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Development of a Jurassic rocky shore complex (Zohar Formation, Makhtesh Qatan, southern Israel)

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ABSTRACT

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The Zohar Formation (Callovian, Middle Jurassic) is exposed as a sequence of limestones, dolomites, siltstones, and shales near the center of Makhtesh Qatan in the Negev Desert of southern Israel. Two dolomite units near the top of these fault-bounded exposures are deeply incised by two perpendicular sets of relatively straight channels. Bivalve borings (*Gastrochaenolites*) in these dolomites show that they were cemented limestones when they were exposed and eroded; dolomitization came later. The dimensions of the channels, along with their orientations and stratigraphic context (they contain later Jurassic sediment), show that they are a series of joints that were widened by bioerosion and erosive currents, most likely from tides and wave action within a rocky shore context. Other trace fossils in these units track the earlier lithification history of these sediments. The soles of the beds show a fabric of *Planolites*, tunnels excavated by deposit-feeding worms that require soft sediments, cut by a large network of *Thalassinoides* burrows, which were created by crustaceans in firm sediments. The Zohar Formation at Makhtesh Qatan thus shows the firming, dewatering, and early cementation of sediments that were then exposed and eroded as part of a rocky shore. This new hypothesis updates previous models, which interpreted these rocks as the products of sabkha deposition.

INTRODUCTION

The Middle Jurassic sediments of Israel were deposited on a shallow shelf that experienced a series of transgressions and regressions. (For the most recent depositional and paleogeographic summaries, see Hirsch et al., 1998, and May, 2000.) One of the interesting stratigraphic issues to explore in this thick sequence of sandstones, siltstones, limestones, and dolomites is where the actual coastlines were at specific times. The Middle Jurassic was also a time when "calcite sea" geochemical conditions dominated carbonate cementation and mineralogy, with distinct effects on shallow marine sedimentology and paleontology (Sandberg, 1983, 1985; Wilkinson et al., 1985; Wilkinson and Given, 1986; Palmer et al., 1988; Stanley and Hardie, 1998; Palmer and Wilson, 2004). Is there evidence of calcite sea geochemistry in the Middle Jurassic shelf

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carbonates of Israel? Goldberg and Friedman (1974, p. 20) reported radial calcitic ooids in the Inmar Formation (Lower Jurassic) of southern Israel, but considered them to be calcitized from original aragonite (see also Ayalon and Longstaffe, 1995). We now know these ooids, along with prominent hardgrounds, to be primary evidence for calcite sea geochemistry (Wilson et al., 1992; Palmer and Wilson, 2004). There are also radial calcitic ooids in the Ardon Formation (Lower Jurassic) of Makhtesh Ramon (B. Buchbinder, personal communication), and the abundance of calcitic sponges in reefs of the Israeli Jurassic is also consistent with calcite sea conditions.

A Middle Jurassic coastline and evidence of calcite sea geochemistry can be seen in the easternmost exposures of the Zohar Formation in Israel. Four fault-bounded blocks of the Haqanaim Member of the Zohar Formation (Callovian) are present in the center of Makhtesh Qatan in the northeastern Negev Desert about 20 km southwest of the Dead Sea (Fig. 1). These rocks were previously described in detail by Gill (1966) and Goldberg (1967). The thickest section in the makhtesh is approximately 25 m of sandstones, limestones, calcareous shales, and dolomites (Fig. 2). Two units near the top, the Lower and Upper Dolomite Beds of Goldberg (1967), have a remarkable series of trace fossils and erosional channels, which are the subject of this study.

LOCATION

Makhtesh Qatan is a breached anticline (see Zilberman, 2000) approximately 6 × 4 km in dimension, 20 km southwest of the southern end of the Dead Sea (Fig. 1). The Zohar Formation exposures within Makhtesh Qatan were mapped by Goldberg (1967, fig. 1), who used earlier work by Grader (1954) and Gill (1966). Our primary measured section (Fig. 2) is in the "eastern segment" of the "southern block" of Goldberg (1967, fig. 1) at N30°56.843′ latitude and E35°12.214′ longitude. We also described and measured channels in the "upper dolomite bed" of the "central block" (Goldberg, 1967, figs. 2, 4, and 14) at N30°57.352′ latitude and E35°12.041′ longitude.

STRATIGRAPHY

The most complete section of the Zohar Formation in Makhtesh Qatan is about 25 m thick (Fig. 2). The base of the formation is not exposed; the top is truncated by a regionally extensive erosion surface. From stratigraphic and lithological evidence, it appears this section is part of the Haqanaim Member of the Zohar Formation, representing a highstand systems tract in "Sequence C" of May (2000).

