Architecture of Oxfordian coral buildups along the Atlantic margin of Morocco

Duval-Arnould, Aude; Bulot, Luc; Charton, Rémi; Jain, Sreepat; Masrour, Moussa; Pomar, Luis; Redfern, Jonathan; Simmons, Mike; Schröder, Stefan

DOI
10.1016/j.jafrearsci.2024.105206

Publication date
2024

Document Version
Final published version

Published in
Journal of African Earth Sciences

Journal of African Earth Sciences 213 (2024) 105206

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Architecture of Oxfordian coral buildups along the Atlantic margin of Morocco

Aude Duval-Arnould [a], Luc Bulot [a], Rémi Charton [b], Sreepat Jain [c], Moussa Masrour [d], Luis Pomar [e], Jonathan Redfern [a], Mike Simmons [f], Stefan Schröder [a,*]

[a] *Basin Studies, Department of Earth and Environmental Sciences, University of Manchester, UK*
[b] *Department of Geoscience and Engineering, Applied Geology Section, TU Delft, Netherlands*
[c] *Department of Applied Geology, Adama Science and Technology University, Adama, Ethiopia*
[d] *Laboratoire de Géologie Appliquée et Géo-Environnement, Université Ibn Zohr, Agadir, Morocco*
[e] *Catedra Guillem Colom, Universitat de les Illes Balears, Palma de Mallorca, Spain*
[f] *Neftex-Halliburton, Abingdon, UK*

A R T I C L E I N F O

Handling Editor: Dr Mohamed Mohamed G Abdelsalam

Keywords:
Oxfordian
Coral buildup
Platy coral
Reef architecture
Subsurface analog

A B S T R A C T

Oxfordian (Upper Jurassic) coral buildups developed widely in Tethys and Atlantic realms, during a time when paleoclimate potentially swung between greenhouse climate and cold snaps. Buildups were constructed by platy and branching corals, sponges and microbialites. Although their initiation is commonly linked to the Upper Jurassic global transgression, a number of global and local factors may have influenced buildup growth and demise (e.g. climate, shelf geometry, detrital input). Extensive outcrops of Oxfordian buildups in Morocco provide an opportunity to investigate the relationship between external drivers and buildup fauna and architecture. Here we show that the interplay of local accommodation changes, rising sea water temperature, and increasing pCO_2 linked to the onset of the Middle Oxfordian global transgression were the main drivers for buildup initiation, which was synchronous across the basin. The demise of the coral buildups in Morocco was linked to a regression, dated no later than Upper Oxfordian, the establishment of partly evaporitic conditions across the basin, and to localized influx of coarse-grained siliciclastics, the latter likely driven by synsedimentary tectonic activity. Serial logged sections, outcrop panoramas and detailed facies analysis show that low-relief deeper-water buildups of *Dimorpharaea* platy corals evolved into higher-relief diversified buildups where shallower-water reworking produced coral rubble and large clinoforms. Buildup diachronicity is apparent, with younger coral bioherms growing in the depressions created between the initial bioherms. Size of buildups ranges from 2 m wide and 0.5 m thick, to 700 m wide and 80 m thick. The outcrops provide constraints on geobody architecture and heterogeneity in the subsurface of Morocco and North America, where facies-controlled dolomitization of high-energy buildup and clinoform facies is a main driver for porosity development.

1. Introduction

The Jurassic was a time of important paleoclimatic fluctuations (Cecca et al., 2005) and paleogeographic changes linked to the breakup of Pangea (Leinfelder et al., 2002), while also recording an important diversification of reef-building organisms following the end-Triassic extinction event (Leinfelder et al., 2002). Due to their specific environmental requirements, reef builders such as corals are excellent proxies for these paleogeographic and paleoclimatic changes. This is particularly the case for the Oxfordian, when coral buildups prospered across the Tethyan and Atlantic domains (Insalaco, 1996; Kiessling and Flügel, 2002, Leinfelder et al., 2002), at a time when paleoclimate potentially varied between greenhouse/high pCO_2 conditions and cold snaps (Dromart et al., 2003a, 2003b; Cecca et al., 2005).

Coral buildups in the Agadir-Essaouira Basin of Morocco's Atlantic margin (EAB; Fig. 1) have so far received less study than their extensively documented counterparts in the Tethyan realm (see overview in Leinfelder et al., 2002). They share similar depositional environments and coral associations with the Tethyan realm (Ourribane et al., 1999; Martin-Garin et al., 2007; Olivier et al., 2012), but have not yet been placed in their wider depositional context to infer intrinsic and extrinsic controls on deposition. Time-equivalent buildups were equally

* Corresponding author.
E-mail address: stefan.schroeder@manchester.ac.uk (S. Schröder).

https://doi.org/10.1016/j.jafrearsci.2024.105206
Received 28 June 2023; Received in revised form 13 February 2024; Accepted 13 February 2024
Available online 14 February 2024

described from the conjugate margin in North America, where they have a significant microbial component (Ellis et al., 1985; Pratt and Jansa, 1989). Furthermore, Oxfordian buildups are proven hydrocarbon reservoirs in the subsurface of Morocco and Nova Scotia (Morabet et al., 1998; Weissenberger et al., 2006). This study aims to determine the intrinsic and extrinsic factors governing Oxfordian coral buildup growth in Morocco. Detailed analysis of buildup facies, geometry and large-scale architecture across the onshore Essaouira-Agadir Basin provides insights into the relative contributions of coral-microbial faunas in buildup construction and constrains the factors controlling buildup growth and demise in the context of Upper Jurassic environmental changes. The extensive outcrop analogs in Morocco also provide important geometric and petrographic constraints on reefal geobodies in the context of subsurface resource exploration.

2. Geological setting

The WSW-ENE trending Atlas mountain chain extends from Tunisia to the Atlantic coast of Morocco. It was formed by Alpine compression of the late Palaeozoic to Lower Jurassic intracontinental Atlas rift (Mattauer et al., 1977; Laville and Piqué, 1992; Frizon de Lamotte et al., 2000, 2009; Piqué et al., 2002; Domènech et al., 2015). The Essaouira-Agadir Basin is located in the onshore and offshore portions of the eastern Atlantic passive margin (Fig. 1; Piqué et al., 1998). It was inverted as part of the Western High Atlas (WHA). The EAB began to form during the Permian as N–S to NNE-SSW trending half grabens (Medina, 1988; Bouatmani et al., 2003). This rift phase was followed by the formation of a sag basin during the Late Triassic (Baudon et al., 2012), and the onset of the passive margin drift phase in the Sinemurian (Hafid, 2000; Sahabi et al., 2004). The Lower Jurassic records the first open-marine carbonate deposition along the margin (Duffaud, 1960; Ambroggi, 1963; Adams et al., 1980; Du Dresnay, 1988), interrupted by terrestrial sedimentation during the Lower Toarcian (Duval-Arnould et al., 2021). The Middle Jurassic Ameskhoud Fm. records continued shallow-marine carbonate deposition in the north of the EAB, but the south is marked by strong siliciclastic influx (Fig. 2; Peybernès et al., 1987; Bouaouda, 2002).

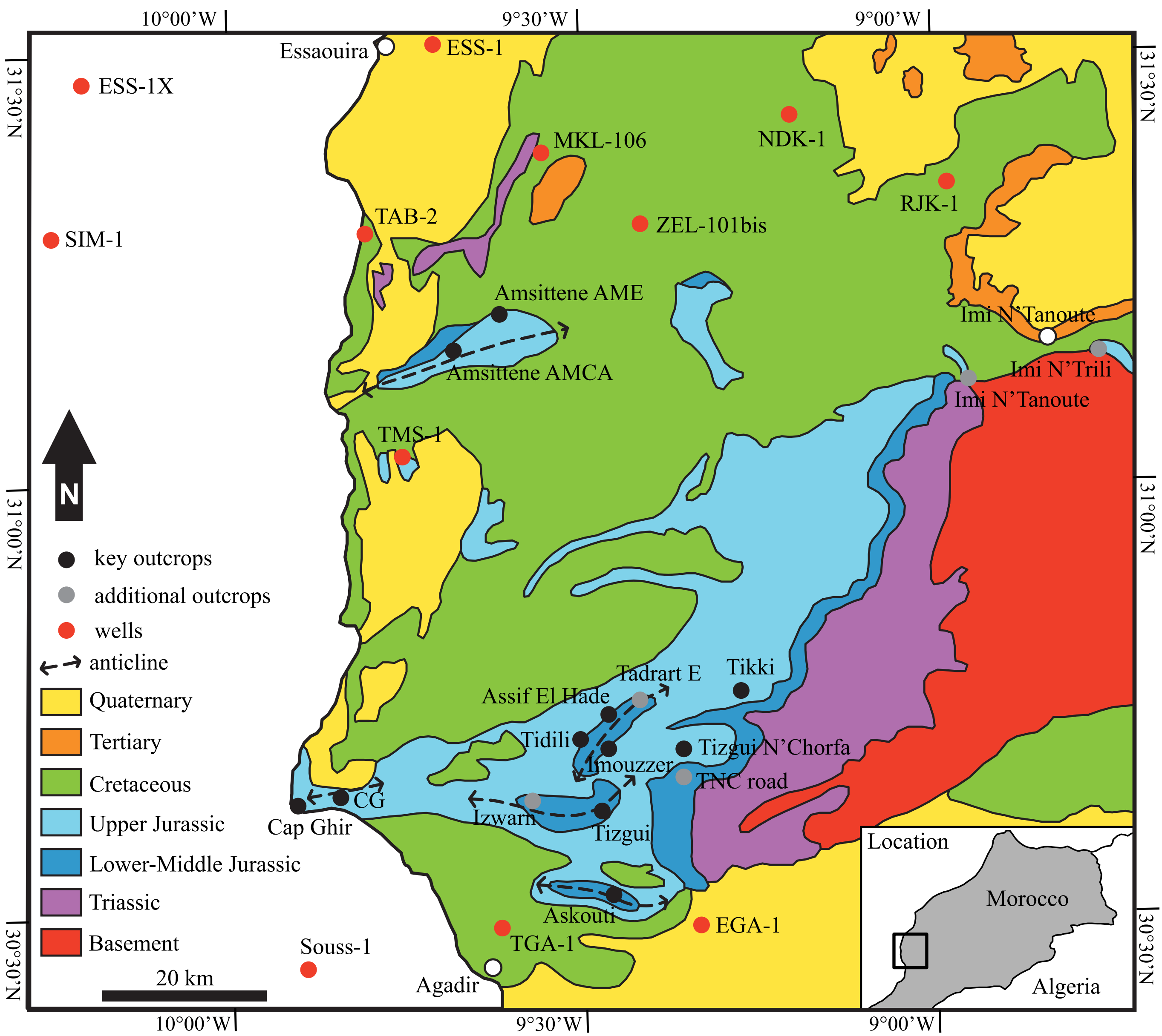

Fig. 1. Geological map of the Essaouira-Agadir Basin with location of the sections logged for the Lalla Oujja Formation. Well locations and additional outcrops used to build the basin-scale facies maps (Fig. 18) are equally shown.

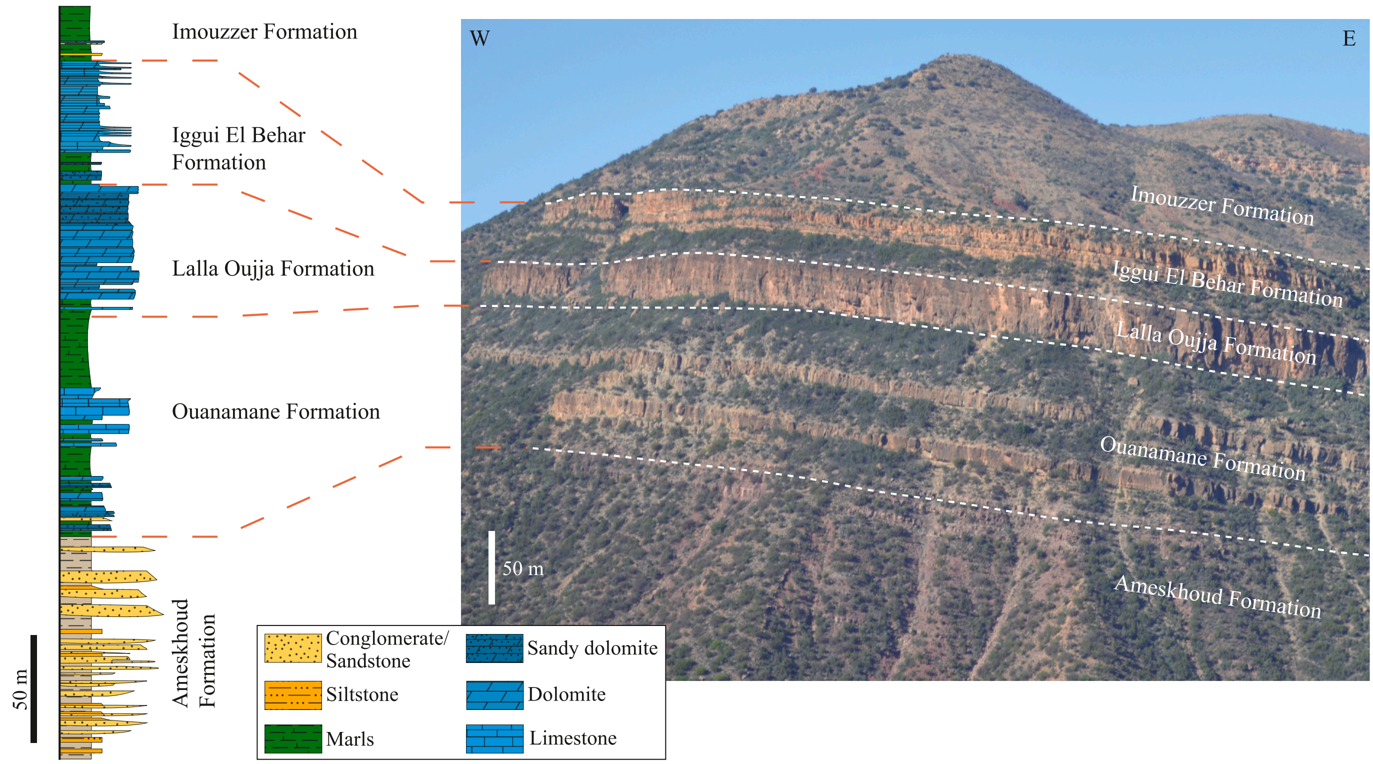

Fig. 2. Stratigraphic overview and simplified section in the proximal part of the basin. Tizgui N'Chorfa location.

The focus of this study is the Upper Jurassic carbonate succession of the EAB (see Fig. 2 for a lithostratigraphic summary). The oldest of these carbonate formations is the Ouanamane Fm., a transgressive unit dominated by oolitic and brachiopod-rich limestones, and by increasing marl deposition upward in the succession. It was comprehensively studied by Duval-Arnould et al. (2024) who demonstrated that it is mostly Callovian in age, with a hiatus in the upper part omitting Early Oxfordian strata. In terms of foraminifera, Duval-Arnould et al. (2024) only found long-ranging taxa such as *Nautiloculina*, *Coscinoconus*, *Lenticulina* and *Ophthalmidium*. This can be compared to the more diverse fauna recorded by Bouaouda (2002) and Bouaouda et al. (2004), and reviewed by Duval-Arnould et al. (2024).

The peak transgression in the Middle Oxfordian is marked by a transition to bioherms of the Lalla Oujja Fm. (Fig. 2; Ambroggi, 1963; Adams, 1979, 1980; Bouaouda, 2002; Duval-Arnould et al., 2024), and was followed by shallow-water to terrestrial carbonates (Oxfordian--Kimmeridgian Iggui El Behar and Imouzzer formations, Fig. 2). The evidence for an age no older than Middle Oxfordian for the base of the Lalla Oujja Fm. was reviewed by Duval-Arnould et al. (2024) and included the presence of the ammonite species *Euaspidoceras* and *Dichotomosphinctes*. Foraminifera, such as Alveosepta jaccardi, reported by , support this age assignment, but have not been found in the material studied here, although may occur in the overlying Iggui El Behar Fm.

The Iggui El Behar Fm. was assigned a Late Oxfordian - Early Kimmeridgian age by Adams et al. (1980), and Duval-Arnould et al. (2024). A rich, although typically poorly preserved foraminiferal fauna was identified in some samples from this formation. This includes specimens that may be *Alveosepta* sp., or *Pseudocyclammina* sp., including forms that are probably *Pseudocyclammina lituus* and possibly *Pseudocyclammina sphaeriodalis*. Also present is *Mohlerina basiliensis*. These support the age assignment since *P. lituus* is thought to be no older than Late Oxfordian , and the oldest *Alveosepta* is Middle Oxfordian (e.g. Mahboubi et al. (2023)). *P. sphaeroidalis* was originally described as a Kimmeridgian species (Hottinger, 1967; Schlagintweit et al., 2005). Species of *Everticyclammina*, *Rectocyclammina*, *Kurnubia* and other large benthic foraminifera recorded by Bouaouda et al. (2004) have not been found in this study.

All Upper Jurassic strata in the EAB show broad facies belts trending N–S and gradually deepen from the paleoshoreline in the east to the Atlantic Ocean in the west (Ambroggi, 1963; Adams, 1979, 1980). They reflect deposition on a westward dipping ramp system (Burchette and Wright, 1992; Olivier et al., 2012).

The Jurassic succession in the onshore EAB is exposed along multiple NE-SW and E-W trending plunging anticlines (Fig. 1). Some of these structures are cored by Triassic salt diapirs (Tidsi and Jbel Hadid diapirs in the Essaouira sub-basin, Cap Ghir anticline in the Agadir sub-basin), and they can be traced offshore using seismic. There is increasing evidence for syn-Jurassic growth of some anticlines, partly salt-driven and comparable to syn-depositional salt diapirism in the Central High Atlas (Michard et al., 2011; Saura et al., 2014; Fernández-Blanco et al., 2020; Charton et al., 2021). However, most of the structures in the WHA do not show evidence for salt movements and seem to have rather formed during the Tertiary Atlasic orogeny.

