# Fill Patterns of Evaporitic Half-Graben Basins, Late Triassic Mohilla Formation, Southern Israel*

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## Abstract

Sediment fill in half-graben basins on rift-edge faults were found to record signals from repeated structural movements, from sea level change, and from a climate signal, often rhythmic. High sensitivity carbonate-evaporite successions strongly record each of these signals as the basin evolves.

The Late Triassic (Carnian) Mohilla Formation was deposited within small (10-20 km wide, 20-60 km in length) half-graben basins situated in a chain along the Levant shelf-edge of the Triassic. Patterns of sedimentation were found that were common to the Ramon outcrops and to the Kurnub, and Qanaim basins penetrated by boreholes. Basin fill is characterized by two main end member facies: an evaporite-rich succession ca. 200 m thick found in the basin center, and a carbonate succession of half this thickness on the barrier. These end members are sometimes juxtaposed near basin-edge faults, with the evaporite facies on the hanging wall side and the carbonate facies on the footwall side. The evaporite succession commences with a lower dolomite, followed by a middle evaporite unit, and terminated by an upper limestone; the carbonate facies is more monotonous. The upper and lower carbonates are mainly microbialites, interspersed with subaerial exposure horizons and marine intercalations.

Control on fill patterns of multiple orders as the Mohilla Fm small basins evolved, may be traced to eustatic, climatic and local tectonic rhythms affecting the flux of fresh and marine waters into these basins. Three orders of basin fill processes were recorded in the Mohilla Fm - long-term eustatically-related restriction and reflooding; intermediate scale fill patterns, with carbonate/evaporite ratios controlled by climate; and short term fill events attributed to movement on basin edge faults. When the barrier is submerged, carbonates dominate from the barrier edge to the basin center; when it is exposed, evaporites are deposited in the basin center.

Climate variability governs intrabasinal sedimentation dynamics. Runoff episodes yield increased siliciclastics, especially shales, and increased proportion of carbonates vs. evaporites within the basin. Changes in carbon isotope ratios in the carbonates were found to track these episodes.

## Introduction

The Mohilla Formation in Israel includes Late Carnian (Late Triassic) evaporite-bearing strata deposited on the northern margin of the Arabian plate. Regionally equivalent evaporites occur in Jordan, Syria and Iraq (Ziegler 2001; Sharland et al., 2004; Makhlouf & El-Haddad, 2006), but the Mohilla evaporites differ in that they are usually spatially limited to basins several tens of kilometres in length at most (Druckman, 1974; Bialik et al. In prep.).

Given the high rate of sedimentation of evaporite systems (Schreiber and Hsü, 1980), the many changes occurring in the Tethys region at this time (Simms and Ruffell, 1989; 1990), and climatic transitions between humid and arid (Stefani et al., 2010), the Mohilla Fm provides a unique high-resolution window to environmental changes occurring on the northern Gondwana margin. In particular, response to events of regional climate vs. local tectonic origin are strongly represented, as the small size of the basins makes them more sensitive to small scale events, compared to epicontinental or oceanic basins.

## Aims

This study was aimed at tracking evolution of the sedimentary environment of the Ramon and nearby basins during the Late Carnian, using vertical and lateral facies and lithological changes as proxies for effects of climate, tectonic and sea level change.

## Materials and Methods

The study was centered on the northern Negev in southern Israel (Figure 1). The Mohilla Formation is exposed in outcrops at Makhtesh Ramon, along with three boreholes. The Avdat 1, Nafha 2 and Boqer 1 boreholes were selected as they are located along a traverse from the landward edge of the proximal Ramon basin, towards a more distal seaward position. Mesoscale (hand sample) features were observed in the outcrops, including recognition of exposure features. Following high-resolution sampling, microscale features were recorded from thin sections from field material and borehole cuttings.