The base of the section is a spiculiferous biomicrite with tubular, lined burrows perpendicular to bedding. Gypsiferous shales, marls, and sandy biosparites follow in succession upwards. The two most distinctive units appear in the upper half of the outcrop: the "Lower Dolomite Bed" and the "Upper Dolomite Bed" of Goldberg (1967, fig. 2), which are intrabiosparites that have been secondarily dolomitized. These massive dolomites are separated by gypsiferous shales and thin sandy dolomites. The Upper and Lower Dolomite

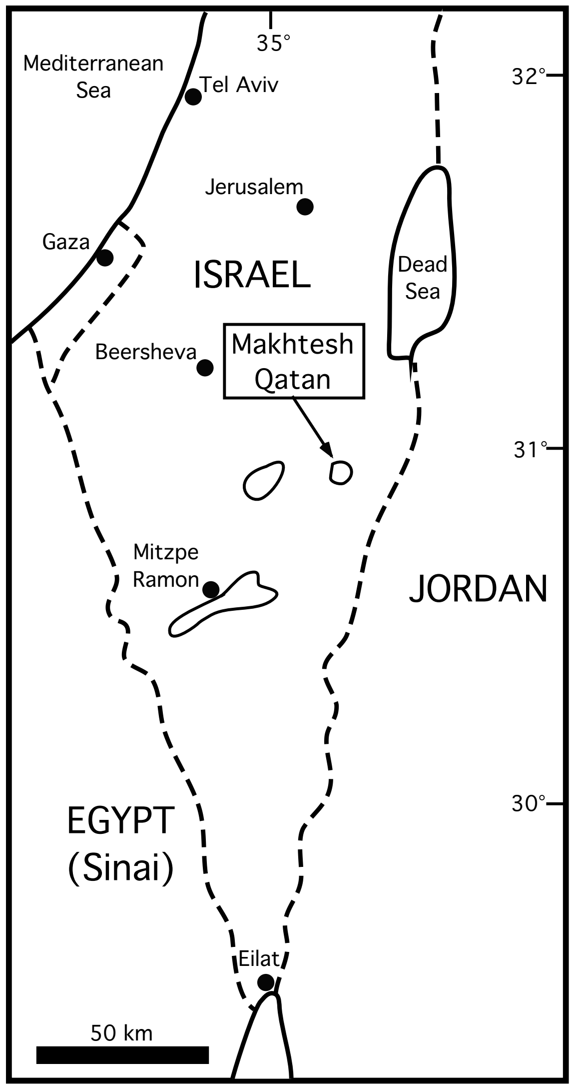

Fig. 1. Location of Makhtesh Qatan in southern Israel.

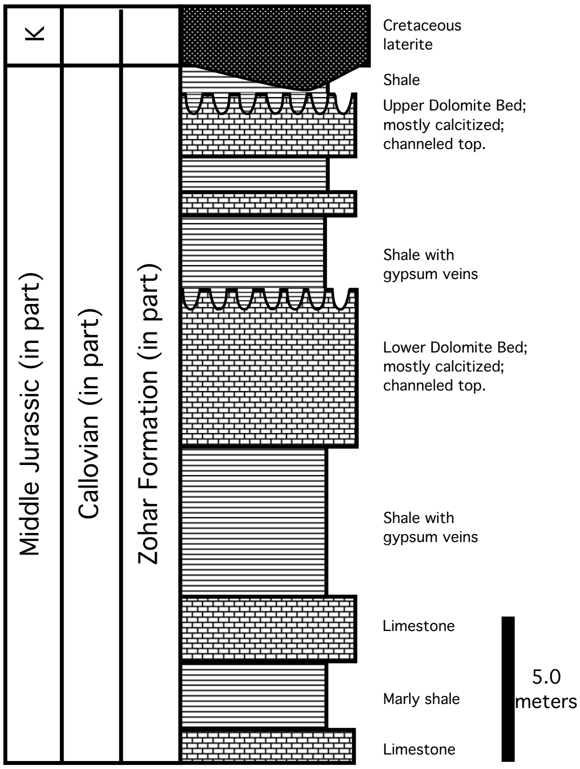

Fig. 2. Stratigraphic column of the Zohar Formation exposed in the center of Makhtesh Qatan.