3. Material and methods

The data presented in this study come from 11 georeferenced outcrop sections logged at scales between 1:100 and 1:200 across the EAB (Fig. 1). Six serial sections at the Tidili locality (Fig. 1) were walked out and correlated to examine local facies variations and buildup geometries. In addition, facies variations were mapped along a Plio-Pleistocene terrace, which cuts into the buildups at Cap Ghir (Fig. 1) and allowed observation of the lateral and vertical changes in sedimentation. The main surfaces and geometries were examined and illustrated using photomosaics. The outcrop-scale observations were linked to sample descriptions and petrographic analyses conducted on 380 hand samples and 55 thin sections with alizarin red S stain and blue-dyed epoxy. Facies were described and classified based on bed geometries, lithology, sedimentary structures, bioturbation, skeletal and non-skeletal grains, grain size, sorting and cement (Table 1). These can be grouped into

Table 1
Facies descriptions for the Lalla Oujja and Iggui El Behar formations.

Facies	Main components	Matrix, mineralogy and diagenesis	Sedimentary features and bioturbation
Facies 1 Wacke/Packstone	Peloids 25–40%; Shell fragments (bivalves)10–30%; Crinoids 0–30%; Brachiopods 10–25%; Bivalves 5–25%; Echinoderms 5–15%, as complete crinoid stalks and isolated columnals; Silt 5–7%; Foraminifera 2–5%; Gastropods 0–3%; Platy corals 0–2%	Micrite and euhedral dolomite crystals	Thinly bedded, 0.5–1.5 m thick
Facies 2 Sponge Boundstone	Sponges 20–30%; Thrombolites 10–30%; Shell fragments 5–10%; Brachiopods 2–10%; Echinoderms 0–5%; Silt 3–5%	Micrite	Beds 0.5–2 m thick
Facies 3 Mud Boundstone	Platy coral 10–40%; Sponges 0–10%; Thrombolites 0–20%; Coral fragments 0–8%; Echinoderm fragments (spicules dominating) 2–5%; Calcispheres 1–2%; Brachiopod fragments 1–2%; Bryozoa <1%; Very small shell fragments <1%; Foraminifera <1%	Micrite; extensively dolomitized: euhedral and saddle dolomite with coral ghosts, vugs up to 5 cm, intercrystalline porosity, fractured	Beds 0.3–2 m thick Locally sponges or thrombolites encrusting platy corals
Facies 4 Mud/Wackestone	Echinoderms 5–10%; Brachiopods 5–8%; Peloids 5–10%; Bivalves 0–5%; Undetermined bioclasts 0–2%	Micrite	Beds 0.1–0.8 m thick
Facies 5 Diverse coral Boundstone	Corals (platy, branching, phaceloid, plocoid/massive) 40–60%; Gastropods 5–10%	Blocky calcite; extensively dolomitized: euhedral and saddle dolomite with coral ghosts, vugs up to 5 cm, intercrystalline porosity, fractured	Massive units up to several m thick
Facies 6 Coral-rich Floatstone	Coral fragments (platy, branching, phaceloid, massive/plocoid) 40–70%; Echinoderm fragments 10–30%; Gastropods 10–20%; Shell fragments 2–15%; Sponge fragments 0–5%; Dacycladacean algae <1%; Foraminifera <1%	Blocky calcite	Beds 0.4–2 m thick
Facies 7 Coral-rich Grainstone	Coral fragments 40–60%; Undifferentiated micritized grains 20–30%; Echinoderm fragments 10–20%; Gastropod fragments 0–5%; Authigenic quartz 0–2%; Dacycladacean algae <1%; Foraminifera 0–5%	Blocky calcite	0.1–1 m thick lenticular and tabular beds
Facies 8 Platy coral Floatstone	Platy-coral fragments 10–30%; Branching and phaceloid coral fragments 0–8%; Shell fragments 5–12%; Brachiopods 0–5%; Gastropods 0–5%	Micrite	0.1–5m thick massive units
Facies 9 Bioclastic Wacke/Packstone	Coral fragments 5–15%; Shell fragments 5–10%; Peloids 5–15%; Brachiopods 0–5%; Gastropods 0–5%	Micrite	0.2–0.5 m thick beds
Facies 10 Peloidal Packstone	Peloids 40–70%; Sponges 7–15%; Coral fragments 5–8%; Shell fragments 5–10%; Green algae 3–10%; Foraminifera 2–10%; Echinoderms 5–8%; Authigenic quartz 5–7%; Oncoids 0–10%; Intraclasts 0–5%	Micrite and microspar	0.2–0.7 m thick beds
Facies 11 Coral and *Nerinea* Float/Rudstone	Coral fragments 10–40%; Large shell fragments (bivalves, gastropods) 20–50%; In-situ branching, phaceloid corals 0–20%; Small shell fragments 20–60%	Not determined	Horizontal bedding, alternation of beds with different bioclast sizes
Facies 12 *Megalodont* Rudstone	*Megalodont* bivalves 40%; Peloids 30–45%; Foraminifera 8–10%; Small massive and branching, phaceloid coral colonies 5–10%; Gastropods 5–10%; Coral fragments 5–12%; Oncoids 2%	Micrite; peloidal packstone (to grainstone) matrix	0.8–1 m thick beds Massive
Facies 13 *Nerinea* - branching coral Float/Rudstone	Branching coral 5–15%; Branching, phaceloid coral fragments 10–35%; Peloids 25–40%; *Nerinea* 10–30%; Shell fragments 25–30%; Chaetetids 5–8%; Bivalves 2–10%; Brachiopods 5–8%; Echinoderms 2–5%; Sponge fragments 0–3%	Micrite, peloidal packstone matrix	Massive Beds 2–4 m thick
Facies 14 Coral and shell Pack/Grainstone with Floatstone to Rudstone horizons	Coral fragments 10–60%; Large shell fragments (bivalves, gastropods) 10–40%; Small shell fragments 20–60%; Peloids 10–20%; Echinoderm 5–10%; Foraminifera 2–5%; Sponge fragments 0–7%	Float- and rudstone matrix consists of grainstone and packstone	Horizontal bedding, planar and trough cross-bedding, local swaley cross-bedding Alternation of beds with different clast sizes *Skolithos, Conichnus* Beds 0.5–2 m thick
Facies 15 Bioclastic sandstone	Medium to coarse quartz grains 40–60% (coated and non-coated); Gastropds 0–40%; Coral fragments 5–30%; Shell fragments 5–20%; Isolated small massive corals 2%	Calcite cement; Locally only quartz grains and euhedral dolomite crystals	Swaley cross-bedding, horizontal bedding, through cross-bedding
Facies 16 Peloidal Wacke/Packstone	Peloids 10–30%; Intraclasts (200–1500 μm diameter) 5–20%; Foraminifera, benthic (3–4%) and planktonic (0–1%); Ooids 0–7%; Gastropods 0–3%; Large oncoids (1000–1500 μm diameter) 3%; Shell fragments 0–10%; Dacyclads 0–2%; Echinoderms 0–2%; Coral fragments 0–1%; Authigenic quartz 0–5%; Ostracods <1%	Micrite and cement (drusy and blocky)	Massive Beds 0.2–0.8 m thick
Facies 17 Mudstone	Ostracods (0–5%); Echinoderm fragments <1%; Shell fragments <1% (50 μm diameter)	Micrite	Massive Beds 0.4–1 m thick Stromatolite horizons with peloids (0–30%)
Facies 18 Foraminifera Wacke/Packstone	Foraminifera 6–20%; Intraclasts 5–10%; Shell fragments 0–2%	Micrite	Massive Beds 0.2–1 m thick
Facies 19 Rip-up clast horizon	Rip-up clasts 10–70%; Foraminifera 0–15%; Shell fragments 0–5%; Echinoderms 0–1%	Micrite	Horizontal and wavy bedding Beds 0.5–1.5 m thick

(*continued on next page*)

Table 1 (*continued*)

Facies	Main components	Matrix, mineralogy and diagenesis	Sedimentary features and bioturbation
Facies 20 Oncoidal Float/Rudstone	Oncoids 30–70%; Foraminifera 0–5%	Micrite	Massive Beds 0.4–1.5 m thick
Facies 21 Gypsum Mudstone	Gypsum crystal molds and pseudomorphosed by microspar 5–15%; Ostracods 0–2%; Shell fragments <1%	Micrite	Massive Beds 0.1–0.5 m thick Stromatolite horizons with peloids (0–30%)
Facies 22 Charophyte Wackestone	Charophytes; Ostracods	Micrite	Thinly bedded

seven facies associations and a single facies corresponding to distinct depositional environments. The coral associations have been described and identified by comparison with previous published work on Upper Jurassic coral buildups in Morocco (Table 2; Martin-Garin et al., 2007; Olivier et al., 2012). In addition, 12 wells and 5 outcrops were included in a wider basin-scale assessment of facies distribution (Fig. 1). Well reports derive from the North Africa Research Group database for Morocco and were consulted for lithological and biostratigraphic information.

4. Depositional environments

4.1. Outer ramp (facies association 1 with facies 1, 2)

4.1.1. Characteristic features

This facies association lies with a sharp conformable contact on marls of the Ouanamane Fm. and is dominated by bioclastic wackestones to packstones (Facies 1) and sponge boundstones (Facies 2). The wackestones and packstones contain angular and poorly sorted bioclasts, including some complete bivalves and echinoderms (as isolated crinoid columnals; Fig. 3A), small coral fragments and rare ammonites (Fig. 3B). A fraction of silt-sized quartz is always present (Fig. 3C) and *Thalassinoides* burrows are common. The wackestones and packstones are locally slightly marly (Fig. 3D). In the sponge boundstones (Fig. 3E), the matrix consists of lime mud with small bioclasts. Thrombolites and brachiopod shells are also common.

4.1.2. Depositional environment

Mud-supported textures with micrite matrix in the wackestones to packstones indicate a low-energy environment. Bioclast preservation, as angular shell fragments and echinoderm plates associated with complete brachiopods and bivalves, indicates low levels of reworking. Crinoids are suspension feeders and thus adapted to low-energy environments (Meyer and Macurda, 1977; Roux et al., 1988). The presence of ammonites overall indicates open-marine conditions. Calcareous sponges were common deeper-water bioherm builders during the Jurassic (Crevello and Harris, 1984; Insalaco, 1996). This association of textures and fauna indicates a relatively deep-water environment, not significantly affected by currents and waves, and interpreted as an outer ramp setting.

4.2. Microsolenid buildups (facies association 2 with facies 3, 4)

4.2.1. Characteristic features

This facies association is dominated by platy *Dimorpharaea* corals in a carbonate mudstone matrix (Facies 3; Fig. 4A and B), and locally passing laterally to mudstones and wackestones with echinoderms, brachiopods and peloids (Facies 4; Table 1). Coral diversity is low (Table 2). Locally, the corals are encrusted by microbialites or sponges (Fig. 4A, C, D).

4.2.2. Depositional environment

The scarcity of bioclasts in this facies association and the dominance of lime mud indicate a low-energy environment below fair-weather wave base. Insalaco (1996) established that *Dimorpharaea* microsolenids are generally subordinate to other corals if light levels are elevated. A growth window for microsolenid buildups is situated within the lower euphotic zone, below the highly diverse shallow-water coral communities (Insalaco, 1996). High water turbidity, resulting in suspension of lime mud in the water column, could also have reduced light penetration, thus favoring *Dimorpharaea* growth over other corals (Hallock and Schlager, 1986; Insalaco, 1996). *Dimorpharaea* colonies present a phenotypic plasticity and can modulate their morphology in response to their environment. Modern counterparts develop a platy shape between c. 30–70 m water depth (Lathuilière et al., 2005). Encrustation by microbialites suggests a relatively low sedimentation rate, which allowed microbial growth on the coral framework (Olivier et al., 2012). Observations are consistent with outer to middle ramp environments.

4.3. Higher diversity buildups (facies association 3 with facies 5 to 7)

4.3.1. Characteristic features

This facies association contains a diverse coral assemblage that has been described in detail previously in the Cap Ghir (Martin-Garin et al., 2007) and Izwarn (Olivier et al., 2012) localities (Table 2). It is composed of coral boundstones (Facies 5), locally at Cap Ghir associated with coral-rich floatstones (Facies 6) and grainstones (Facies 7), and extensively replaced by dolomite. Coral genera are dominated by phaceloid (e.g. *Cladophyllia*, *Stylosmilia*), more massive plocoid (e.g. *Isastrea*, *Stylina*) and solitary forms (Fig. 4E and F; Table 2). Coral genera diversity and abundance differs from one location to another (Martin-Garin et al., 2007; Olivier et al., 2012).

Facies 6 and 7 were observed in Cap Ghir only, at the top of the main reef unit (cf section 5.1). The coral-rich grainstones (Facies 7) contain up to 60% of well-sorted and rounded coral material (Fig. 5A), which is organized in lenticular beds up to 10 m wide and 50 cm thick. The coral-rich floatstones (Facies 6) are composed of coral debris associated with common gastropods and echinoderms (Fig. 5B) and occur on the flanks of the main buildup. The groundmass of Facies 6 is made of coral-rich grainstone (Facies 7). The buildups are generally very dolomitized, and locally can only be identified by the differential dolomitization between corals and matrix. The coral skeletons tend to be replaced by white anhedral and saddle dolomite, whereas the matrix is grey or pink with smaller dolomite crystals (Al-Sinawi, 2022). These highly dolomitized facies contain large vugs (>5 cm) as well as visible intra- and intercrystalline porosity.

4.3.2. Depositional environment

The diverse coral assemblage always lies directly on top of microsolenid buildups and displays an upward increase in phaceloid and massive-plocoid coral colonies. The higher percentage of bioclastic material relative to microsolenid buildups reflects relatively higher-energy settings. The diverse and large colonies, and the decrease in the relative amount of microsolenids, suggest efficient coral growth where light was not a limiting factor. The growth of these diverse colonies implies higher water energy, higher sedimentation rate and

Table 2
Coral genera identified in previous studies of Oxfordian buildups in the EAB.

Depositional environment	Ecological stage (Olivier et al., 2012)	Cap Ghir (Martin-Garin et al., 2007)	Izwarn (Olivier et al., 2012)	This study
Back reef	Back reef	*Stylina, Psammogyra, Thamnasteria, Calamophylliopsis, Aplosmilia, Cryptocoenia, Actinastrea, Cladophyllia, Dendrararea, Ironella, Cyathophora, Donacosmilia, Fungiastrea, Isastrea, Microsolena, Thecosmilia, Actinaraea, Comoseris, Complexastrea, Meandraraea, Montlivaltia, Myriophyllia, Rhipidogyra, Stylosmilia*	*Actinaraea, Cladophyllia, Stylosmilia, Calamophylliopsis, Dimorpharaea, Enallhelia, Stylina*	Higher-diversity buildups
Fore reef slope (above fair-weather wave base)	Diversification stage	*Microsolena, Etallonasteria, Isastrea, Thamnasteria, Calamophylliopsis, Haplarea, Montlivaltia, Myriophyllia, Psammogyra, Cladophyllia, Stylina, Thecosmilia*	*Thecosmilia, Dimorpharaea, Actinaraea, Calamophylliopsis, Stylosmilia, Fungiastraea, Dermoseris, Microsolena, Stylina, Cladophyllia, Comoseris, Cryptocoenia, Isastrea, Rhipidogyra, Thamnasteria*	
Fore reef slope (above storm wave base)	Diversification stage		*Dimorpharaea, Enallhelia, Stylosmilia, Calamophylliopsis, Dermoseris, Cryptocoenia, Epistreptophyllum, Microsolena, Montlivaltia, Isastrea*	
Fore reef slope (below storm wave base)	Colonization stage	*Dimorpharaea, Thecosmilia, Goniocora*	*Dimorpharaea, Enallhelia, Thecosmilia, Cryptocoenia, Stylosmilia*	Microsolenid buildups

increased light penetration relative to the conditions favoring microsolenids (Insalaco, 1996; Insalaco et al., 1997; Lathuilière et al., 2005; Olivier et al., 2012).

The lenticular coral-rich grainstones (Facies 7) indicate that currents repeatedly reworked the buildup. They could represent coral debris-filled shallow channels that developed on top of the buildup. The floatstones (Facies 6) also contain other species living on the buildup (gastropods and echinoderms). These are interpreted as debris sheets, resulting from storm erosion of part of the buildup (Insalaco et al., 1997). This facies association formed around and above fair weather wave base and characterizes the middle to inner ramp transition (Lathuilière et al., 2005; Olivier et al., 2012).

4.4. Coral buildup rubble (facies association 4 with facies 8 to 10)

4.4.1. Characteristic features

This facies association is composed of coral-rich floatstone (Facies 8), bioclastic wackestones (Facies 9), and peloidal packstones (Facies 10), with variable dolomitization of individual beds. Platy corals and solitary corals form the main types of coral fragments in Facies 8 (Fig. 5C and D). The groundmass to these platy-coral floatstones is a wackestone, locally packstone (Facies 9, 10), comprising smaller well-rounded fragments of coral, echinoderm, bivalves, brachiopods, as well as peloids. Large vugs and calcite-cemented fractures are present as well as some intra- and intercrystalline porosity. In the locality of Tidili, these facies are vertically and laterally interbedded within clinoforms prograding off a

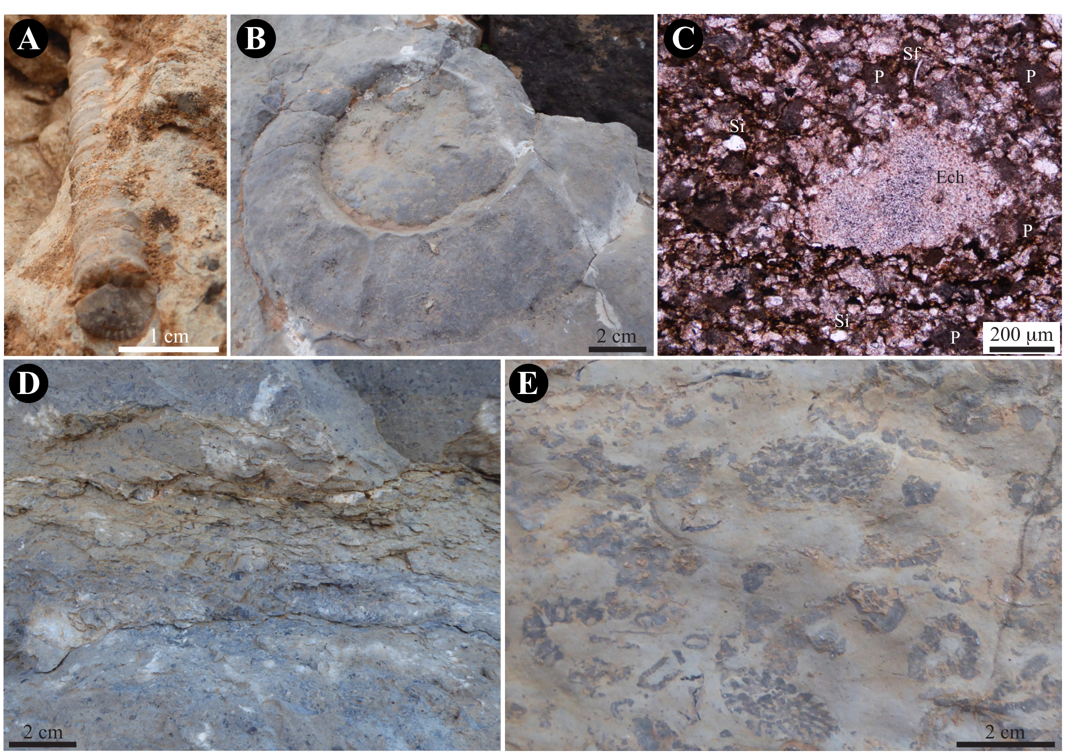

Fig. 3. Outer ramp facies from Tidili location. (A) Crinoid stalk. (B) Ammonite. (C) Peloidal and bioclastic packstone, partially dolomitized, with silt (Si), peloids (P), shell fragments (Sf), and echinoderm plate (Ech). (D) Facies 1, marly bioclastic horizon. (E) Facies 2, sponge boundstone.