## Results

The Mohilla Formation in the Ramon outcrop is 172 m thick, of which the M1 Member is 31.7 m, the M2 Member is 100.5 m, and the M3 Member is 34.8 m. The lithofacies is mainly carbonate, with evaporite present in M1 and M2 as well as some shale (Figure 2, col. B). Depositional environment indicating facies sets rapidly alternates within the unit, resulting in 53 cycles that can be recognized in the outcrop (Figure 2, col. C and D). M1 is mainly dolomite, with two horizons that include some evaporites and five exposure horizons that are recognized by meteoric diagenetic features. Restricted environments are evident by poorly diverse microfauna, and by stromatolites. The first sabkha surface, passing laterally into a truncation surface, is found at the transition from M1 to M2. M2 is a thick succession composed of rapidly alternating beds of dolomite, gypsum and shale, mostly barren of biota, and there were only three exposure events. M2 passes to M3 across a small angular unconformity marked by a 5m shale bed. M3 is composed of bedded mudstone and peloidal packstone between stromatolitic bioherms that were periodically exposed. Environments were monotonous and restricted, with poorly diverse microfossils. In total 12 cycles of exposure and reflooding are represented in the Ramon outcrop, half of them in M1 (Figure 2, col. D). The top of M1 represents a significant change in the environmental settings and bears evidence of a major exposure event, suggesting this boundary represents a sequence boundary.

In the Boqer 1 borehole, the Mohilla Formation is 177 m thick (2,206-2,383 m), of which M1 is 21 m thick, M2 is 114 m thick, and M3 is 36 m thick. M1 is mainly limestone and dolomitic limestone with one anhydrite interval. Diagenetic features that may indicate exposure are present in the upper part of the unit. Carbonate facies include mudstone and packstone with echinoderms, foraminifera and thin-shelled bivalves. M2 is mainly dolomite/anhydrite mixture alternating with dolostone and shale. One event of exposure is identified in this unit. M3 is mainly limestone alternating with shale and dolomitic limestone with foraminifera. Near the top of the unit, vugs and meteoric cements are present and possibly some breccias.

The Mohilla Formation is only 64 m thick in the Avdat 1 borehole (1,969-2,033 m), consisting mainly of dolomite and limestone, alternating with thin shaley horizons. Facies range from mudstone to grainstone with cortoids and peloids. Microbial lamination, probably stromatolitic, is present in the lower half of the unit. Biota include green algae and foraminifera. Division into members is not possible as the lithology is fairly constant, but based on packing and facies, three intervals can be recognized in the carbonates: mudstones with some pyrite (1,969-1,984 m); packstones and grainstones (1,984-2,026 m); fossiliferous mudstones and packstones (2,026-2,033 m).

Vugs and meteoric cements are present in five intervals: 1,978-1,984 m, 1,987-1,993 m, 2,005-2,008 m, 2,014-2,017 m and 2,023-2,033 m – suggesting at least five events of subaerial exposure.

In the Nafha 2 borehole, the unit is 84 m thick (1,290-1,377 m). It is mainly dolomite, at times interbedded with quartz silt and shale. Mudstones and mudstone with quartz silt are dominant among the carbonates, also with stromatolites and ooid grainstone. Five exposure horizons are indicated by breccias, possible flat pebble conglomerates, and intervals of vugs and joints filled with meteoric cement. Three of these horizons are underlain by ooid grainstone and stromatolites. Pyrite is present. Again, the Mohilla Formation is not subdivided into members here, as the lithology is fairly constant.  Packing and facies changes suggest three main intervals: mudstone (1,290-1,317 m); ooid packstones, cortoids and stromatolites with evidence of subaerial exposure (1,317-1,359 m); and again mudstone (1,359m-1,377 m).

## Discussion

The Mohilla Formation can be divided into three parts in all the sections. At Ramon and Boqer 1 these are the members M1, M2 and M3 of Zak (1963). These members were originally identified as a lower pre-evaporite dolomite, a middle evaporite and an upper carbonate unit. More to the northwest, the evaporite-free Avdat 1 and Nafha 2 boreholes continue this three-fold subdivision, but based on facies properties rather than lithology, with the middle subdivision represented by carbonates formed under relatively more energetic conditions. In the most distal section at Boqer, the Ramon pattern was resumed. In this way, it is possible to correlate between the various localities (Figure 3).

Changes in thickness can be observed at all scales, albeit these changes are somewhat reduced in the M3 member. The bulk of the missing M2 evaporite member in the Avdat 1 and Nafha 2 boreholes is related to non-deposition of evaporites outside the basin centers.