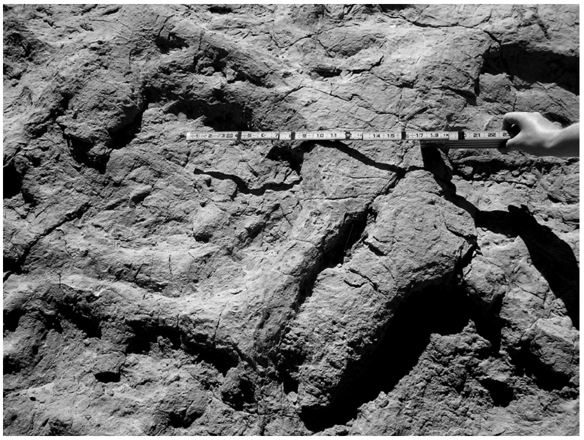

Fig. 3. *Thalassinoides* trace fossils on the underside of a block from the upper channeled dolomite unit of the Zohar Formation at Makhtesh Qatan. These are infillings of a network of large crustacean burrows. Between the branches of *Thalassinoides* is the smaller unbranching trace *Planolites*. The scale is divided into tenths of a meter.

Fig. 4. Dedolomite structure in a thin-section view (with crossed-polarization) from the upper dolomite unit of the Zohar Formation at Makhtesh Qatan. All the rhombic crystals have been calcitized. The scale bar is 100 microns long.

Beds both have deep channels on their top surfaces (see below). The Upper Dolomite Bed is eroded in such a way that convex hyporeliefs of trace fossils are visible on its sole surface. This section agrees with the composite section drawn by Goldberg (1967, fig. 2) except that the "negative mudcracks" he placed at the base of the Upper Dolomite Bed are here recognized as the trace fossil *Thalassinoides* (see below).

TRACE FOSSIL SUCCESSION

The trace fossils in the Upper Dolomite Bed reveal aspects of the biological and sedimentological changes as the sediment went from water-saturated carbonate subtidal sand to the lithified intertidal limestone of a rocky shore. The sole of this unit has a series of trace fossils exposed in convex hyporelief. *Planolites* isp. covers the undersurface; superimposed on it are two generations of *Thalassinoides suevicus* (Fig. 3; see also fig. 20 of Goldberg (1967), where they are referred to as "negative mudcracks"). The upper surface (which is cut by the erosional channels) has scattered *Gastrochaenolites* isp. borings in concave epirelief.

Planolites are horizontal burrows that are unlined and straight to gently curved, with diameters of a couple millimeters to just over a centimeter. They were formed by a worm-like deposit-feeder working through the sediment and back-filling the tunnels behind it (Keighley and Pickerill, 1995). *Planolites* formed in well-oxygenated, soft, water-saturated sediments (Savrda and Bottjer, 1986; Olóriz and Rodríguez-Tovar, 2002; Löwemark et al., 2004). In shallow marine waters of the Mesozoic they ranged from upper subtidal through intertidal environments (MacEachern and Burton, 2000; Zonneveld et al., 2001; Olóriz and Rodríguez-Tovar, 2002).

Thalassinoides are horizontal, regularly-branching, cylindrical burrows connected at intervals to the surface through ventilation shafts. *Thalassinoides* is one of the largest trace fossils, with tunnel diameters ranging from a few centimeters to over 20 cm. They were almost certainly made by filter-feeding crustaceans (Bromley, 1996). *Thalassinoides* traces formed in well-oxygenated marine waters. These burrows are characteristic of firm, dewatered sediments (Bromley, 1975; MacEachern and Burton, 2000), but are also found in softer sediments (Savrda et al., 2001). The Zohar *Thalassinoides* have sharp boundaries that truncate the earlier *Planolites* traces, indicating that they are of the dewatered firmground variety described as "type 2" (Savrda et al., 2001). These traces are also preserved well enough in the Zohar to classify them as *T. suevicus*. As with *Planolites*, the range of *Thalassinoides* in shallow marine waters is from the upper subtidal through the intertidal (Zonneveld et al., 2001).

Gastrochaenolites are clavate, single-opening borings excavated into hard substrates such as shells, rockgrounds, and hardgrounds (see Taylor and Wilson, 2003, for a review of all borings, including *Gastrochaenolites*). They range in widest diameter from a few millimeters to up to five centimeters. *Gastrochaenolites* were especially common in upper subtidal to intertidal rockgrounds and hardgrounds during the Jurassic (Wilson and Palmer, 1994). Their presence is often used to indicate that the substrate they excavated was mineralized primarily with calcium carbonate because these bivalves used a primarily chemical form of substrate dissolution to bore their holes (Taylor and Wilson, 2003). In the Upper Dolomite of the Zohar, *Gastrochaenolites* is excised into the sides of the erosional channels on the upper surface, meaning this rock was limestone and not dolomite at the time.