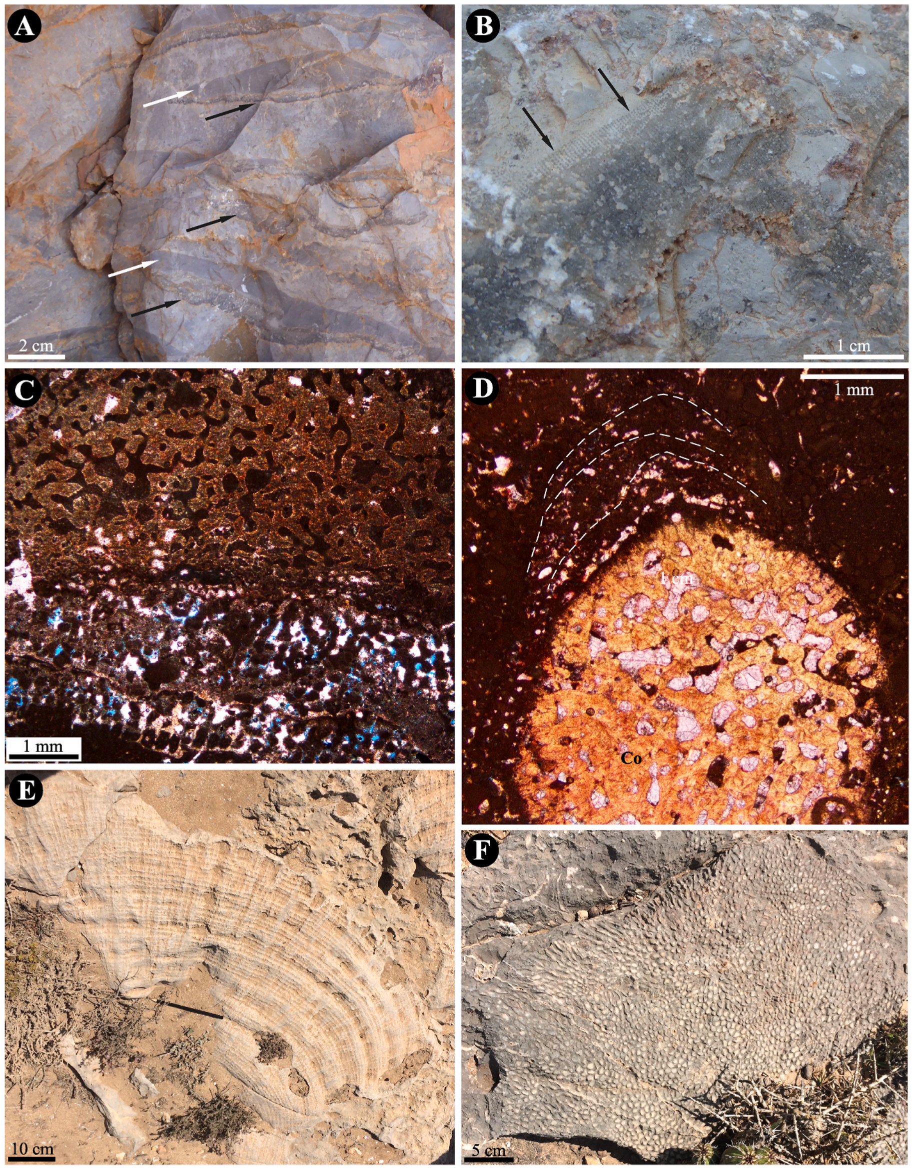

Fig. 4. Macro- and microfacies of the Lalla Oujja Formation coral buildups. (A) Facies 3, *Dimorpharaea* (black arrow) encrusted by microbialites (white arrow). Imouzzer location. (B) Close-up view of a *Dimorpharaea* coral with septae (black arrows). Tidili location. (C) Thin section view of *Dimorpharaea* (bottom) encrusted by a sponge (top). (D) Coral (Co) encrusted by microbial (spongiostromate?) crusts. White lines highlight possible growth lines of crust. Cap Ghir location. (E) Large *Psammogyra* coral head with a total diameter of 180 cm. Facies 5, Cap Ghir location. (F) Phaceloid branching coral colony. Facies 5, Cap Ghir location.

microsolenid buildup. Floatstones are more common towards the topsets of the clinoforms. Towards the bottomsets they grade to packstones and wackestones.

4.4.2. Depositional environment

The large amount of coral fragments in this facies association indicates its proximity to the coral factory. The roundness of the bioclasts suggests significant reworking; however, sedimentation occurred in a lower-energy environment where micrite could accumulate. The identification of clinoform geobodies with down-slope gradation from floatstones to wackestones indicates transport directly from the top of individual buildups and a down-slope decrease in energy levels. The high amount of mud in the system suggests that reworking by currents was not very frequent. This environment was located below fair-weather wave base, in a middle to outer ramp setting (Burchette and Wright, 1992).

4.5. Middle ramp (facies 11)

4.5.1. Characteristic features

In the eastern part of the basin, the bioherms are replaced by coral fragment and *Nerinea* floatstones and rudstones, containing isolated branching coral colonies (Facies 11; Fig. 6A). This facies is organized in horizontal beds, separated by highly bioturbated surfaces as indicated by *Thalassinoides* burrows (Fig. 6A and B). Some horizons show strata-bound dolomitization (Fig. 6B). The amount of bioclastic material varies laterally and vertically, and bioclasts are generally horizontally aligned (Fig. 6C). The *Nerinea* are mainly complete. In some horizons colonies of phaceloid and branching corals are also found in situ, and some rare colonies of massive corals can be observed.

4.5.2. Depositional environment

This environment is marked by alternation of higher and lower energy conditions. The horizontal alignment of the bioclasts in the rudstones beds indicates currents, while the horizons with delicate

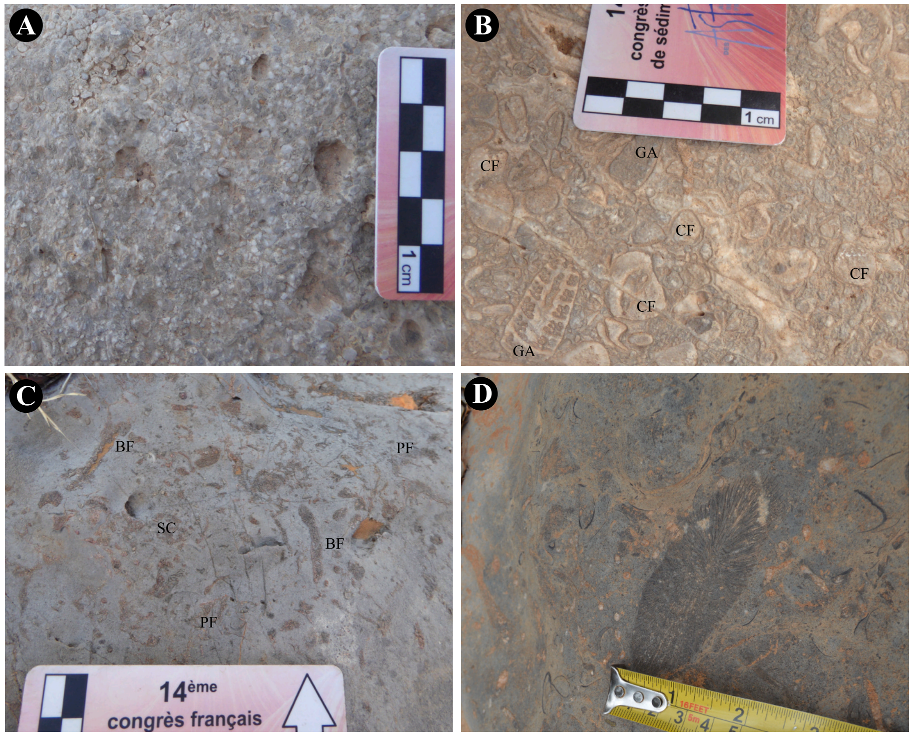

Fig. 5. Facies associated with higher-diversity buildups. (A) Facies 7, coral-rich grainstone. Cap Ghir location. (B) Facies 6, coral-rich floatstone with *Nerinea* (GA) and coral fragments (CF). Cap Ghir location. (C) Facies 8, platy coral-rich floatstone with branching coral (BF), solitary coral (SC) and platy-coral (PF). Tidili location. (D) Facies 8, coral-rich floatstone with shell fragments and large coral (possible *Thecosmilia*). Tidili location.

branching corals and intense bioturbation by *Thalassinoides* indicate lower energy conditions. These deposits record periods of turbulence, interpreted as periodic storm reworking, alternating with quieter periods, characteristic of middle ramp settings (Christ et al., 2012).

4.6. Inner ramp (facies association 5 with facies 12, 13)

4.6.1. Characteristic features

Facies 12 and 13 contain micrite with abundant peloids, shell fragments (bivalves and brachiopods) and foraminifera (Fig. 7A). In the western part of the basin (locality of Cap Ghir), Facies 12 rudstones contain large *Megalodont* shells, as well as *Nerinea* and isolated phaceloid, branching and massive coral colonies (Fig. 7B–E). In the eastern part of the basin (Imouzzer locality), Facies 13 rudstones and floatstones are dominated by smaller coral colonies and tabular chaetetids, *Nerinea*, gastropods and bivalves (Fig. 7C and D).

4.6.2. Depositional environment

The peloidal packstones with large amounts of *Nerinea* gastropods indicate good oxygenation and high nutrient levels in both facies, associated to a relatively moderate-energy environment (Sohl and Kollmann, 1985; Chrząstek and Wypych, 2018). The presence of similar coral morphologies in both facies indicates equivalent environmental conditions. Tabular chaetetid colonies in Facies 13 suggest shallow subtidal conditions (West and Kershaw, 2012). Megalodonts are usually associated with shallow, peritidal waters (Todaro et al., 2012; Yümün et al., 2013). These two facies thus formed in similar environments in an inner ramp setting.

4.7. High-energy inner ramp (facies association 6 with facies 14, 15)

4.7.1. Characteristic features

These deposits are dominated by bioclastic pack- and grainstones and floatstones to rudstones (Facies 14) across the basin, with a significant component of bioclastic sandstones (Facies 15) in the north and east of the basin. The siliciclastic horizons contain up to 60% of medium- to coarse-grained quartz, partially coated by micrite, and few quartzite granules (Fig. 8A). Some of these horizons have been dolomitized and present intercrystalline porosity. The sedimentary features in these beds are horizontal bedding, trough cross-bedding (Fig. 8B), and local swaley cross-bedding. Rare in-situ small colonies of massive corals are also present (Fig. 8C). The more fossiliferous horizons are grainstones rich in gastropods, coral fragments, rounded shell fragments and peloids (Facies 14). These units locally present floatstone to rudstone horizons with larger bioclastic material (mainly gastropods and coral fragments; Fig. 8D). Trace fossils include *Skolithos* and possible *Conichnus* (Fig. 8E). At the top of this facies association, gastropod floatstones or rudstones (Fig. 8F) are common.

4.7.2. Depositional environment

The dominance of grainstones and floatstones to rudstones in Facies 14, well rounded elements, and absence of carbonate mud, all indicate reworking in high-energy settings. Echinoderm fragments suggest open marine conditions. Suspension feeding organisms formed *Skolithos* and *Conichnus* trace fossils in a high-energy shoreface environment subject to unstable substrate conditions (*Skolithos* ichnofacies; MacEachern et al., 2006; Gérard and Bromley, 2008). This facies association represents high-energy deposits with local influx of siliciclastics, possibly carbonate shoals. Although deposited by persistent traction and oscillatory currents above fair-weather wave base in the inner ramp, localized storm influence is documented by swaley cross-bedding (Dumas and Arnott, 2006).

4.8. Restricted inner ramp (Iggui El Behar Fm.; facies association 7 with facies 16 to 22)

4.8.1. Characteristic features

The Iggui El Behar Fm. consists of a thinly bedded alternation of six facies. Mudstones (Facies 17), foraminifera-rich wackestones (Facies 18), peloidal packstones (Facies 16), and oncoidal floatstones to

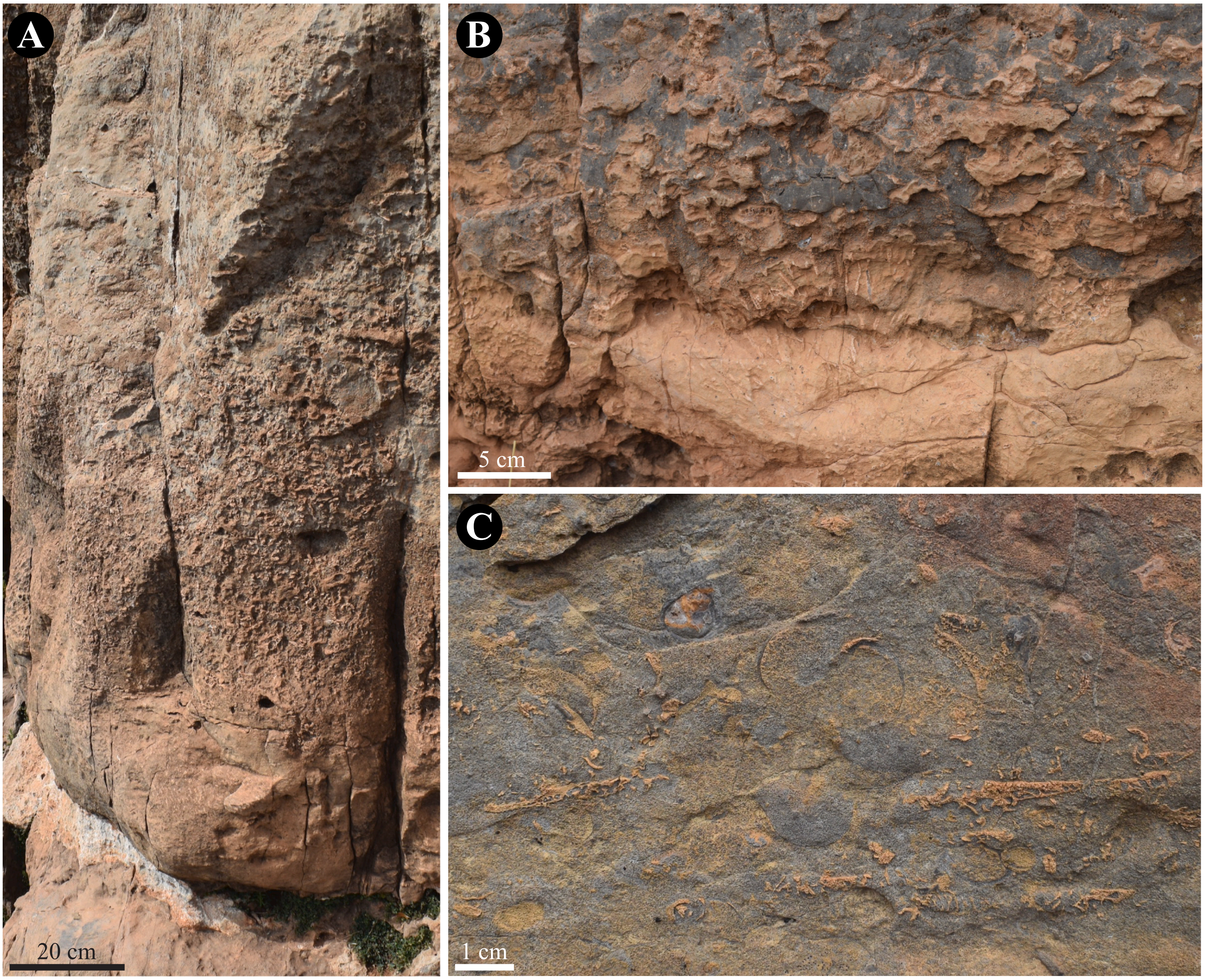

Fig. 6. Middle ramp facies (Facies 11). Tizgui N'Chorfa location. (A) Overview of one bed: base dolomitized with branching corals, followed by bioclastic material, upper part bioturbated by *Thalassinoides*. (B) Dolomitized branching coral at base, followed by intense *Thalassinoides* bioturbation. (C) Gastropod floatstone with horizontally oriented gastropods.

rudstones (Facies 20) dominate in the lower part. Upwards in the formation they progressively pass to a cyclic alternation of rip-up clast horizons (Facies 19), foraminifera-rich wackestones (Facies 18), mudstones (Facies 17), and gypsum mudstones (Facies 21).