There is some basis for a relationship between deposition of evaporites and relative sea level (RSL) change (Bąbel, 2004). The number of exposure events in the distal Boqer 1 borehole is substantially less then at the inland locations. The exposure events for the most part bound the evaporite parts, probably representing the completion of the base-level-fall cycle of evaporite deposition followed by basin fill. The simple explanation is that in inland basins, carbonates are the response to high RSL in all settings, while within inland basins, increasing restriction and accommodation fill generates first evaporites and then shales during low RSL (Figure 4). Tectonic activation of the barrier or high-frequency climatic changes can affect water (marine or fresh) input into the basin, thus generating rapid changes in the local sedimentary settings, and forming the high-order TR cycles observed at Ramon.  Likely, high-resolution cycling is present in the other boreholes but would be invisible in the carbonate-only session regardless of the detail of the well-log data. The larger scale of change resulting in exposure is of lower frequency, and could have been due either to an isostatic, or more likely to a eustatic mechanism.

The M1 member at Ramon (Figure 2) demonstrates sharp changes in depositional environment, small amounts of evaporites, and multiple exposure features with evidence of meteoric diagenesis. In the Nafha 2 borehole, only a single exposure surface within M1 can be identified, while only the uppermost one is found in Avdat 1. There the changes in thickness are greatest and the unit was truncated and exposed, a regressive setting indicating relative low RSL.

M2 of the Ramon outcrop and Boqer 1 boreholes comprises interbedded evaporites, shales and dolomites and is fairly thick. At Avdat 1 and Nafha 2, the thin middle unit is proportionate in thickness to M2 at Ramon but is indicative of relatively high water energy on the basin margin during rising sea level. Formation of evaporites within the basins requires filling of pre-existing accommodation space (Schreiber et al., 2007) at the time of RSL rise. These are therefore transgressive evaporites (cf. Schlager, 2005).

Finally, M3 is monotonous carbonate, and changes little in thickness and the indications for low water energy.  Avdat 1, Nafha 2 and Boqer 1 have mudstones containing pyrite indicating oxygen deprivation, although the Ramon outcrops show this unit to be rich in stromatolites indicating photic conditions. Exposure events occurred only near the base of the unit and only at the more proximal Avdat 1, Nafha 2 and Ramon successions, corroborated by dominance of stromatolites. This suggests a RSL rise or high RSL with water depth low. This configuration implies that M1 represents a lowstand systems tract; M2 is a transgressive systems tract, possibly with tectonic augmentation to generate the barrier and the accommodation space (Bialik et al. In prep), while M3 represents a highstand systems tract (Figure 5).

## Conclusions

Multiscale control on deposition of the Mohilla Fm in the Ramon and adjacent basins during the Late Carnian encompasses paleostructural, climatic as well as RSL elements. As RSL changes, the unit proceeds from LST via TST to HST, with higher order cycling of sea level change overprinted by climate. Short-term cycling follows climatic cycling overprinted by paleostructural movements.