The sequence of *Planolites–Thalassinoides–Gastrochaenolites* in the Upper Dolomite Bed of the Zohar shows the dewatering, lithification, and erosion of these carbonate sediments before they were dolomitized.

CARBONATE PETROGRAPHY

The Lower and Upper Dolomites in the channeled portion of the Zohar Formation at Makhtesh Qatan have a distinctive petrographic appearance first described by Gill (1966) and Goldberg (1967). The crystals are zoned rhombs with layers of limonite, generally about 0.1 mm in diameter (Fig. 4). They are classic examples of "dedolomitization", or "dolomite rhombs with a core and/or zones replaced by calcite" (Thériault and Hutcheon, 1987, p. 956, who preferred the term "calcitization"). Goldberg (1967) showed that the western equivalents of these units in Makhtesh Qatan are biosparites and that there is a transition zone towards the east as they become increasingly dolomitized. The cement between the bioclasts and the rhombic crystals is calcite in the non-dolomitized and transitional sections, and completely dolomitized in the dolomite sections.

Goldberg (1967) hypothesized that the original biosparites were cemented by aragonite (using the standard understanding of carbonate precipitation at the time), and that the aragonite cement was converted to calcite by subaerial diagenesis. The dolomitization then took place later through the seepage reflux of magnesium-rich brines, possibly associated with (unrecorded) sabkha deposits above. "Dedolomitization" likely took place as a replacement phenomenon when these units were exposed to meteoric waters during the Early Cretaceous, the Neogene, or the Pleistocene.

We now know that calcite was the likely original inorganic carbonate precipitate in these sediments because the Jurassic was a time of calcite sea sedimentation (see Palmer and Wilson, 2004, for a review of calcite seas and their associated petrographic manifestations). These sediments were likely cemented by calcite in the shallow subtidal waters, as was common in Jurassic carbonate environments (see Wilson and Palmer, 1994, for one of many examples). The cemented units were next exposed in the intertidal zone, then dissected by erosional channels (see below) and bored by bivalves (*Gastrochaenolites*). Since the bivalves could not bore dolomite, we know the dolomitization came later, maybe much later, than this depositional cycle.

The origin of the "dedolomite" is the key to the later diagenesis of the Upper and Lower Dolomites. Do the zoned crystals represent dolomite that was formed in one diagenetic interval and then replaced by calcite in another? Or were they formed during the same diagenetic episode? Most of the literature supports the later replacement model to explain the calcitization of dolomite (see Thériault and Hutcheon, 1987, and references therein). This replacement was mediated by fluids generated by either subaerial exposure (e.g., Back et al., 1983) or during burial (e.g., Budai et al., 1984). There is some dissent from the replacement hypothesis, though. Katz (1971, p. 45), writing about zoned dolomite crystals in general, stated that "the texture of the calcian and ferroan dolomite zones and their crystallographic orientation ... show that they represent growth stages of the dolomite crystals". This is a position also recently held by Deelman (1999, 2005). It is possible that the same event, such as subaerial exposure, may have formed the zoned rhombs in the Zohar by a fluctuation of magnesium-rich and magnesium-poor diagenetic fluids. The dolomites in Makhtesh Qatan may thus not require an association with overlying sabkha sedimentation.

THE CHANNELS

The top surfaces of both the Lower and Upper Dolomite Beds are deeply dissected by channels, first described by Gill (1966) and Goldberg (1967). The channels in both units range from one to two meters in width and up to a meter in depth, with the dimensions varying considerably depending on erosional exposure (Figs. 5 and 6). They have rounded edges and bottoms. The channels in the Lower Dolomite are only intermittently exposed; those visible show Y-shaped branching junctions and broad, flattened floors. The channels in the Upper Dolomite are very well exposed on the floor of the makhtesh and can be more completely described.

The Upper Dolomite channels are in two sets intersecting with each other at nearly right angles. The channels are mostly straight, with one set trending approximately 330°–150° and the other 60°–240°, but some gently curve in broad arcs. The intersecting channels produce raised rectangular blocks between them roughly 2 × 3 m. The channels themselves have U-shaped cross sections. The sides of the channels have a few rare *Gastrochaenolites* borings, primarily in the upper 20 cm. These borings are eroded so that

Fig. 5. Channels on the top surface of the Upper Dolomite unit of the Zohar Formation in Makhtesh Qatan. The students are pointing to the present north.