Larger (<4 cm) porostromate oncoids dominate Facies 20 in the lower part of the formation, whereas oncoids are smaller (0.2–1 cm) in the upper part of the formation (Fig. 9A). Foraminifera-rich (poorly preserved foraminifera, but including forms that could be assigned to *Pseudocyclammina* and *Alveosepta*; Fig. 9B–D) and peloidal wackestones to packstones are associated with a low-diversity fauna of scarce shell fragments, gastropods and ostracods, dasycladacea and ooids (Facies 16, 18). Horizontal burrows are common and belong to trace fossils *Thalassinoides*, *Rhizocorallium* (Fig. 9E) and *Cylindrichnus* (Fig. 9F).

Meter-scale cycles characterize the upper Iggui El Behar Fm. Above a microkarst (Fig. 9G), cycles start with rip-up clast "conglomerate" graded beds (Facies 19; Fig. 9F), followed by foraminifera-rich wackestones and/or mudstones (Facies 17, 18). The mudstones contain mud cracks, or are topped by highly bioturbated horizons. Towards the top of the formation stromatolitic horizons and mudstones with gypsum molds and pseudomorphs appear (Fig. 9H; Facies 21). In the eastern part of the basin, mudstones and marls with ostracods and charophyte gyrogonites (Fig. 9I; Facies 22) of the Iggui El Behar Fm. rest directly on the Lalla Oujja Fm. carbonates.

4.8.2. Depositional environment

The presence of corals, dasycladacea and benthic foraminifera in the lower part of the formation indicates a shallow-marine setting. This environment was of low energy and partly restricted as suggested by the lower-diversity fauna in packstones, the large oncoids (Gradziński et al., 2004), and *Rhizocorallium* and *Cylindrichnus* trace fossils in a muddy matrix (Gérard and Bromley, 2008). Although species-level foraminifera identification in the studied material remains ambiguous, the presence of *Pseudocyclammina*/*Alveosepta* (Fig. 9B–D) supports an Upper Oxfordian shallow-marine inner ramp setting.

Each cycle in the upper part of the formation shows an evolution from shallow (*Pseudocyclammina* foraminifera) via restricted and saline (stromatolites, gypsiferous mud) to emergent (microkarsts, mud cracks) conditions. Rip-up clast horizons at the cycle base consistently overlie microkarsts, gypsum-rich muds, mudcracks or very bioturbated horizons, and rework the material of the underlying cycle. Originally interpreted as subtidal storm deposits by Ager (1974), they are here re-interpreted as reworked exposed supra/intertidal crusts (Matter, 1967; Kwon et al., 2002). Collectively, these are features of saline mud flats (Demicco and Hardie, 1994), and the cycles are interpreted as

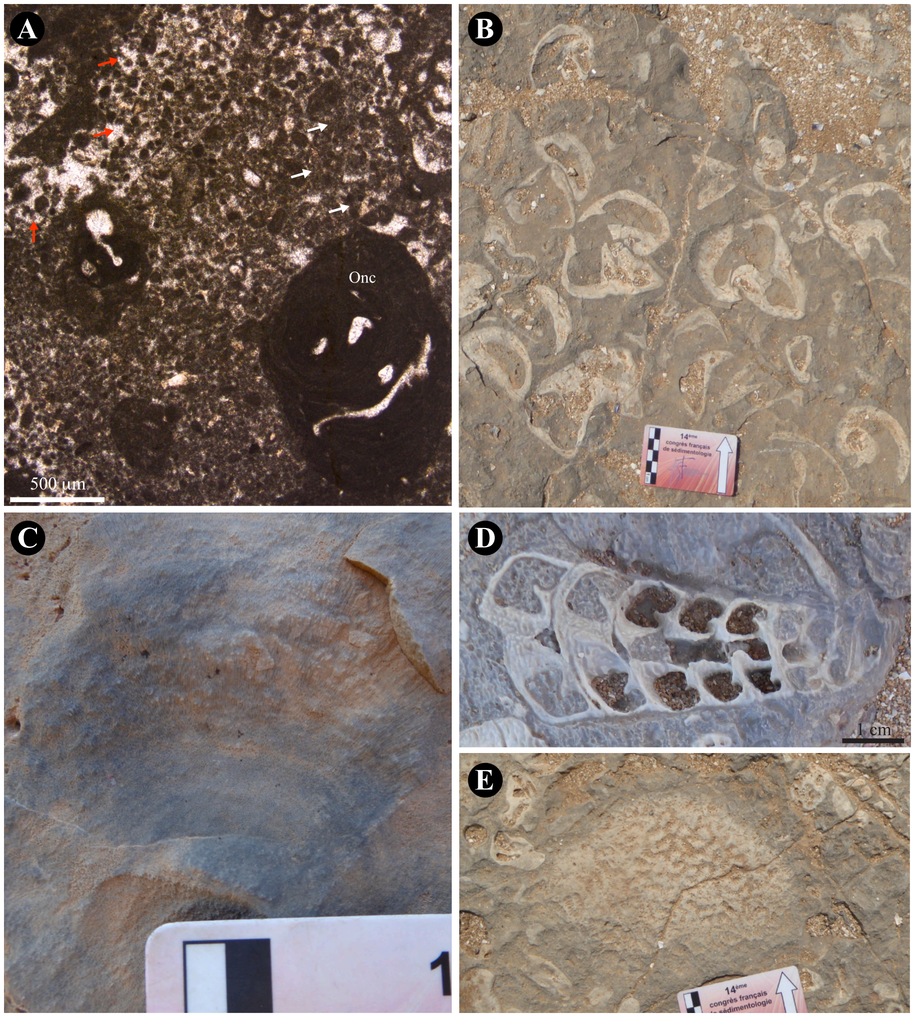

Fig. 7. Inner ramp facies. Cap Ghir location. (A) Peloidal packstone (to grainstone) groundmass with an oncoid (Onc). White arrows show areas of micrite between peloids, whereas locally this passes to grainstone textures with sparite (red arrows) (Facies 12). (B) *Megalodont* bivalves (Facies 12). (C) Chaetetid (Facies 13). (D) *Nerinea* gastropod (Facies 13). (E) Coral colony (Facies 12).

peritidal shallowing-upward cycles.

The Iggui El Behar Fm. therefore displays an overall shallowing from very shallow and partly restricted subtidal to peritidal (mudflat) environments in a proximal part of the platform. Ostracod and charophyte-bearing beds in the eastern part of the basin likely indicate brackish marginal marine conditions (Pereira et al., 2003).

5. Buildup geometries and lateral variations

The base of the buildups everywhere corresponds to the development of platy corals in a muddy environment, resting on outer ramp deposits. Buildup size varies from 2 m to 700 m wide and up to 80 m thick. Smaller buildups are solely platy coral bioherms typically capped by outer ramp deposits, whereas the larger ones are either made up exclusively of platy corals, or display an evolution to phaceloid, branching and plocoid/massive coral morphologies. Even where coral genera could not be determined, this upward trend is analogous to observations by Martin-Garin et al. (2007) and Olivier et al. (2012), who established that it reflects a more diverse suite of coral species (Table 2). No buildups were identified in the eastern part of the basin, where they are replaced by middle ramp deposits (Facies 11) with coral fragments and isolated coral colonies.

5.1. Cap Ghir lighthouse transect

Along the coast of Cap Ghir, a Plio-Pleistocene terrace cuts Oxfordian strata that are folded in the Cap Ghir Anticline, providing exceptional exposure of lateral and vertical facies variations inside and surrounding a buildup. Five different environments have been identified along this transect (Fig. 10).

The buildup itself is about 700 m wide and about 50 m thick. Its coral population is dominated by *Dimorpharaea* corals on the lower fore-reef (as defined by Martin-Garin et al., 2007), with a more diverse association of massive corals (*Isastrea*, *Microsolena*, *Thamnasteria*) developing on the upper fore-reef (as defined by Martin-Garin et al., 2007, Table 2). The immediate back-reef is dominated by stylinids (e.g. *Stylina*), rhipidogyrids (*Aplosmilia*, *Psammogyra*, Fig. 4E) and massive corals (*Thamnasteria*) (Table 2; Martin-Garin et al., 2007). Together, these coral-dominated facies belong to facies association 3. Towards the south, the amount of bioclastic material decreases and the coral colonies become more isolated. The dominant fauna are large *Megalodont* bivalves. Together with a reduced fraction of coral fragments, they occur in a peloidal packstone groundmass (Fig. 10). These facies formed in a partially protected inner ramp environment (facies association 5). Further south, the high-energy inner ramp facies association 6 erodes into the inner ramp facies and is itself overlain by oncoidal rudstones of

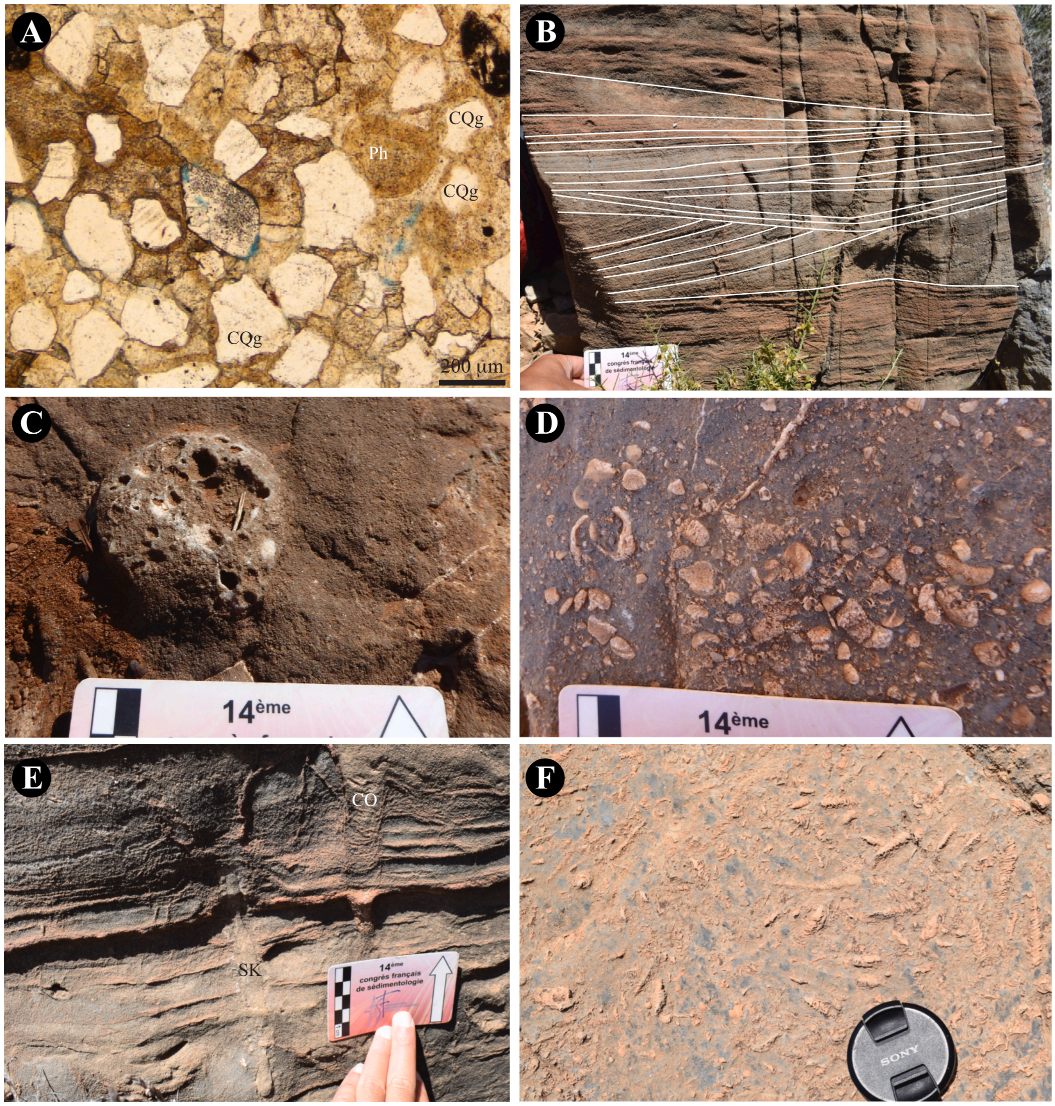

Fig. 8. Facies and sedimentary structures of the high-energy inner ramp (shoreface). (A) Dolomitic sandstone, coated quartz grains (CQg), relics of peloids or ooids (Ph) (Facies 15). Tikki location. (B) Planar to trough cross-bedding (Facies 15). Tikki location. (C) Small coral in Facies 15 sandstone. Amsittène location. (D) Coral, gastropod and bivalve floatstone to rudstone (Facies 14) Assif El Hade location. (E) *Skolithos* (SK) and *Conichnus*? (CO) trace fossils. Amsittène location. (F) Gastropod rudstone (Facies 14). Tikki location.

the restricted inner ramp (Iggui El Behar Fm., facies association 7; Fig. 10).

North of the buildup, the large coral colonies become more massive and then disappear, and the amount of bioclasts increases (Fig. 10). These floatstones and grainstones are interpreted as coral-debris channels (Facies 6 and 7). Storm-induced debris sheets indicate that this is the northern extremity of the buildup with partial reworking by high energy currents. In summary, the lateral facies variations show a W-E orientation of the buildup, with the open sea to the north and an area protected by the buildup to the south.

5.2. Cap Ghir southern flank section

On the southern flank of Cap Ghir Anticline, the Lalla Oujja Fm. contains a succession of smaller platy coral-dominated buildups (Fig. 11). Most do not exceed 10–50 m in width, although some buildups are up to 800 m wide and 20 m thick. Buildups are separated and underlain by dark marly mudstones and wackestones, locally floatstones, rich in crinoids, coral fragments and bivalves (Facies 1, outer ramp). Lithologies between the buildups are generally well-preserved limestones, whereas the coral-rich facies are partially or totally replaced by crystalline dolomite. The contact to the overlying Iggui El Behar Fm. is a sharp surface covered by thick oncolithic grainstones (Facies 20, restricted inner ramp).

5.3. Tidili transect

At Tidili, a complex of bioherms and biostromes is exposed on the SW flank of the Imouzzer Anticline. Buildups are up to 400 m wide and >50 m thick with associated clinoforms (Fig. 12). They provide both along strike and downdip panoramas of buildup architecture (Fig. 13). Widespread dolomitization did not allow identification of coral genera, but growth morphologies serve as proxies for coral diversity. The main buildup (Fig. 13, buildup 1) is dominated by platy corals growing in a mudstone to wackestone matrix. Towards the top, phaceloid, branching and plocoid forms increase and occur in a packstone matrix. Laterally to the west and south, *c.* 80 m thick clinoforms prograde off the structure at an angle of 35° (Figs. 12 and 13). The clinoform foresets are made of coral fragment floatstones and rudstones in a wackestone to packstone matrix (facies association 4), and extend for 600 m away from the

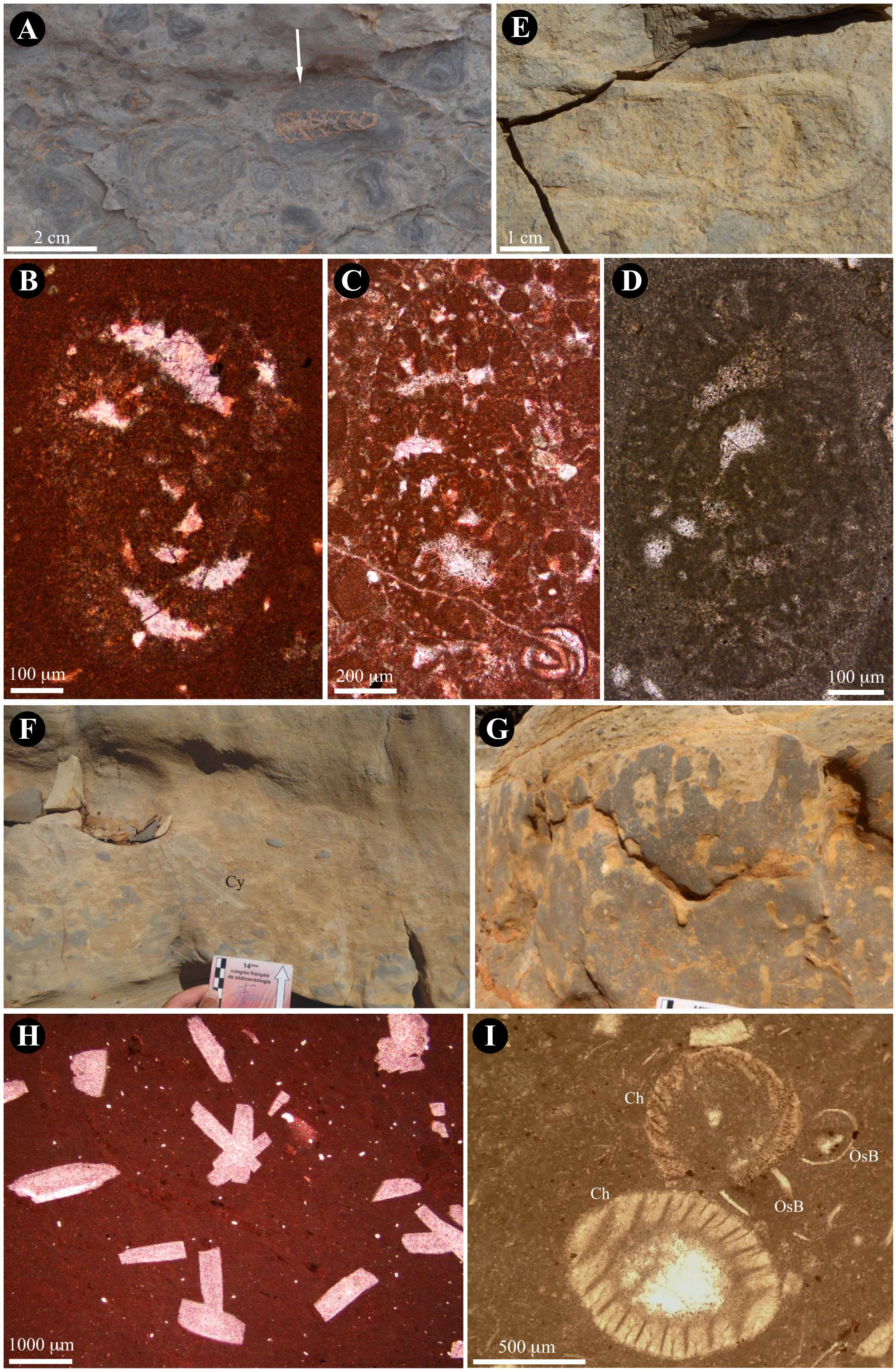

Fig. 9. Facies of the Iggui El Behar Formation. (A) Rudstone of large porostromate oncoids, with gastropod and a coral fragment as nuclei (arrows) (Facies 20). Imouzzer location. (B–D) Poorly preserved *Alveosepta/Pseudocyclammina* foraminifera in Facies 18 wackestones. Imouzzer location. (E) *Rhizocorallium* trace fossil. Imouzzer location. (F) Graded rip-up clast horizon (Facies 19). *Cylindrichnus* trace fossil (Cy). Imouzzer location. (G) Microkarst surface in mudstone with gypsum molds. Imouzzer location. (H) Calcite pseudomorphs after gypsum in Facies 21 mudstone. Imouzzer location. (I) Charophyte gyrogonites (Ch) and fragments of ostracods (OsB). Tizgui N'Chorfa location.

buildup, where they pass to bottomsets comprising wackestones and packstones. Small-scale (2–5 m wide) platy coral buildups occur on the clinoform top surfaces (Fig. 13), and are thus slightly younger than the main buildup 1.