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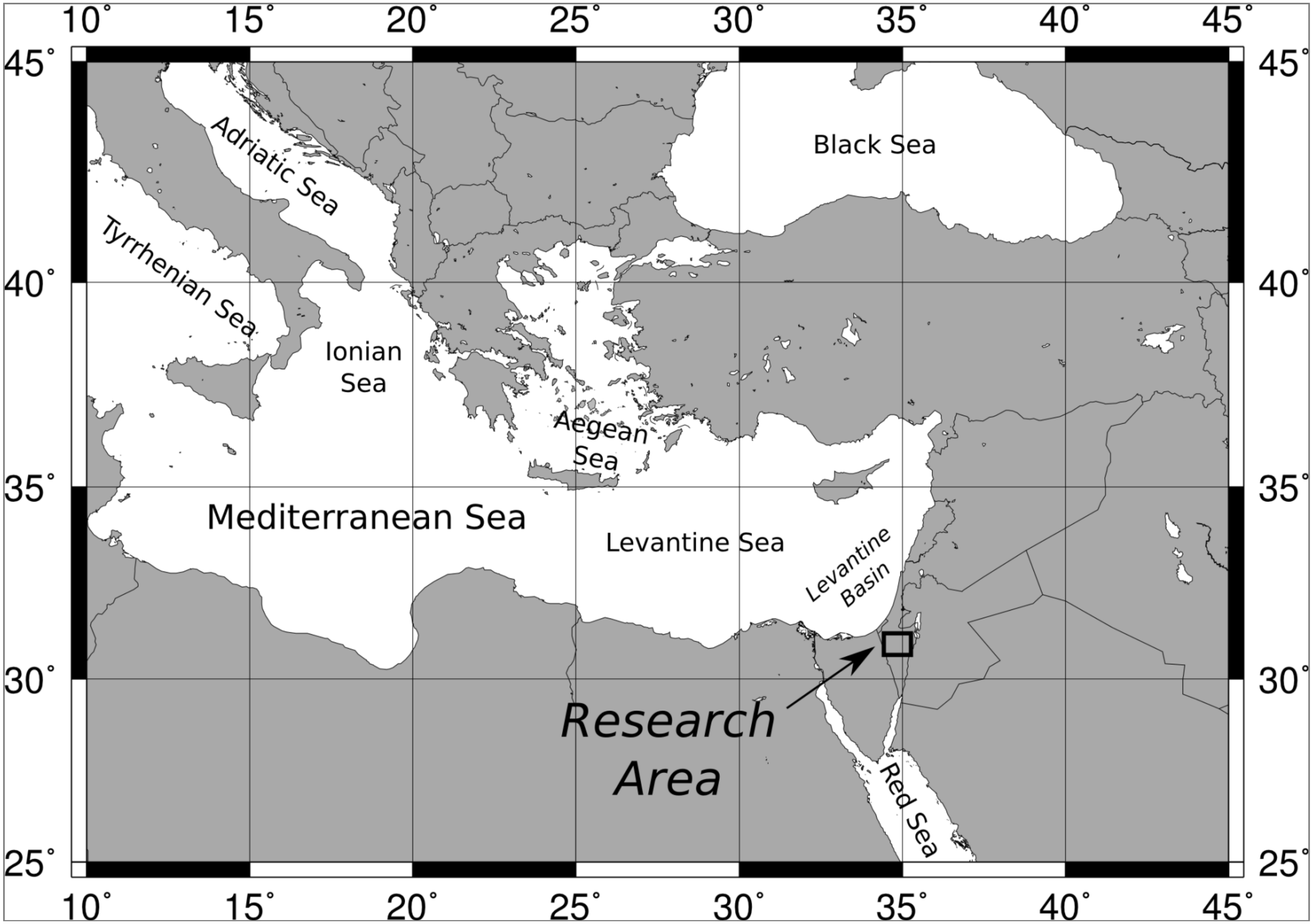


Figure 1. Location of research area.