Fig. 6. Channels on the top surface of the Upper Dolomite unit of the Zohar Formation in Makhtesh Qatan.

most show only the distal portions of the clavate excavation. Where preserved, the channels in both units are filled with a dolomitic silty shale that appears to have been deposited in a marine lagoon. Since these shales in the Upper Dolomite channels are sometimes capped by the thick Cretaceous laterite above, it is clear that they are also Jurassic in age.

Goldberg (1967) noted, and we have confirmed, that the channels in both the Lower and Upper Dolomite Beds have joints exposed in the center of the channels running their lengths. These joints have the same general orientations in these dolomites (330°–150° and 60°–240°) as they do in other competent beds lying below. The channels thus appear to be joint sets that have been widened by erosion. The primary erosive agents were likely tides, waves, and bioerosion, as shown by the marine *Gastrochaenolites* borings in their sides.

DEVELOPMENT OF THE ROCKY SHORE

The trace fossil *Planolites* indicates that the carbonate sediments that formed the Lower and Upper Dolomite Beds were originally deposited in a shallow subtidal environment with high levels of water saturation and oxygen. The succeeding generations of *Thalassinoides* traces with their sharp boundaries indicate that the sediments were becoming firmer and less water saturated. This may be due to a drop in overlying sea level, the beginnings of early seafloor cementation, or a combination of both. The sediments were next completely cemented, forming a subtidal carbonate hardground. Relative sea level then dropped low enough to expose this hardground in the intertidal zone as a rocky shore. At the same time, regional stresses produced two joint sets perpendicular to each other. These joints provided weak zones which were preferentially eroded by tidal currents and waves, augmented by bivalve bioerosion. Later, relative sea level rose again, submerging this channeled rocky shore under quiet subtidal waters. This sequence occurred twice to produce the lower and upper units. Later, possibly in association with exposure and erosion of this sequence in the Cretaceous, these channeled rocky shore limestones were dolomitized and then calcitized to form the distinctive dedolomite texture.

Comparison with other Jurassic Rocky Shores

Johnson (1988, 1992) pioneered the study of rocky shores and their deposits in the geologic record, in the process making clear that while never abundant, ancient rocky shores are preserved far more often than previously expected. The key is to look for fossil evidence of rocky shore organisms (such as oysters, barnacles, particular borings, and so forth) and rocky surfaces at unconformities that may have been truncated by littoral erosion. This exposure of the Zohar Formation in Makhtesh Qatan easily meets these criteria of an ancient rocky shore with its channeled dolomites and trace fossil evidence of lithification and intertidal exposure.

Carbonate hardgrounds are common in the Jurassic System because of the prevailing calcite seas conditions, which facilitated early cementation of carbonate sediments in shallow waters (see for review Wilson and Palmer, 1992, and Taylor and Wilson, 2003). Exposure of these substrates as rockgrounds in the Jurassic intertidal is much less common. The closest analogue may be a Lower Carboniferous limestone in Wales and England, which was exhumed during the Middle Jurassic, encrusted with corals and oysters, and bored by bivalves (forming *Gastrochaenolites*) and worms (Johnson and McKerrow, 1995; Cole and Palmer, 1999). In some locations this limestone surface even has channels similar in size to those of the Zohar (Johnson and McKerrow, 1995, fig. 3c). There are also karstic Jurassic surfaces in Scotland (Farris et al., 1999) and Germany (Helm, 1998) that are similarly encrusted and bored. The Zohar sequence is thus far the only such Jurassic rocky shore known from equatorial latitudes. With further study it may yield additional evidence of the organisms that inhabited it, which will be important data for the general understanding of hard substrate community evolution (Johnson and Baarli, 1999; Taylor and Wilson, 2003).

PALEOENVIRONMENTAL IMPLICATIONS

We can now place a shoreline of the Tethys in southeastern Israel during the late Middle Jurassic (Callovian). It developed by a combination of early cementation and dewatering of carbonate sediments in a normal marine setting, followed by a drop in relative sea level. The paleoenvironment was probably much like that of a low-relief rocky shoreline on the eastern coast of equatorial Africa. We no longer require a sabkha environment to explain the "mega-mudcracks" of Goldberg (1967) because they are the normal marine trace fossil *Thalassinoides* and joint-controlled tidal channels excavated in exposed limestones.

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