About 300 m along strike south of buildup 1, on top of the toeset of the last clinoform, a 200 m wide and 30 m thick buildup was observed (Fig. 13, buildup 2). It contains platy corals at the base and a transition to increasingly more phaceloid, branching and massive forms towards the top. It is followed by transgressive marly mudstones (facies association 1, outer ramp), which pass laterally to a third buildup (Fig. 13,

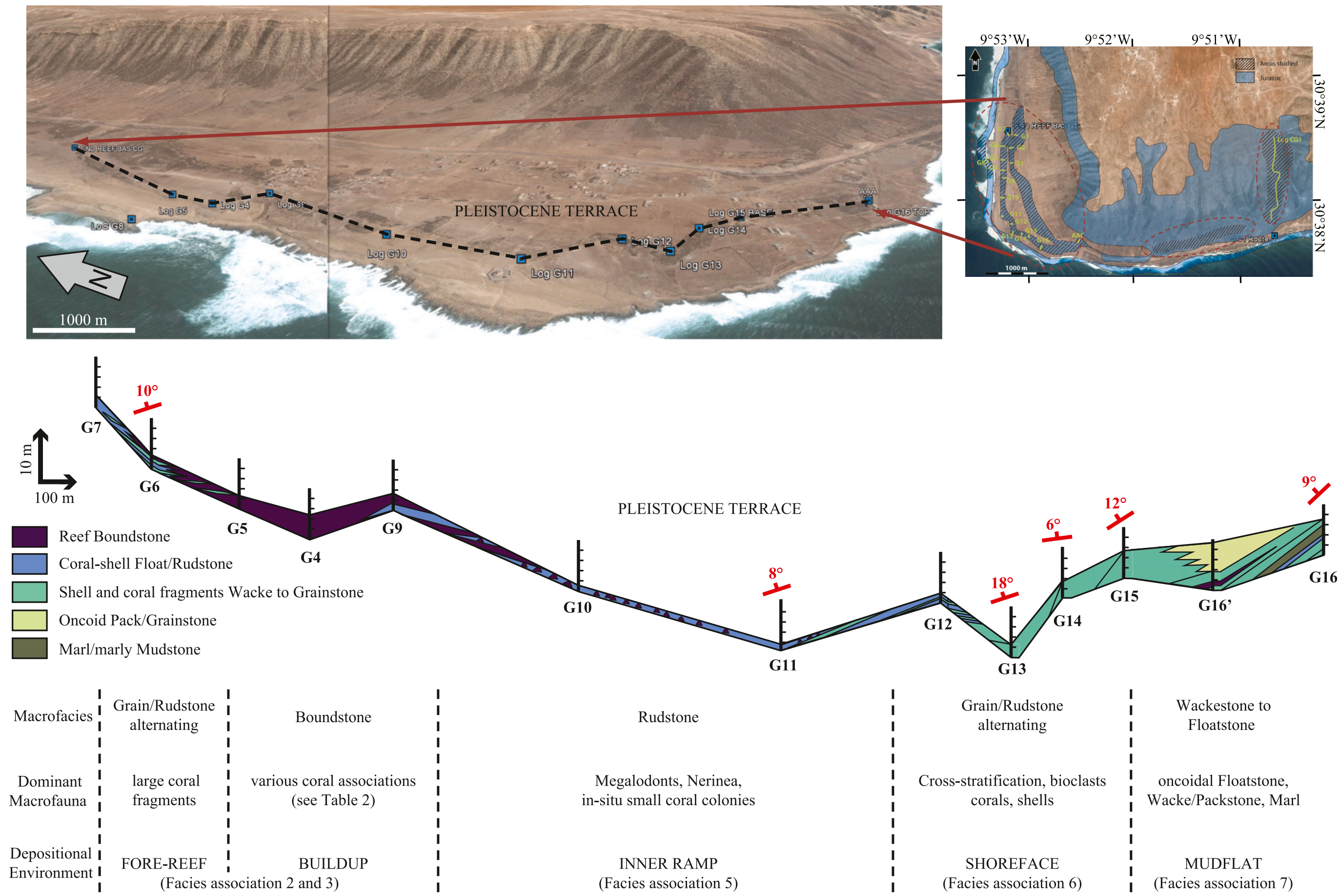

Fig. 10. Facies variations determined from 13 short sections measured along the Cap Ghir lighthouse transect. Satellite images at the top show location and the bottom panel shows the correlations between sections. The strata are tilted northwards and provide a N–S transect from the seaward to the landward side of a large buildup.

buildup 3), less than 2 m vertically above buildup 2. This buildup contains exclusively deeper-water platy coral boundstones (facies association 2).

The southern flank of the anticline provides a downdip panorama of buildup architecture. Two buildups were mapped, a larger one at the base, followed by a smaller one, which passes laterally to wackestones present at the base of buildup 3 (Fig. 13). The entire buildup succession is overlain by the shallower facies of the Iggui El Behar Fm.

Higher-diversity coral facies association 3 with phaceloid, branching and massive corals tends to be more dolomitized than the muddier horizons of platy corals (facies association 2). The clinoform foresets are also very dolomitized, and fractures are common throughout buildups and clinoforms. Vuggy and intercrystalline porosity in these dolomite bodies are related to the dolomitization process (Table 1; Al-Sinawi, 2022).

5.4. Tizgui transect

On the southern flank of the Anklout anticline, the microsolenid corals form a low relief horizontal biostrome, followed by m-scale bioherms, still dominated by microsolenid corals, but associated with small colonies of phaceloid, branching corals and solitary corals, as well as thrombolites (Fig. 14). These slightly more diverse buildups create some relief, filled with floatstones made of brachiopods and coral fragments in a muddy matrix (Fig. 14).

6. Stratigraphic and depositional architecture

6.1. Facies correlations

Two correlation panels oriented E-W (proximal to distal) and N–S (along strike) illustrate the lateral variation of the depositional environments at the basin scale (Fig. 15). The stratigraphic evolution of the Lalla Ouija Fm. begins with outer ramp deposits (facies association 1), followed by the development of coral buildups (facies associations 2–4) across the basin. In the west, the buildup unit consists of multiple stacked smaller buildups, separated from each other by marl and wackestones, whereas in the eastern part of the basin, individual buildups are thicker and separated by coral-rich floatstones (Fig. 15, transect A). Buildup thickness also varies along strike: in the Tizgui locality, overall buildup thickness is smaller than in the rest of the basin, whereas in this locality the microsolenids dominate over diverse colonies (Fig. 15, transect B).

Buildups pass eastward to mid-ramp facies (Facies 11; Fig. 15, transect A), whereas upsection, the mid-ramp facies are intercalated with buildups in the transition to overlying protected and high-energy inner ramp facies (facies associations 5 and 6; Fig. 15, transect B). High-energy inner ramp deposits are preferentially developed in the north and east of the basin (Assif El Hade and Tizgui N'Chorfa localities; Fig. 15). Restricted and peritidal deposits of the Iggui El Behar Fm. form the upper part of all the sections studied, with some very restricted and brackish deposits in the east of the basin (facies association 7; Fig. 15).

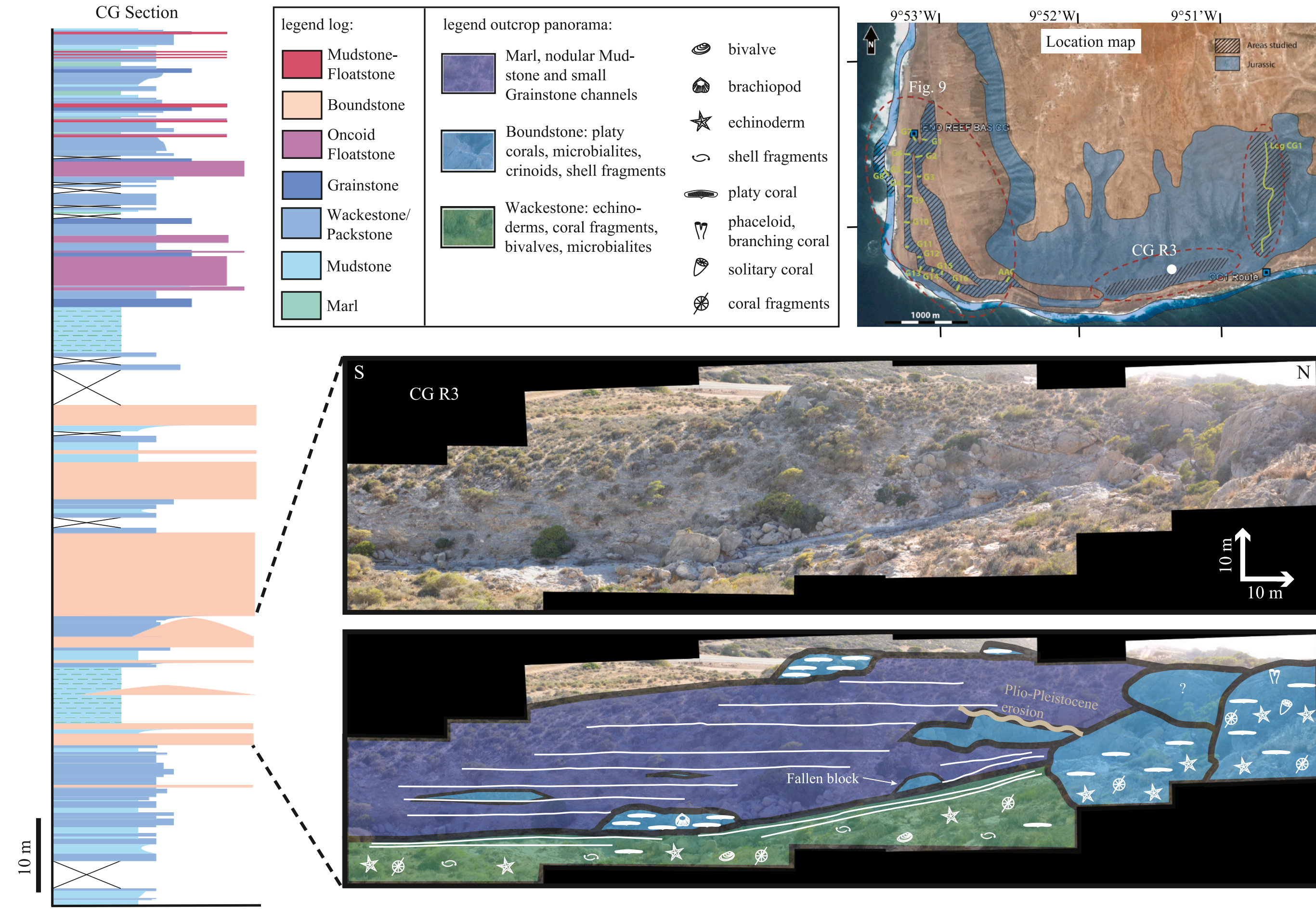

Fig. 11. Left: Log of the CG1 section, southern flank of the Cap Ghir Anticline. Bottom right: Photomosaic of the base of the Lalla Oujja Formation at location CG R3. The top right inset map shows locations of the Cap Ghir South location.

Fig. 12. Clinoforms prograding off the buildup in the Lalla Oujja Formation, Tidili transect. The image was tilted ~30° clockwise to flatten on the top of the Lalla Oujja Formation buildup visible in the top right (buildup 1 in Fig. 13).

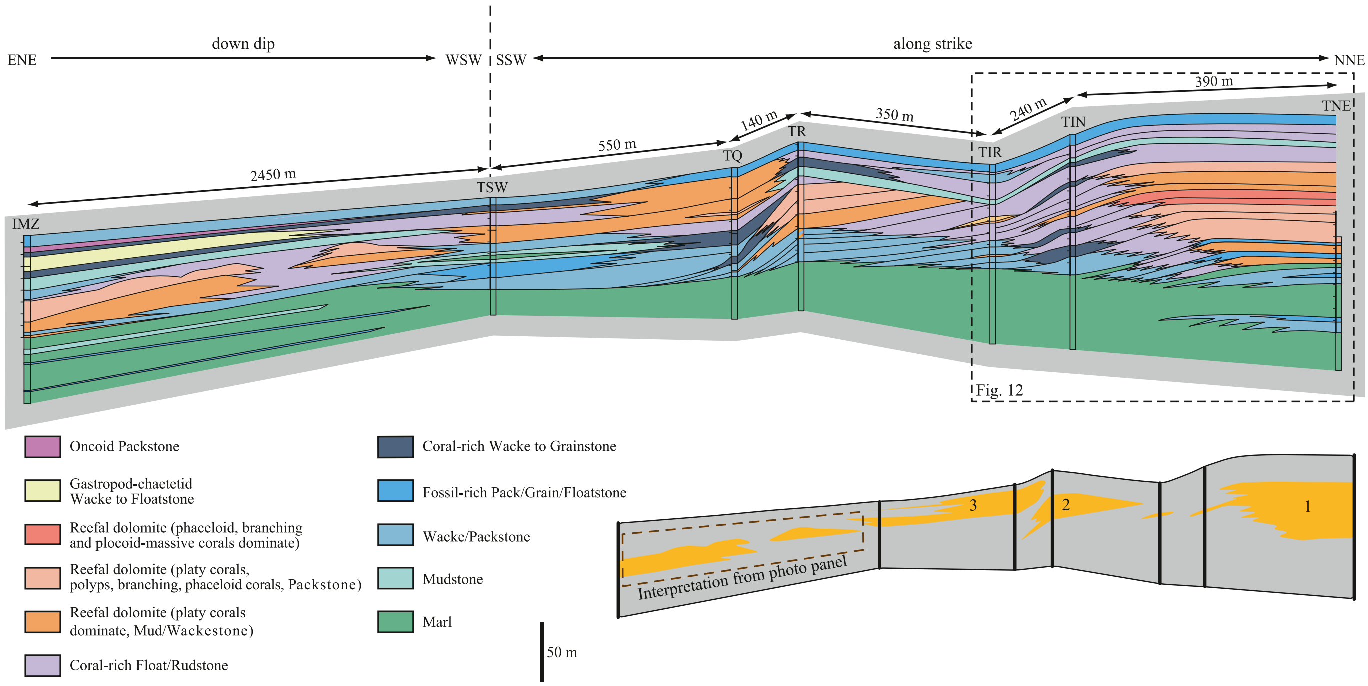

Fig. 13. 3D facies correlations of serial sections in the locality of Tidili to illustrate the lateral and vertical stacking of buildups. The upper panel shows the detailed correlations and the lower panel shows the position of the buildups described in the text. Position of photo in Fig. 12 is indicated. In-situ facies of the buildup cores are shown in orange colors, whereas purple colors reflect clinoforms. Blue and green colors show clinoform toe-of-slope facies and outer ramp facies, respectively.

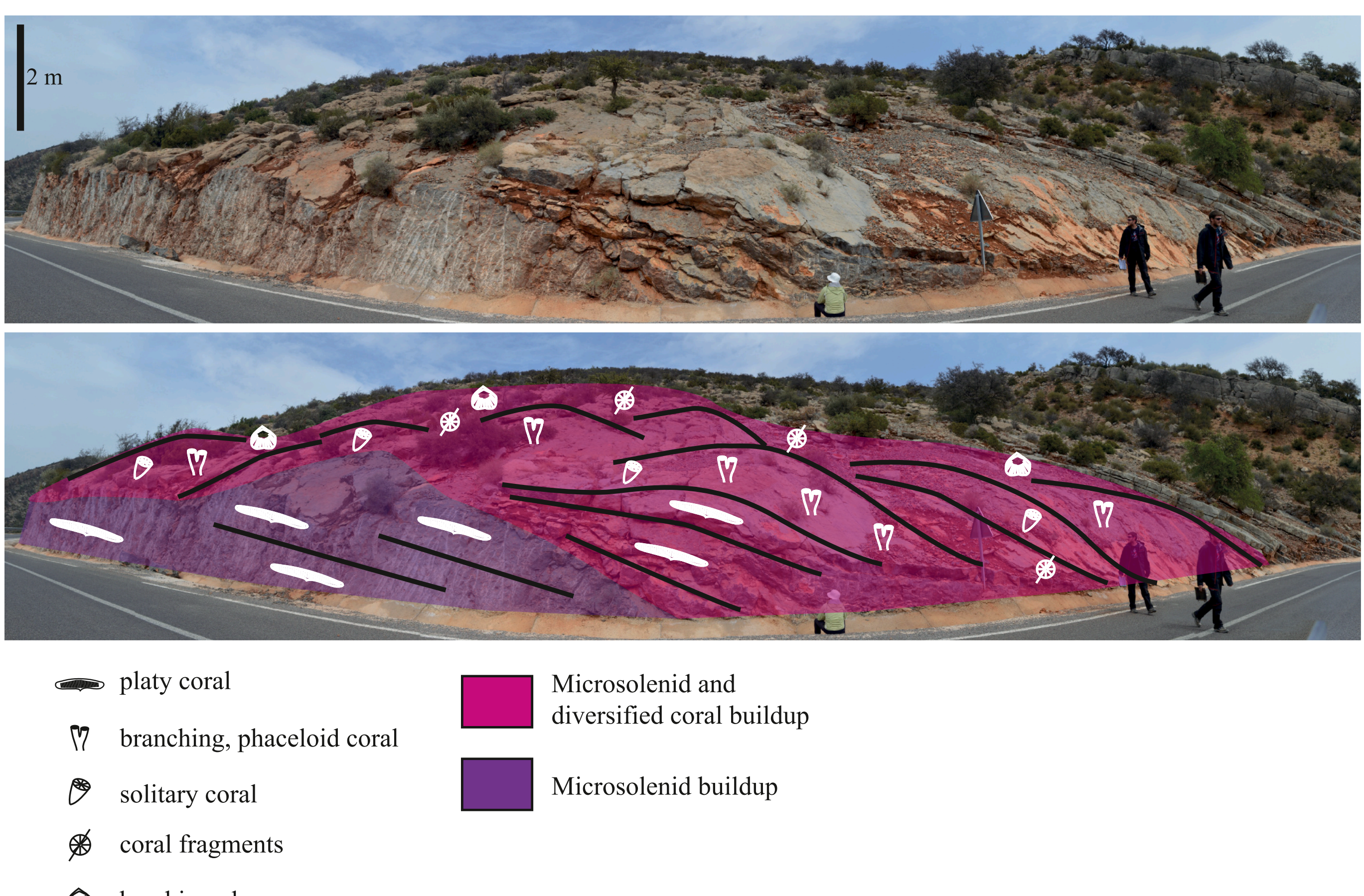

Fig. 14. Buildup evolution and geometries in the Tizgui transect. The top panel shows an uninterpreted panorama of a buildup. Distribution of main coral groups and facies are shown in the lower panel.