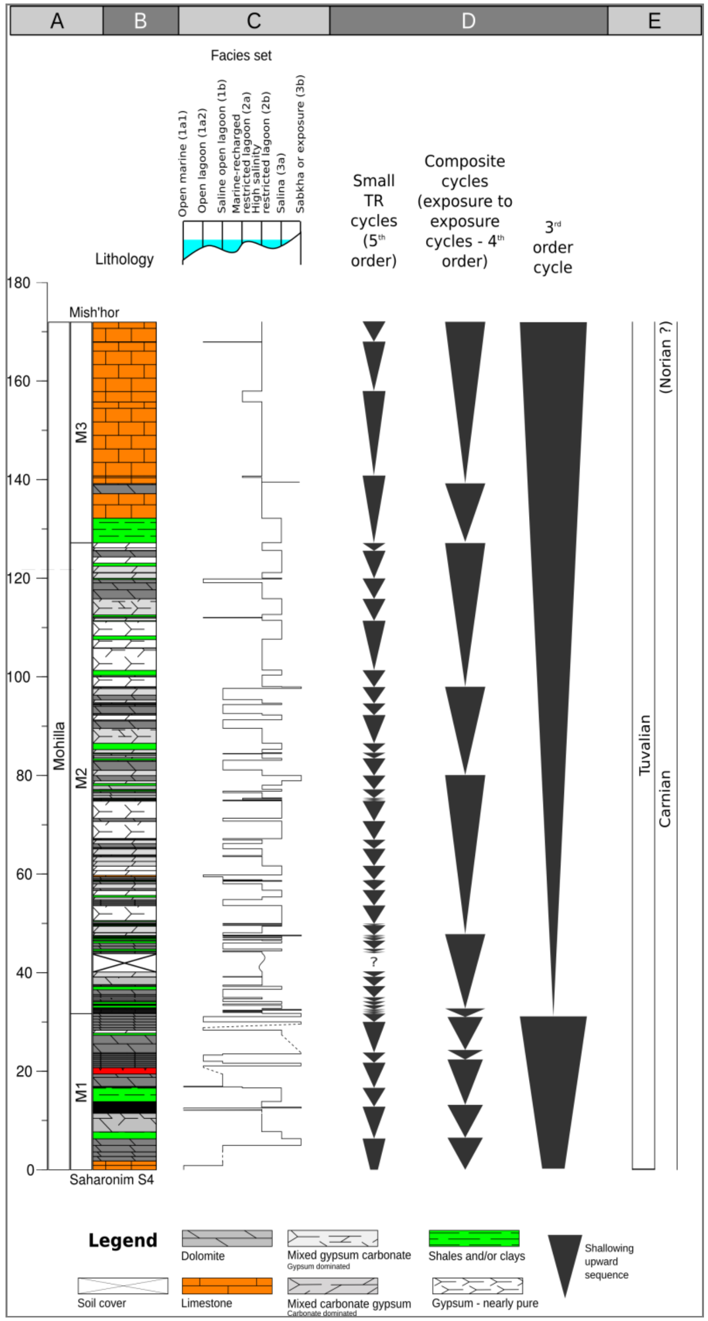


Figure 2. The Ramon outcrop. Column A - stratigraphy; B - lithology; C - sedimentary facies sets, D - deduced cycles derived from the shifts in facies sets; E - geochronology.

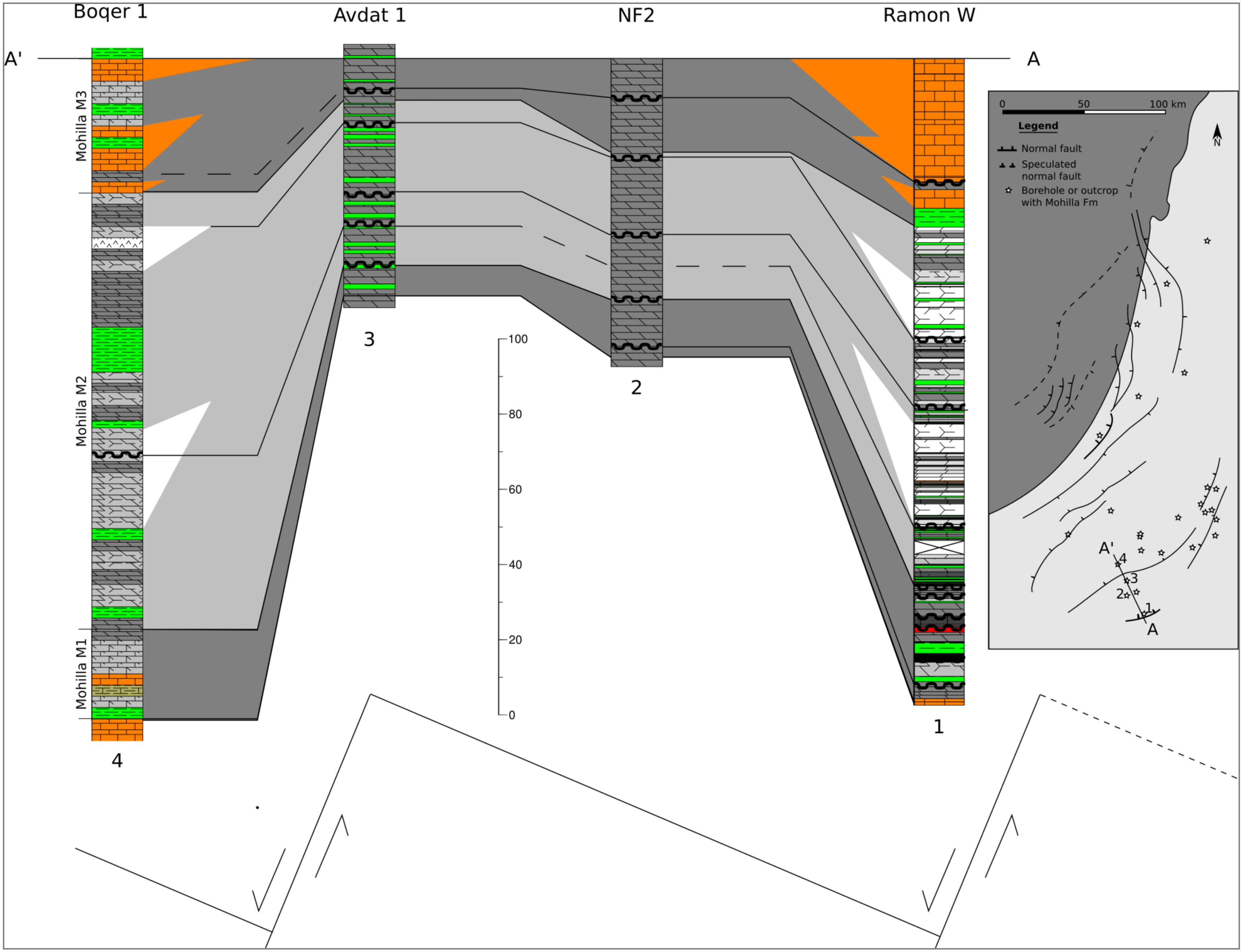


Figure 3. Traverse from SE to NW showing changes in thickness, lithology and correlation of surfaces. See Figure 2 for lithological legend.

