggests that the flooding of the Arabian Platform edge in the latest Jurassic was dominantly influenced by a long-term eustatic sea-level rise (i.e. second order).

Conclusions

The Middle Jurassic series at the edge of the Arabian Platform in the central Oman Mountains is composed of a mixed siliciclastic–carbonate unit overlain by a carbonate (oolite) complex. These Jurassic sequences were deposited in environmental settings ranging from outer shoals that intermittently underwent subaerial exposure, to a deeper, gently dipping shelf interior. Stratigraphic organization of the Jurassic Sahtan Group across Jabal Akhdar reveals both syndepositional export of sediments and post-depositional erosion of sequences. The Sahtan Group is capped by a planed-off, toplap surface resulting in a very gentle (c. 0.1°) angular unconformity. The Rayda Formation, which overlies the unconformity, represents a typical coastal onlap pattern. The lower Rayda shows shallow-water depositional facies and makes up a typical deepening-upwards sequence. The unconformity is interpreted to have been caused by subaerial carbonate dissolution maintained by a general uplift of the platform edge. The following transgression, which resulted in the deposition of the Rayda Formation, is ascribed to a eustatic sea-level rise.

New biostratigraphic data indicate that the youngest sequences preserved beneath the unconformity in Jabal Akhdar are of Late Bathonian–Early Callovian age, and that the oldest deposits overlying the unconformity are Tithonian in age. This dating has the implication that the uppermost Sahtan Group in the central Oman Mountains is temporally equivalent to the Uwainat and Atash Members, which were deposited in the United Arab Emirates and Saudi Arabia, respectively. It is further speculated that the barrier, represented by the emerged platform edge during the Oxfordian–Kimmeridgian period, favoured the development of restricted environments in the southern Persian Gulf with the deposition of source rocks (Hanifa and Diyab Formations). Finally, the lowermost Rayda of central Oman is here considered to be the outer equivalent of the uppermost Hith Formation of Abu Dhabi.

The combination of biostratigraphic, geometric and petrographic information suggests that most of the bulk of the deep-sea carbonate fan of the Guweyza Formation (i.e. intermediate

unit) was shed from the platform edge while it was submerged (i.e. the Oolite system). Paradoxically, the mass of rocks transferred into the Hamrat Duru Basin was much more limited during the platform edge uplift and the correlative sea-level lowstand. Lithoclasts were eroded from the carbonate platform by fluvial streams that cut deeply down into the subaerial carbonate plateau, most of the surface of which was probably subjected to karstification.

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