6.2. Depositional model and buildup paleogeography

Above the transgressive Ouanamane Fm. (Duval-Arnould et al., 2024), the stratigraphic architecture studied here records a gradual shallowing-upwards trend through the Lalla Oujja and Iggui El Behar formations, from outer ramp to peritidal deposits (Fig. 15). A major regressive shift is observed at the transition from the Lalla Oujja to the Iggui El Behar Fm., when restricted inner ramp deposits (facies association 7) developed in the east and abruptly overlie buildups in the south and west of the basin (Fig. 15). High-energy inner ramp carbonates and sandstones (facies association 6) reflect siliciclastic influx in the basin from east and north.

The Lalla Oujja Fm. coral buildups developed near the start of this shallowing-upwards trend. Buildups initially formed below fair weather-wave base, possibly in water depths <70 m (Insalaco et al., 1997), and only the upper parts grew into agitated waters above fair weather wave base (Fig. 16). No evidence for a break in slope (e.g. gravity deposits) was observed. Instead, storm waves were able to impinge on the seabed as evidenced by middle ramp deposits (Facies 11) and locally the high-energy inner ramp deposits (Facies 14, 15). Thus, overall facies evolution of the Lalla Oujja and Iggui El Behar formations reflects progressive shallowing along a ramp-like depositional profile (Fig. 16).

In all localities across the basin, the base of the buildups corresponds to the development of platy corals in a muddy environment, resting on outer ramp deposits. Echinoderms, sponges, microbes and microsolenid corals colonized and lithified the soft substrate of the outer ramp during pioneer and colonization stages (Fig. 17, stages 1–3; Olivier et al., 2012). The major microsolenid buildups then evolved into more diverse coral assemblages during the diversification stage (Fig. 17, stages 4–5; Olivier et al., 2012). Smaller microsolenid bioherms remained isolated or grew in the depressions between the main buildups (Fig. 17, stages 4–5), including on clinoforms during periods of buildup stabilization and reduced sediment shedding (Fig. 13). The Tidili transect demonstrates that although buildup initiation was relatively synchronous across the basin (Duval-Arnould et al., 2024), further buildup development was diachronous (Fig. 13). The major buildups could be age equivalent (buildup 1 and buildups on the southern flank) and might have created accommodation space between them, which was later filled by other buildups (Fig. 13). Similar juxtaposition of buildup generations were reported from other basins, e.g. the Asturian Coalfield Basin (Carboniferous; Samankassou et al., 2013). Buildup growth was not exclusively constrained by accommodation space however, as buildup thickness does not increase to the west (Fig. 15, transect A). At the Tizgui locality, microsolenid facies dominates over diverse coral facies despite an overall reduced buildup thickness (Fig. 14; Fig. 15, transect B). This could be explained by deeper water conditions or more turbidity in the water column compared to the rest of the basin.

Integration of outcrop and well data illustrates the basin-scale distribution of coral buildups (Fig. 18A). They are prominent in the eroded anticlines in the Agadir sub-basin, but have been equally intersected by various wells in the Essaouira sub-basin. No buildups were identified in well ESS-1X, where outer ramp conditions prevailed, and in the eastern part of the basin. In the Argana valley, the same time interval is represented by bioclastic middle ramp deposits with coral fragments and *Nerinea* assemblages (Facies 11; Fig. 15, transect A; Fig. 18A). In the north, near the Amsittène Anticline (AMCA), equally no major buildups were identified. The last ammonites collected here are Middle Callovian in age, and the Callovian Ouanamane Fm. is directly overlain by cross-stratified sandstones and carbonate grainstones (facies association 6). This mixed unit could be the equivalent of the Lalla Oujja Fm. at the basin margin, or it could belong to the Iggui El Behar Fm. following erosion or non-deposition of the Lalla Oujja Fm. at this locality (Duval-Arnould et al., 2024). In either scenario, deposition of the high-energy (shoreface) facies reflects shallow-water conditions and siliciclastic input that was likely localized around syn-depositional growth of the Amsittène Anticline, possibly influenced by Triassic evaporites (Fig. 18A–C). The influx of siliciclastics could have prevented the growth of coral buildups or eroded them entirely at this locality.

As part of the overall shallowing-upward succession, the upper Lalla Oujja Fm. records a siliciclastic influx coming from the north of the

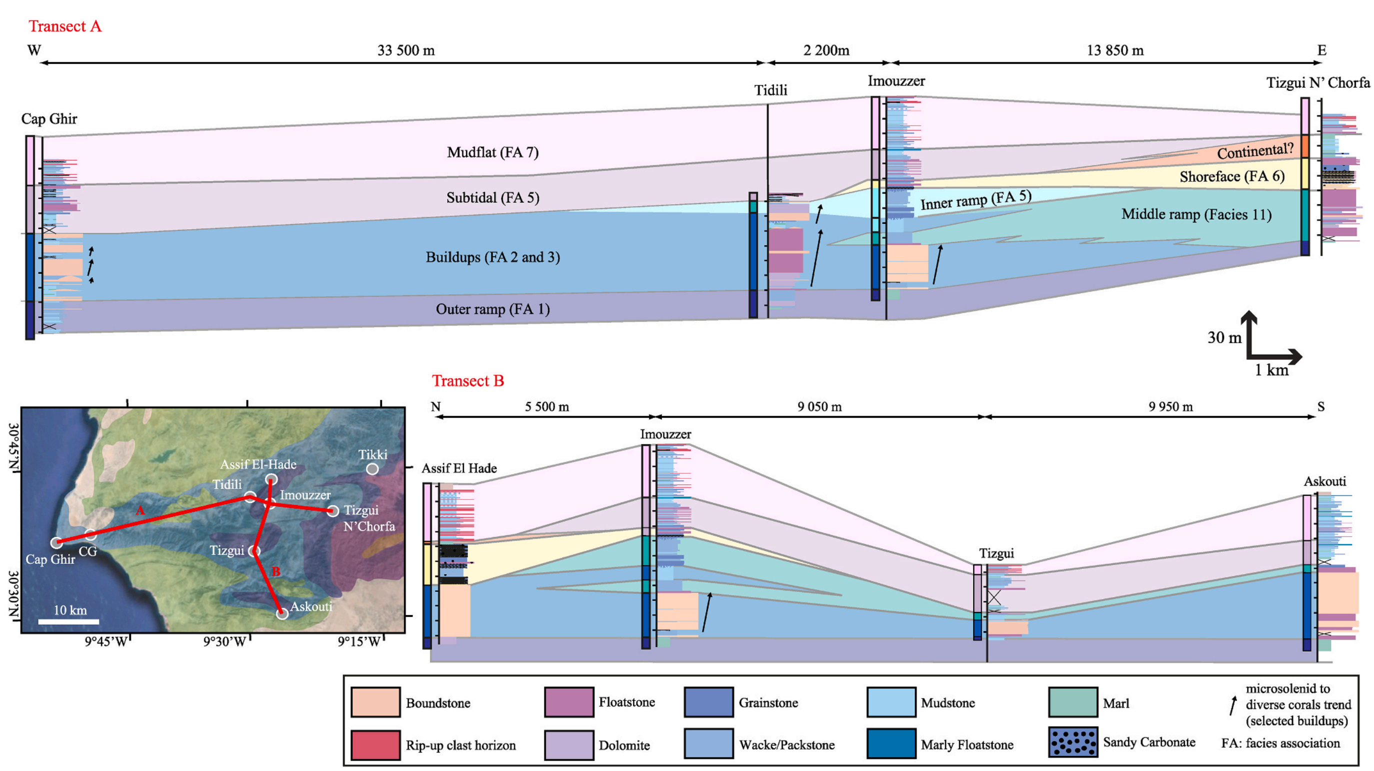

Fig. 15. E-W and S–N cross sections across the Essaouira-Agadir Basin to illustrate the facies architecture at basin scale. Small black arrows show the upsection evolution from microsolenid to diverse coral buildups for a selection of buildups.

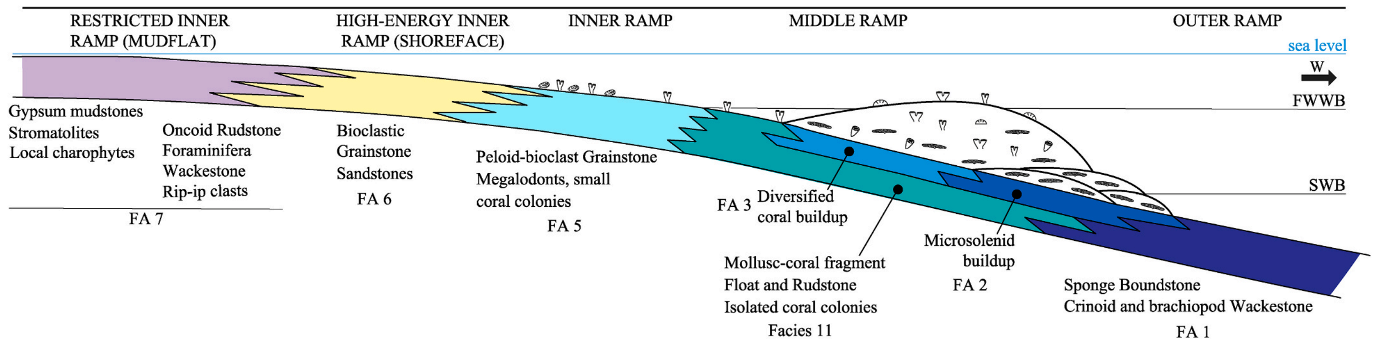

Fig. 16. Depositional model for the Lalla Oujja and Iggui El Behar formations, representing a ramp profile open to the west. Microsolenid buildups developed initially in outer ramp facies. These buildups locally develop upwards to high-diversity buildups that reached to and above the fair-weather wave base. Buildups pass laterally at basin scale to middle ramp facies. Clinoform facies associated with some buildups (facies association 4) is not represented. FA = facies association.

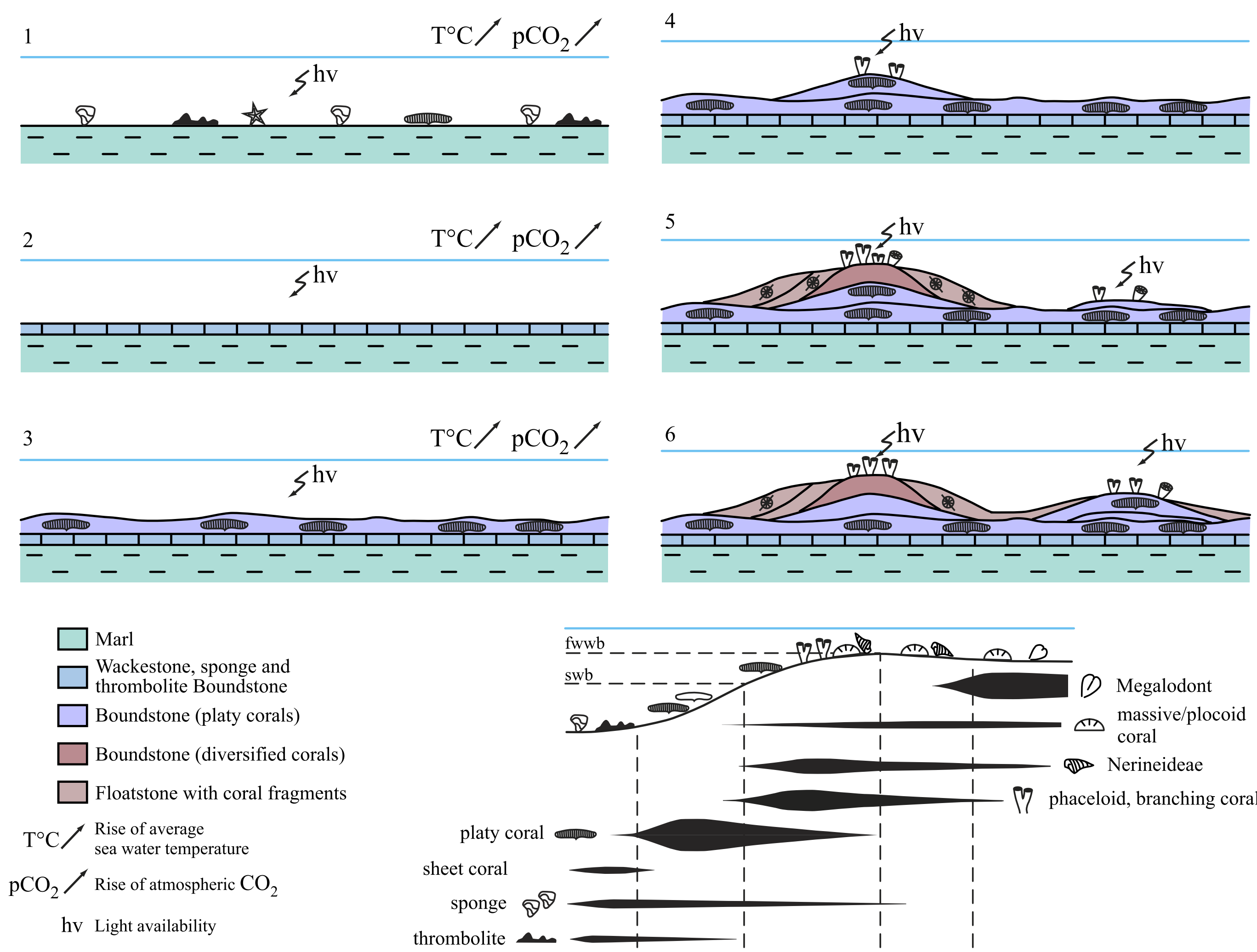

Fig. 17. Buildup development and evolution (1–6) and biozonation of the main macrofauna during the Middle-Upper Jurassic in the Essaouira-Agadir Basin.

basin. This led to the development of siliciclastic and carbonate high-energy inner ramp (shoreface) deposits (facies association 6), which erode into the middle and inner ramp facies (facies association 5) (Figs. 15 and 18B). Some wells in the northeast and northwest of the basin, and outcrops in the southwest do not record this siliciclastic influx, which constrains these deposits to the center and north of the basin, forming a possible barrier island or strand plain complex (Fig. 18B). A potential sabkha environment extended further to the east (locality Imi N'Tanoute and well EGA-1), with continental conditions postulated for the far eastern part of the study area (Fig. 18B). As the regression continued, very restricted to possibly continental deposits of the Iggui El Behar Fm. extended west across the area previously occupied by coral buildups (Fig. 18C). In summary, buildups disappeared most likely due to a combination of higher-energy conditions in the northern and eastern sectors of the basin, siliciclastic input, and establishment of restricted environments in the Upper Oxfordian. Buildup deposition may have shifted to the current offshore sector, but coral buildups drilled offshore have not been precisely dated.