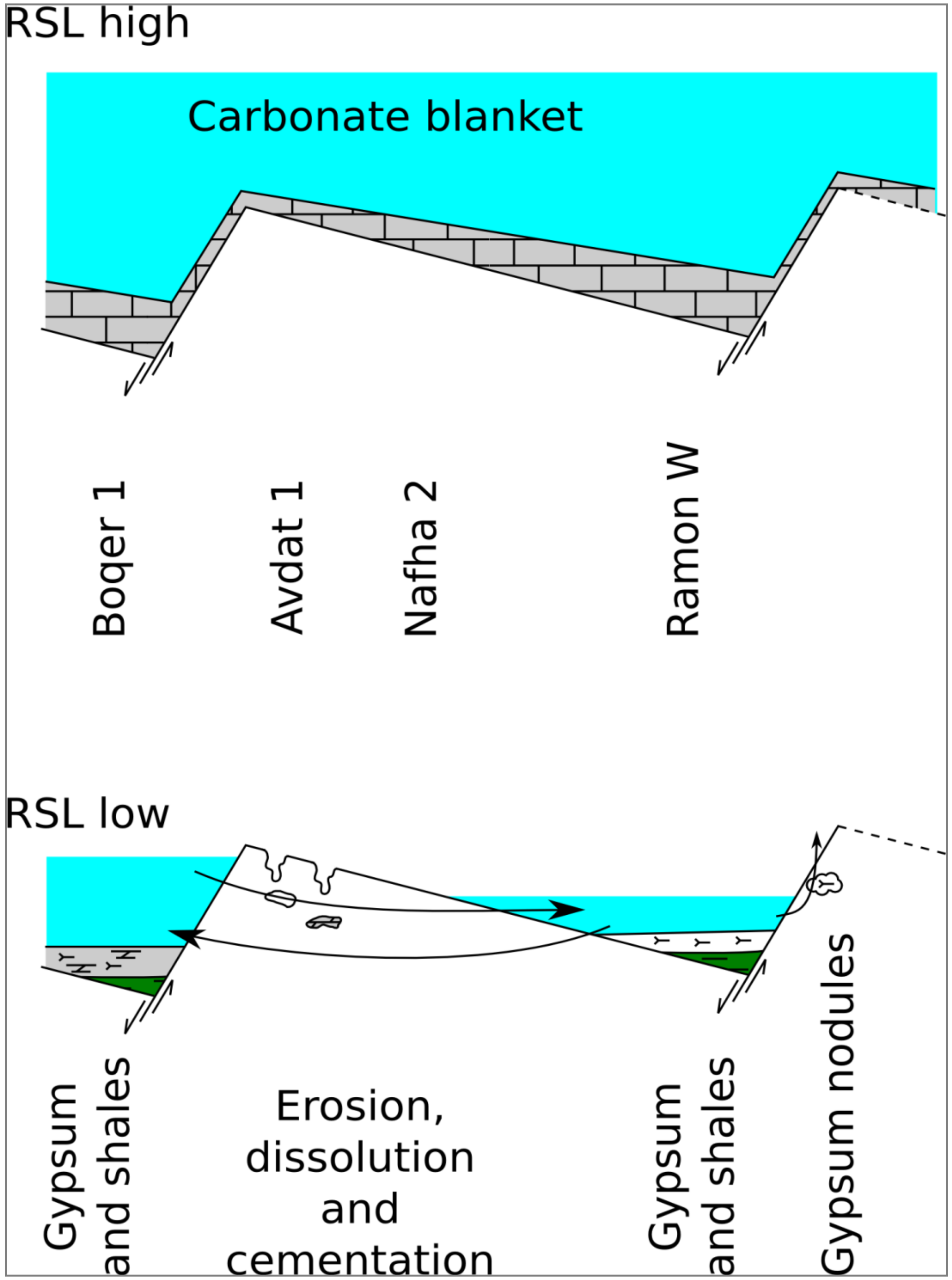


Figure 4. Illustration of the lateral control on the M2 member with changes in RSL. High RSL will result in blanketing of carbonate, possibly limited by distal restriction and initial composition. Low RSL will result in shale or gypsum, depending on climate.