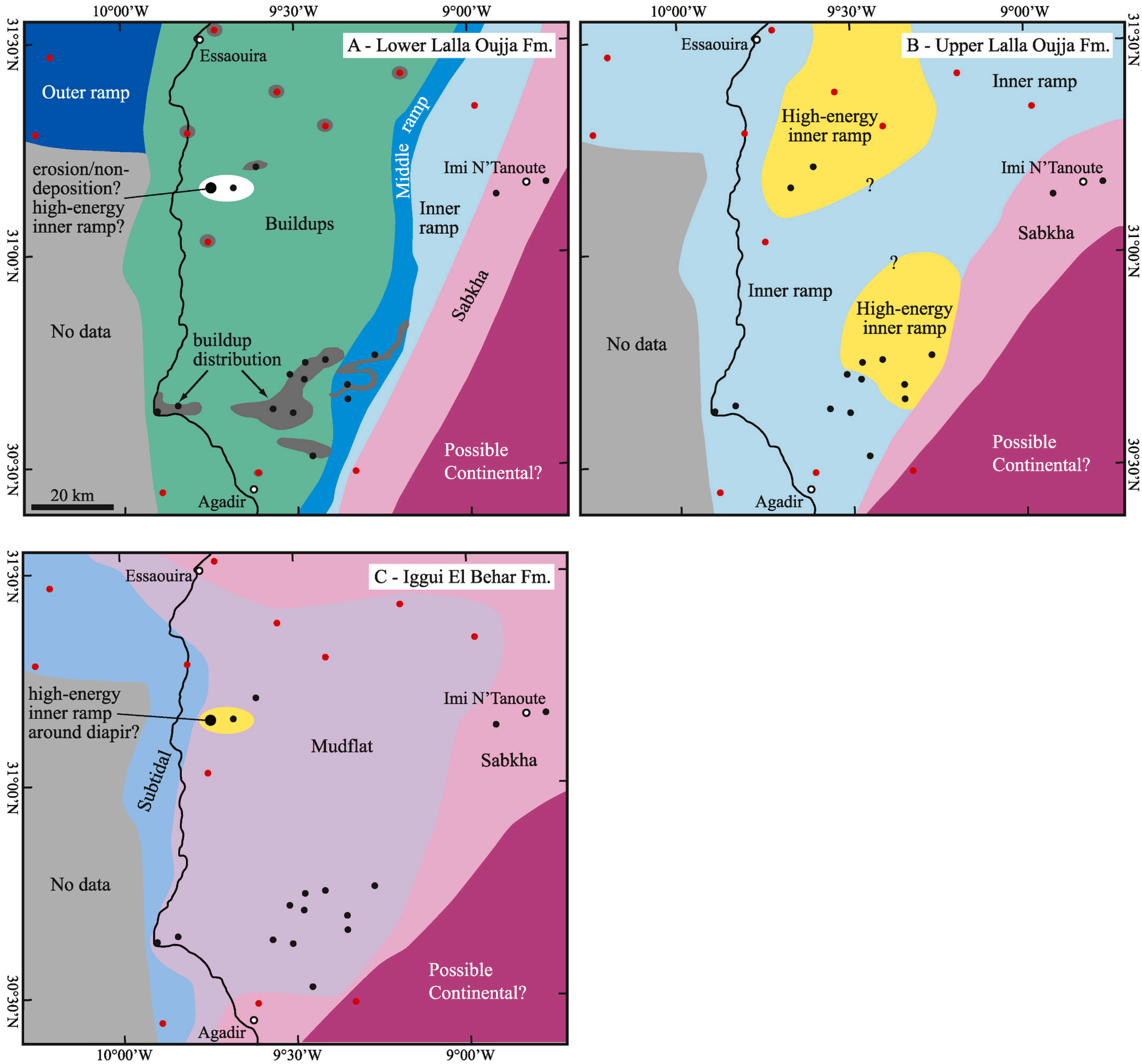

Fig. 18. Paleogeographic maps of the Upper Jurassic, based on outcrop and well observations. (A): Lower Lalla Oujja Formation. The grey zones indicate where coral buildups were observed. (B) Upper Lalla Oujja Formation. (C) Iggui El Behar Formation.

7. Discussion

7.1. Environmental transition to coral domination

Microsolenid buildups in the Essaouira-Agadir Basin were not restricted to the Oxfordian. The fauna composing the buildup framework was already present during the Callovian, but only formed small bioherms (20 m wide) and biostromes (1 m thick) (Duval-Arnould et al., 2024). More extensive buildup construction initiated in the Middle Oxfordian, based on the updated biostratigraphy for the Essaouira-Agadir Basin (Duval-Arnould et al., 2024). Large Upper Jurassic microsolenid buildups are well documented from the Tethyan realm in the French-Swiss Jura (Gygi et al., 1998; Lathuilière et al., 2005; Gygi, 2013), Paris Basin (Menot, 1980; Bertling and Insalaco, 1998; Chevalier et al., 2001), Poland (Kołodziej, 2015), England (Ali, 1983; Insalaco, 1999), Iberian Basin (Benito and Mas, 2006), and across the central Atlantic conjugate margins (Ellis et al., 1985; Weissenberger et al., 2006).

Middle Oxfordian coral development in Morocco was preceded by a hiatus or condensed interval during the Upper Callovian to Lower Oxfordian, which correlates with a depositional hiatus and/or regression across the Tethys realm (Duval-Arnould et al., 2024). This interval was marked by a shift to cooler temperatures and lower pCO_2, as well as more continental runoff in a humid climate (Dromart et al., 2003a, 2003b; Cecca et al., 2005; Andrieu et al., 2016), leading to reduced carbonate production. Subsequent coral expansion in Morocco is recorded above a Middle Oxfordian maximum flooding interval (Duval-Arnould et al., 2024) and coincided with the Oxfordian-Kimmeridgian global 2^{nd}-order transgression (Haq, 2018). Temperatures and pCO_2 rose again globally during this time (Dromart et al., 2003a, 2003b; Cecca et al., 2005). Climate was likely more arid and monsoon-like, with a decelerated carbon cycle (Martinez and Dera, 2015; Andrieu et al., 2016). These factors caused carbonate supersaturation in shallow seas. Coupled with a shift to calcite seas (Stanley and Hardie, 1998), this would have stimulated the carbonate factory and enabled the development and rapid expansion of coral colonies from the Middle Oxfordian onward.

7.2. Factors controlling buildup development

Variation in microsolenid buildup facies and geometry depends on the environmental conditions. They are usually dominated by in-situ microsolenid corals that form a coherent framework and display a bedded sheet-like biostromal geometry (Insalaco, 1996). These biostromes are found at comparable stratigraphic positions within the reef succession and their faunal associations are quite similar. In many localities, the microsolenid biostromes developed on top of sponge-rich intervals (Insalaco, 1996; Chevalier et al., 2001), which has also been observed in the EAB. The microsolenid biostromes typically evolve towards more diverse coral associations and develop a higher depositional relief (Insalaco, 1996; Lathuilière et al., 2005; Benito and Mas, 2006).

Different ecozones have been identified by Lathuilière et al. (2005), depending on the coral associations and their associated sediments. They identified the deeper facies as being dominated by non-encrusted *Dimorpharaea*, in marls and wackestones matrix, and followed by the *Microsolena* ecozone, followed by the *Dendraraea* ecozone, where the morphology of the dominating corals shifts from sheet-like to branching. These authors identified a water depth control on the ecozones. Insalaco (1996) proposed another interpretation by looking at the siliciclastic content of the different sections, observing that *Dimorpharaea* dominates where the siliciclastic content is higher, and *Microsolena* dominates in purer limestones, and linked this to the morphology differences between the two species. Microsolenid buildups can further reflect mesotrophic conditions and nutrient stress from elevated detrital input (Dupraz and Strasser, 2002).

Water depth, siliciclastic input and associated nutrient stress could be valid factors for the buildups in the EAB. *Dimorpharaea* dominate at the base of the succession where fine detritus is present in what is interpreted as the deepest water environments. Both water depth and detrital fraction decrease upsection in parallel with a reduction in relative abundance of *Dimorpharaea*.

Locally, the microsolenid buildups developed into higher-diversity buildups with phaceloid and more massive (plocoid) growth forms, as well as stylinid corals (Table 2). These coral groups are light dependent, and thus indicate shallower water conditions. Stylinid corals thrived in nutrient-poor waters, whereas phaceloid forms were adapted to relatively quiet water conditions, but with higher rates of carbonate mud sedimentation and/or soft substrates (Dupraz and Strasser, 2002). Clinoforms with coral detritus and the local development of massive corals do support however periodic reworking by high-energy currents in middle to inner ramp environments. It therefore seems that the diverse buildups in the EAB reached above fair weather wave base, but likely never shallowed up to sea level (Fig. 16). The composition of reef builders in Morocco is comparable to other Oxfordian reefs documented in Tethys and North Atlantic, including the microbial component previously reported for the North Atlantic (Leinfelder et al., 2002). This study and the previous work by Martin-Garin et al. (2007) and Olivier et al. (2012) underline however that corals were at least of equal importance relative to microbial components in these North Atlantic buildups.

7.3. Environmental controls over coral disappearance

The sedimentary architecture of coral buildups in the Essaouira-Agadir Basin suggests a more local control on the termination of coral development. Buildup demise coincided with the arrival of detrital-rich inner ramp sediments in the northern part of the basin (facies association 6). This rapid influx of siliciclastics into the environment could have triggered the disappearance of coral buildups locally. However, the demise of the coral buildups appears to be relatively synchronous across the basin (no later than Upper Oxfordian). In the Assif El Hade locality, isolated corals are still present in-situ within the inner ramp deposits. Therefore, conditions still allowed coral growth, and coral disappearance may not be only related to the influx of siliciclastics, but rather to a combination of factors. All over the eastern and central part of the basin, high-energy inner ramp deposits are followed by charophyte-rich wackestone and marl, which indicate a change to restricted or brackish conditions as a result of a rapid regressive event. It is more likely that this drastic change of bathymetry and associated change in water salinity triggered the final disappearance of the buildups rather than the siliciclastic influx alone, which affected only in the north and east of the basin. The sudden influx of detrital material was related to increased hinterland erosion in the Massif Ancien and Meseta of Morocco, as well as syn-depositional diapiric growth of anticlinal structures (e.g. Amsittène Anticline) (Fernández-Blanco et al., 2020; Charton et al., 2021).

7.4. Analogs for the architecture of subsurface porous geobodies

The outcrops studied here provide analogs for the architecture of Oxfordian buildups in the subsurface of the Moroccan and Canadian conjugate margins, where they are proven to be porous, in particular when dolomitized (Ellis et al., 1985; Pratt and Jansa, 1989; Morabet et al., 1998; Weissenberger et al., 2006). The Canadian buildups are dominated by microbial and siliceous sponge and microsolenid coral mounds, but equally contain branching corals and coral rubble (Ellis et al., 1985; Pratt and Jansa, 1989; Eliuk, 2016). Buildups consist of stacked geobodies, separated by coral debris and finer-grained facies (Kidston et al., 2005; Eliuk, 2016). The depositional heterogeneity is mirrored by porosity, which is commonly developed in the buildup facies (moldic, vuggy, intra- and intergranular porosity up to 24%; Eliuk, 1978; Kidston et al., 2005; Wierzbicki et al., 2006). Porosity development is strongly dependent on near-surface to burial dolomitization, which affected mainly permeable skeletal and buildup facies, but is also controlled by faults (Wierzbicki et al., 2006; Al-Sinawi, 2022). While the subsurface facies are thus comparable to those observed in outcrop, the sedimentary and diagenetic controls on porosity and dolomite distribution can equally be observed in the Moroccan outcrops (Al-Sinawi, 2022). Dolomite is partly facies-controlled and typically affects buildup facies and reworked skeletal textures, whereas micrite-rich textures remained mostly limestone. Buildups with diverse coral colonies tend to be more dolomitized than platy coral-dominated buildups. Burial dolomite in the buildups is controlled by faults and can extend up to 10's of kilometers from faults (Al-Sinawi, 2022). Dolomitized horizons tend to be more fractured, although dolomite cementation can reduce porosity and permeability. Dolomitization of the Lalla Oujja Fm. buildups was promoted by accumulation of Mg-rich fluids below the more impermeable Iggui El Behar Fm. and Kimmeridgian marls in a hydrothermal dolomitization system (Davies and Smith, 2006; Al-Sinawi, 2022).

The outcrops studied here allow quantification of this significant heterogeneity in terms of buildup size and facies architecture between isolated buildups and associated facies. Buildups form a mosaic of geobodies, which are preferentially dolomitized, and encased in more micrite-rich textures that tend to preserve as limestones. Stacking of buildups with internal low-permeability zones is common (Fig. 13; Al-Sinawi, 2022). The heterogeneity of this sedimentary architecture occurs at the scale of 10's to 100's of meters (Fig. 13), which is resolvable by seismic (Harvey and MacDonald, 1990). Furthermore, the buildups formed an extensive belt in the EAB (Fig. 18A; Adams, 1979), which probably extended into the subsurface. Granular sediment in the clinoforms, as well as in the middle ramp and shoreface facies, contains abundant intra- and intergranular porosity and is partially dolomitized, thus potentially providing petrophysical connectivity between individual buildups (cf. Adams et al., 2005).

8. Conclusions

The Essaouira-Agadir Basin provides one of the few outcrop locations in the Atlantic realm for detailed study of Oxfordian coral buildup composition and architecture, vertical biological and sedimentary evolution, and the wider depositional context. This study determines the driving factors for buildup initiation and demise and establishes important constraints to interpret the architecture of porous reefal geobodies in the subsurface of Morocco, Canada and elsewhere. Key conclusions are.

(1) The studied buildups are dominated by microsolenid bioherms that developed in a low-light and low-energy environment on a ramp. They locally developed upsection into larger buildups growing in shallower water. These were constructed by more diverse associations of phaceloid, branching and massive corals. A significant microbial component is present throughout the studied buildups.
(2) Coral-dominated facies developed across the basin, except in the eastern proximal part, as isolated buildups, located meters to 100's of meters apart, and separated by reef-rubble and mudstone to wackestone horizons. Buildup size ranges from 2 m wide and 0.5 m thick microsolenid colonies up to 700 m wide and 80 m thick more diverse coral colonies. The microsolenid bioherms do not form high-relief structures, but small bioherms or laterally extensive biostromes.
(3) Larger buildups are typically associated with coral-rich clinoforms resulting from dismantling of buildups in a relatively high-energy shallow-water environment around and above the fair weather wave base. Transects indicate a complex architecture of larger buildups and clinoforms, with distinct diachroneity of buildups, and smaller buildups developing on clinoforms.
(4) Initiation of buildup development was synchronous in the Middle Oxfordian. Local changes in accommodation, increasing sea water temperature and pCO_2 linked to the onset of the Middle Oxfordian global transgression are the main drivers for buildup development. Buildup demise was likely related to local factors. It is postulated that Middle-Upper Oxfordian uplift in Morocco caused a local regression, the spread of restricted more evaporitic conditions across the Essaouira-Agadir Basin, and the influx of siliciclastics from eroded hinterland and local uplifted anticlines.
(5) The coral buildups serve as analogs to constrain geobody architecture and heterogeneity in the subsurface of Morocco and Canada. Porous geobodies, normally dolomitized, developed in buildups and clinoforms, but are interbedded and interfinger at outcrop scale (10's to 100's of meters) with finer-grained facies that usually contain little porosity.

CRediT authorship contribution statement

Aude Duval-Arnould: Writing – original draft, Investigation, Conceptualization. **Luc Bulot:** Writing – original draft, Supervision, Investigation. **Rémi Charton:** Writing – review & editing, Investigation. **Sreepat Jain:** Investigation. **Moussa Masrour:** Writing – original draft, Investigation. **Luis Pomar:** Investigation. **Jonathan Redfern:** Writing – review & editing, Investigation, Funding acquisition. **Mike Simmons:** Writing – review & editing, Investigation. **Stefan Schröder:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This study forms part of the lead author's PhD at the University of Manchester and integrates into the North Africa Research Group (NARG) project on the Mesozoic Evolution of the Moroccan Atlantic Margin. The authors would like to express their gratitude to the sponsoring companies of NARG for their financial and scientific support, and to The Office National des Hydrocarbures et des Mines (ONHYM) for their logistical and scientific support, in particular Mr Nahim, Ms Habid and Mr Aabi. We thank Benoit Vincent and two anonymous reviewers of the Journal of African Earth Sciences for their constructive comments that improved the manuscript.

References

Adams, A.E., 1979. Sedimentary environments and palaeogeography of the western high Atlas, Morocco, during the middle and late Jurassic. Palaeogeogr. Palaeoclimatol. Palaeoecol. 28, 185–196.
Adams, A.E., 1980. The stratigraphy and sedimentology of a Jurassic marine transgression, Western High Atlas, Morocco. Geol. Mediterr. 7, 223–231.
Adams, A.E., Ager, D.V., Harding, A.G., 1980. Géologie de la région d'Imouzzer des Ida-ou-Tanane (Haut-Atlas Occidental). Notes et Mémoires du Service géologique du Maroc 41, 59–80.
Adams, E.W., Grotzinger, J.P., Watters, W.A., Schröder, S., McCormick, D.S., Al-Siyabi, H.A., 2005. Digital characterization of thrombolite-stromatolite reef distribution in a carbonate ramp system (terminal Proterozoic, Nama Group, Namibia). AAPG (Am. Assoc. Pet. Geol.) Bull. 89, 1293–1318.
Ager, D.V., 1974. Storm deposits in the Jurassic of the Moroccan high Atlas. Palaeogeogr. Palaeoclimatol. Palaeoecol. 15, 83–93.
Ali, O.E., 1983. Microsolenid corals as rock-formers in the Corallian (Upper Jurassic) rocks of England. Geol. Mag. 120, 375–380.
Al-Sinawi, N., 2022. Dolomitization of Jurassic Carbonates in the Western High Atlas of Morocco: Processes and Implications for Reservoir Properties. Unpublished PhD Thesis. The University of Manchester, p. 267.
Ambroggi, R., 1963. Étude géologique du versant méridional du Haut-Atlas Occidental et de la plaine de Souss. Notes et Mémoires du Service géologique du Maroc, Rabat 157, 1–321.
Andrieu, S., Brigaud, B., Barbarand, J., Lasseur, E., Saucède, T., 2016. Disentangling the control of tectonics, eustasy, trophic conditions and climate on shallow-marine carbonate production during the Aalenian–Oxfordian interval: from the western France platform to the western Tethyan domain. Sediment. Geol. 345, 54–84.
Baudon, C., Redfern, J., Van Den Driessche, J., 2012. Permo-triassic structural evolution of the Argana valley, impact of the atlantic rifting in the high Atlas, Morocco. J. Afr. Earth Sci. 65, 91–104.
Benito, M.I., Mas, R., 2006. Sedimentary evolution of the Torrecilla reef complex in response to tectonically forced regression (early kimmeridgian, northern Spain). Sediment. Geol. 183, 31–49.
Bertling, M., Insalaco, E., 1998. Late Jurassic coral/microbial reefs from the northern Paris Basin—facies, palaeoecology and palaeobiogeography. Palaeogeogr. Palaeoclimatol. Palaeoecol. 139, 139–175.
Bouaouda, M.S., 2002. Micropaléontologie de la plateforme du Bathonien-Oxfordien des régions d'Imi'N-Tanout et du Jbilet Occidental (Maroc), Essai de biozonation. Revue de Paléobiologie, Genève 21, 223–239.
Bouatmani, R., Medina, F., Aït Salem, A., Hoepffner, C., 2003. Thin-skin tectonics in the Essaouira basin (western High Atlas, Morocco): evidence from seismic interpretation and modelling. J. Afr. Earth Sci. 37, 25–34.
Bouaouda, M.S., Peybernès, B., Peybernès, M., 2004. Foraminiferes benthiques complexes du Bathonien supérieur au Kimméridgien inférieur de la marge atlantique marocaine ("Bassin" d'Agadir): stratigraphie et paléobiogéographie. Revue de Micropaléontologie 47, 13–27.
Burchette, T.P., Wright, V.P., 1992. Carbonate ramp depositional systems. Sediment. Geol. 79, 3–57.
Cecca, F., Garin, B.M., Marchand, D., Lathuiliere, B., Bartolini, A., 2005. Paleoclimatic control of biogeographic and sedimentary events in Tethyan and peri-Tethyan areas during the Oxfordian (Late Jurassic). Palaeogeogr. Palaeoclimatol. Palaeoecol. 222, 10–32.
Charton, R., Kluge, C., Fernández-Blanco, D., Duval-Arnould, A., Bryers, O., Redfern, J., Bertotti, G., 2021. Syn-depositional Mesozoic siliciclastic pathways on the Moroccan Atlantic margin linked to evaporite mobilisation. Mar. Petrol. Geol. 128, 105018.
Chevalier, F., Garcia, J.P., Quesne, D., Guiraud, M., Menot, J.C., 2001. Corrélations et interprétations génétiques dans les formations récifales oxfordiennes de la haute vallée de l'Yonne (sud-est du Bassin de Paris, France). Bull. Soc. Geol. Fr. 172, 69–84.
Christ, N., Immenhauser, A., Amour, F., Mutti, M., Tomas, S., Agar, S.M., Alway, R., Kabiri, L., 2012. Characterization and interpretation of discontinuity surfaces in a Jurassic ramp setting (High Atlas, Morocco). Sedimentology 59, 249–290.