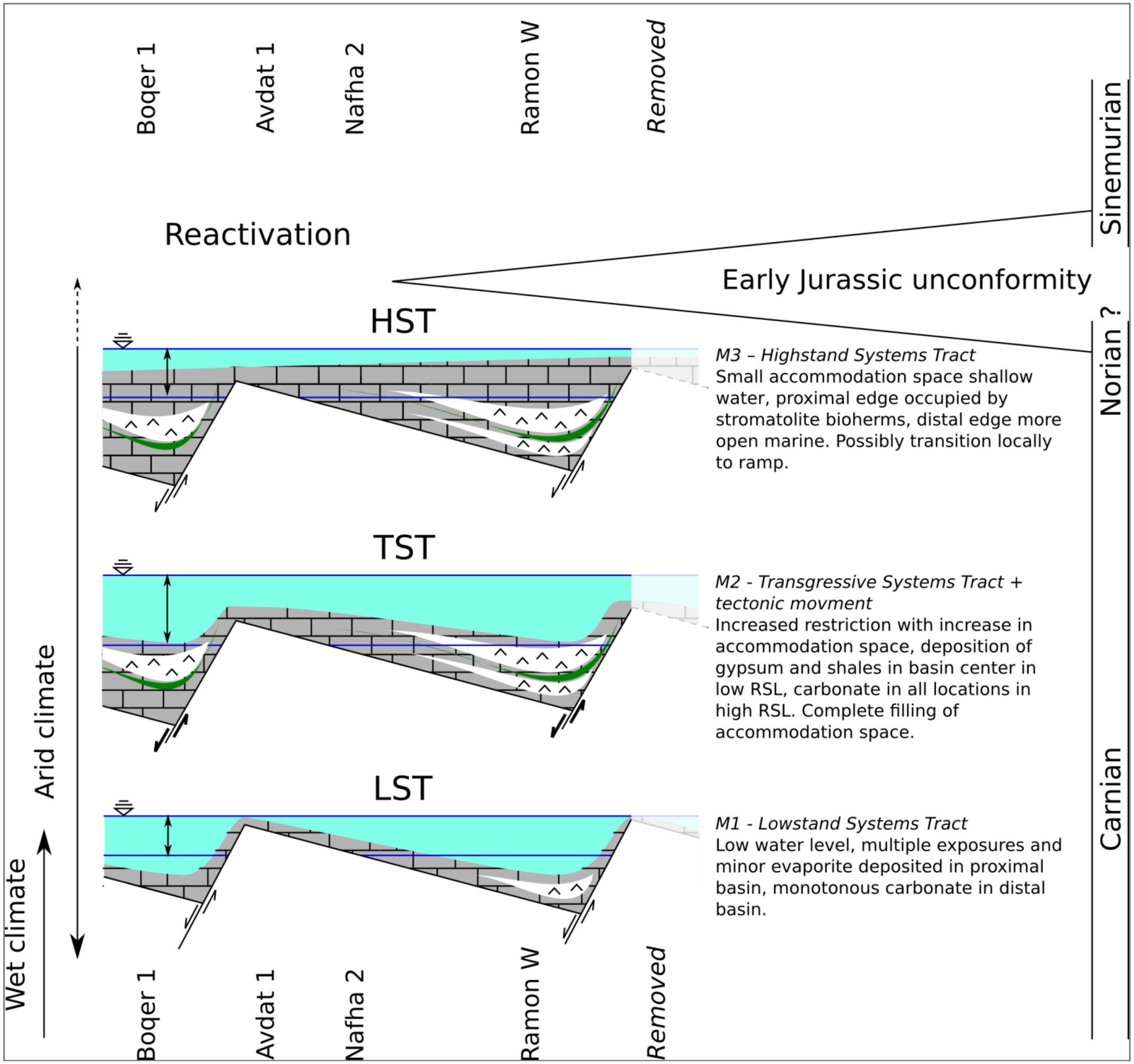


Figure 5. Concept model for the basin fill of the Ramon basin within a tectonic/ sequence stratigraphy framework.