Chrząstek, A., Wypych, M., 2018. Coniacian sandstones from the North Sudetic Synclinorium revisited: palaeoenvironmental and paleogeographical reconstructions based on trace fossil analysis and associated body fossils. Geologos 24, 29–53.
Crevello, P.D., Harris, P.M., 1984. Depositional models for Jurassic reefal buildups. In: Proceedings Gulf Coast Section of SEPM Third Annual Research Conference, pp. 57–101.
Davies, G.R., Smith Jr., L.B., 2006. Structurally controlled hydrothermal dolomite reservoir facies: an overview. AAPG (Am. Assoc. Pet. Geol.) Bull. 90, 1641–1690.
Demicco, R.V., Hardie, L.A., 1994. Sedimentary structures and early diagenetic features of shallow marine carbonate deposits. SEPM Atlas Series 1.
Domènech, M., Teixell, A., Babault, J., Arboleya, M.L., 2015. The inverted Triassic rift of the Marrakech High Atlas: a reappraisal of basin geometries and faulting histories. Tectonophysics 663, 177–191.
Dromart, G., Garcia, J.-P., Picard, S., Atorps, F., Lecuyer, C., Sheppard, S.M.F., 2003a. Ice age at the middle-late jurassic transition. Earth Planet Sci. Lett. 213, 205–220.
Dromart, G., Garcia, J.-P., Gaumet, F., Picard, S., Rousseau, M., Atrops, F., Lecuyer, C., Sheppard, S.M.F., 2003b. Perturbation of the carbon cycle at the Middle/Late Jurassic transition: geological and geochemical evidence. Am. J. Sci. 303, 667–707.
Du Dresnay, R., 1988. Répartition des dépôts carbonatés du Lias inférieur et moyen le long de la côte Atlantique du Maroc : conséquences sur la paléogéographie de l'Atlantique naissant. J. Afr. Earth Sci. 7, 385–396.
Duffaud, F., 1960. Contribution à l'étude stratigraphique du bassin secondaire du Haut-Atlas Occidental (Sud-Ouest marocain). Bull. Soc. Geol. Fr. 2, 728–743.
Dumas, S., Arnott, R.W.C., 2006. Origin of hummocky and swaley cross-stratification - the controlling influence of unidirectional current strength and aggradation rate. Geology 34, 1073–1076.
Dupraz, C., Strasser, A., 2002. Nutritional modes in coral-microbialite reefs (Jurassic, Oxfordian, Switzerland): evolution of trophic structure as a response to environmental change. Palaios 17, 449–471.
Duval-Arnould, A., Schröder, S., Charton, R., Joussiaume, R., Razin, P., Redfern, J., 2021. Early post-rift depositional systems of the central atlantic: Lower and Middle Jurassic of the Essaouira-Agadir Basin, Morocco. J. Afr. Earth Sci. 178, 104164.
Duval-Arnould, A., Bulot, L., Marour, M., Simmons, M., Bonnot, A., Charton, R., Redfern, J., Schröder, S., 2024. The development and evolution of an Atlantic margin carbonate ramp during the Callovian to middle Oxfordian: Agadir-Essaouira Basin, Morocco. J. Afr. Earth Sci. 210, 105164.
Eliuk, L.S., 1978. The Abenaki Formation, Nova Scotia Shelf, Canada - a depositional and diagenetic model for a Mesozoic carbonate platform. Bull. Can. Petrol. Geol. 26, 424–514.
Eliuk, L.S., 2016. Abenaki Carbonate Platform in Relation to the Jurassic-Cretaceous Sable Island Delta, Offshore Nova Scotia, Canada. Unpublished PhD Thesis. Dalhousie University, Halifax, Nova Scotia, p. 422.
Ellis, P.M., Crevello, P.D., Eliuk, L.S., 1985. Upper jurassic and lower cretaceous deep-water buildups, Abenaki formation, Nova scotian shelf. In: Crevello, P.D., Harris, P. M. (Eds.), Deep-water Carbonates, vol. 6. SEPM Core Workshop, pp. 212–248.
Fernández-Blanco, D., Gouiza, M., Charton, R., Kluge, C., Klaver, J., Bräutigam, K., Bertotti, G., 2020. Anticline growth by shortening during crustal exhumation of the Moroccan Atlantic margin. J. Struct. Geol. 140, 104125.
Frizon de Lamotte, D., Leturmy, P., Missenard, Y., Khomsi, S., Ruiz, G., Saddiqi, O., Guillocheau, F., Michard, A., 2009. Mesozoic and Cenozoic vertical movements in the Atlas system (Algeria, Morocco, Tunisia): an overview. Tectonophysics 475, 9–28.
Frizon de Lamotte, D., Saint Bezar, B., Bracène, R., Mercier, E., 2000. The two main steps of the Atlas building and geodynamics of the western Mediterranean. Tectonics 19, 740–761.
Gérard, J.R.F., Bromley, R.G., 2008. Ichnofabrics in Clastic Sediments: Applications to Sedimentological Core Studies, p. 97.
Gradziński, M., Tyszka, J., Uchmann, A., Jach, R., 2004. Large microbial-foraminiferal oncoids from condensed Lower–Middle Jurassic deposits: a case study from the Tatra Mountains, Poland. Palaeogeogr. Palaeoclimatol. Palaeoecol. 213, 133–151.
Gygi, R.A., 2013. Integrated stratigraphy of the oxfordian and kimmeridgian (late jurassic) in northern Switzerland and adjacent southern Germany. Memoirs of the Swiss Academy of Sciences 104, 151. Birkhäuser.
Gygi, R.A., Coe, A.L., Vail, P.R., 1998. Sequence stratigraphy of the oxfordian and kimmeridgian stages (late jurassic) in northern Switzerland. In: De Graciansky, P.-C., Hardenbol, J., Jacquin, T., Vail, P.R. (Eds.), Mesozoic and Cenozoic Sequence Stratigraphy of European Basins, vol. 60. SEPM Special Publication, pp. 3–29.
Hafid, M., 2000. Triassic–early Liassic extensional systems and their Tertiary inversion, Essaouira Basin (Morocco). Mar. Petrol. Geol. 17, 409–429.
Hallock, P., Schlager, W., 1986. Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios 389–398.
Haq, B.U., 2018. Jurassic sea-level variations: a reappraisal. GSA Today (Geol. Soc. Am.) 28, 4–10.
Harvey, P.J., MacDonald, D.J., 1990. Seismic modelling of porosity within the Jurassic aged carbonate bank, offshore Nova Scotia. Can. J. Explor. Geophys. 26, 54–71.
Hottinger, L., 1967. Foraminifères imperforés du Mésozoique marocain. Notes et Mémoires du Service géologique du Maroc 209, 1–168.
Insalaco, E., 1996. Upper Jurassic microsolenid biostromes of northern and central Europe: facies and depositional environment. Palaeogeogr. Palaeoclimatol. Palaeoecol. 121, 169–194.
Insalaco, E., 1999. Facies and palaeoecology of upper jurassic (middle oxfordian) coral reefs in England. Facies 40 (1), 81–99.
Insalaco, E., Hallam, A., Rosen, B., 1997. Oxfordian (Upper Jurassic) coral reefs in Western Europe: reef types and conceptual depositional model. Sedimentology 44, 707–734.
Kidston, A.G., Brown, D.E., Smith, B.M., Altheim, B., 2005. The Upper Jurassic Abenaki Formation Offshore Nova Scotia: A Seismic and Geologic Perspective. Canada-Nova Scotia Offshore Petroleum Board, Halifax, Nova Scotia, p. 168.
Kiessling, W., Flügel, E., 2002. Paleoreefs – a database on Phanerozoic reefs. In: Kiessling, W., Flügel, E., Golonka, J. (Eds.), Phanerozoic Reef Patterns, vol. 72. SEPM Special Publication, pp. 77–92.
Kołodziej, B., 2015. Corals of the Štramberk-type limestones from Poland: taxonomic and palaeoecological aspects. Neues Jahrbuch Geol. Palaontol. Abhand. 276, 181–199.
Kwon, Y.K., Chough, S.K., Choi, D.K., Lee, D.J., 2002. Origin of limestone conglomerates in the choson supergroup (Cambro–Ordovician), mid-east Korea. Sediment. Geol. 146, 265–283.
Lathuilière, B., Gaillard, C., Habrant, N., Bodeur, Y., Boullier, A., Enay, R., Hanzo, M., Marchand, D., Thierry, J., Werner, W., 2005. Coral zonation of an Oxfordian reef tract in the northern French Jura. Facies 50, 545–559.
Laville, E., Piqué, A., 1992. Jurassic penetrative deformation and Cenozoic uplift in the Central High Atlas (Morocco): a tectonic model. Geol. Rundsch. 81, 157–170.
Leinfelder, R.R., Schmid, D.U., Nose, M., Werner, W., 2002. Jurassic reef patterns - the expression of a changing globe. In: Kiessling, W., Flügel, E., Golonka, J. (Eds.), Phanerozoic Reef Patterns, vol. 72. SEPM Special Publication, pp. 468–520.
MacEachern, J.A., Pemberton, S.G., Gingras, M.K., Bann, K.L., 2006. The ichnofacies paradigm: a fifty-year retrospective. In: Miller III, W. (Ed.), Trace Fossils: Concepts, Problems, Prospects. Elsevier, Amsterdam, pp. 52–77.
Mahboubi, C.Y., Naimi, M.D., Mehadji, A.O., Garah, A., Langer, M.R., Limam, H., 2023. First evidence of the benthic foraminifera *Alveosepta jaccardi* from the Oxfordian of the Saharan Atlas (Algeria): palaeoenvironmental and palaeoecological implications. Neues Jahrbuch Geol. Palaontol. Abhand. 307, 91–100.
Martin-Garin, B., Lathuilière, B., Geister, J., Chellai, E.H., Huault, V., 2007. Geology, facies model and coral associations of the Late Jurassic reef complex at cape Ghir (Atlantic High Atlas, Morocco). Compt. Rendus Geosci. 339, 65–74.
Martinez, M., Dera, G., 2015. Orbital pacing of carbon fluxes by a ~9-My eccentricity cycle during the Mesozoic. Proc. Natl. Acad. Sci. USA 112, 12604–12609.
Mattauer, M., Tapponnier, P., Proust, F., 1977. Sur les mécanismes de formation des chaines intracontinentales; l'exemple des chaines atlasiques du Maroc. Bull. Soc. Geol. Fr. 7, 521–526.
Matter, A., 1967. Tidal flat deposits in the Ordovician of western Maryland. J. Sediment. Petrol. 37, 601–609.
Medina, F., 1988. Tilted-blocks pattern, paleostress orientation and amount of extension, related to Triassic early rifting of the Central Atlantic in the Arnzri area (Argana basin, Morocco). Tectonophysics 148, 229–233.
Menot, J.C., 1980. Formations récifales du Jurassique Supérieur de la vallée de l'Yonne. Geobios 13, 47–53.
Meyer, D.L., Macurda, D.B., 1977. Adaptive radiation of the comatulid crinoids. Paleobiology 3, 74–82.
Michard, A., Ibouh, H., Charrière, A., 2011. Syncline-topped anticlinal ridges from the High Atlas: a Moroccan conundrum, and inspiring structures from the Syrian Arc, Israel. Terra. Nova 23, 314–323.
Morabet, A.M., Bouchta, R., Jabour, H., 1998. An overview of the petroleum systems of Morocco. In: Macgregor, D.S., Moody, R.T.J., Clark-Lowes, D.D. (Eds.), Petroleum Geology of North Africa, vol. 132. Geological Society, London, Special Publications, pp. 283–296.
Olivier, N., Martin-Garin, B., Colombie, C., Cornée, J.J., Giraud, F., Schnyder, J., Kabbachi, B., Ezaidi, K., 2012. Ecological succession evidence in an Upper Jurassic coral reef system (Izwarn section, High Atlas, Morocco). Geobios 45, 555–572.
Ourribane, M., Chellaï, E.H., Ezaidi, A., Içame, N., 1999. Un complexe récifal à stromatoporidés, coraux et microbialites: exemple du Kimméridgien de Cap-Guir (Haut-Atlas atlantique, Maroc). Geol. Mediterr. 26, 79–88.
Pereira, R., Feist, M., Azerêdo, A.C., 2003. New charophytes from the Upper Jurassic of the Lusitanian Basin (Portugal). J. Micropalaeontol. 22, 113–126.
Peybernès, B., Bouaouda, M.S., Alméras, Y., Ruget, C., Cugny, P., 1987. Stratigraphie du Lias et du Dogger du bassin côtier d'Essaouira (Maroc) avant et pendant le début de l'expansion océanique dans l'Atlantique central. In: Comparaison avec le bassin d'Agadir, vol. 305. Comptes-Rendus de l'Académie des Sciences, Paris, pp. 1449–1455.
Piqué, A., Le Roy, P., Amrhar, M., 1998. Transtensive synsedimentary tectonics associated with ocean opening: the Essaouira–Agadir segment of the Moroccan Atlantic margin. J. Geol. Soc. 155, 913–928. London.
Piqué, A., Tricart, P., Guiraud, R., Laville, E., Bouaziz, S., Amrhar, M., Ouali, R.A., 2002. The Mesozoic-Cenozoic Atlas belt (North Africa): an overview. Geodin. Acta 15 (3), 185–208.
Pratt, B.R., Jansa, L.F., 1989. Late Jurassic shallow water reefs of offshore Nova Scotia. In: Geldsetzer, H.H.J., James, N.P., Tebbutt, G.E. (Eds.), Reefs, Canada and Adjacent Areas, vol. 13. Canadian Society of Petroleum Geologists Memoir, pp. 741–747.
Roux, M., Bourseau, J.P., Bas, T., Dumont, T., de Graciansky, P.C., Lemoine, M., Rudkiewicz, J.L., 1988. Bathymetric evolution of the Tethyan margin in the western Alps (data from stalked crinoids): a reappraisal of eustatism problems during the Jurassic. Bull. Soc. Geol. Fr. 4, 633–641.
Sahabi, M., Aslanian, D., Olivet, J.L., 2004. Un nouveau point de départ pour l'histoire de l'Atlantique central. Compt. Rendus Geosci. 336 (12), 1041–1052.
Samankassou, E., von Allmen, K., Bahamonde, J.R., 2013. Growth dynamics of Pennsylvanian carbonate mounds from a mixed terrigenous-carbonate ramp in the Puebla de Lillo area, Cantabrian Mountains, Northern Spain. J. Sediment. Res. 83, 1099–1112.
Saura, E., Verges, J., Martin-Martin, J.D., Messager, G., Moragas, M., Razin, P., Grelaud, C., Joussiaume, R., Malaval, M., Homke, S., Hunt, D.W., 2014. Syn- to post-rift diapirism and minibasins of the Central High Atlas (Morocco): the changing face of a mountain belt. J. Geol. Soc. 171, 97–105.

Schlagintweit, F., Gawlick, H.J., Lein, R., 2005. Mikropaläontologie und Biostratigraphie der Plassen-Karbonatplattform der Typlokalität (Ober-Jura bis Unter-Kreide, Salzkammergut, Österreich). J. Alp. Geol. 47, 11–102.
Sohl, N.F., Kollmann, H.A., 1985. Cretaceous Actaeonellid Gastropods from the Western Hemisphere, p. 151. USGS Professional Paper 1304.
Stanley, S.M., Hardie, L.A., 1998. Secular oscillations in the carbonate mineralogy of reef-building and sediment-producing organisms driven by tectonically forced shifts in seawater chemistry. Palaeogeogr. Palaeoclimatol. Palaeoecol. 144, 3–19.
Todaro, S., Zarcone, G., Mindszenty, A., Di Stefano, P., 2012. Karstic overprint of upper triassic peritidal cycles: the example of the panormide carbonate platform at san vito lo capo (sicily). In: 86° Congresso Della Società Geologica Italiana, vol. 21, pp. 1020–1022. Cosenza, Italia.
Weissenberger, J.A.W., Wierzbicki, R.A., Harland, N.J., 2006. Carbonate sequence stratigraphy and petroleum geology of the Jurassic deep Panuke field, offshore Nova Scotia, Canada. In: Harris, P.M., Weber, L.J. (Eds.), Giant Hydrocarbon Reservoirs of the World: from Rocks to Reservoir Characterization and Modeling, vol. 88. AAPG Memoir, pp. 395–431.
West, R., Kershaw, S., 2012. Chaetetid Habitats. Fossil and Recent Sponges, p. 445pp.
Wierzbicki, R., Dravis, J.J., Al-Aasm, I., Harland, N.J., 2006. Burial dolomitization and dissolution of upper jurassic Abenaki platform carbonates, deep panuke reservoir, Nova Scotia, Canada. AAPG (Am. Assoc. Pet. Geol.) Bull. 90, 1843–1861.
Yümün, Z.Ü., Kılıç, A.M., Martini, R., Metzger, J., Tunç, M., 2013. Late triassic and lower jurassic foraminifera of the carbonate platform of the beyaz aladağ group (eastern taurus, Turkey): new stratigraphic implications. Geobios 46, 447–459.