# MORPHOLOGY AND DYNAMICS OF CRESCENTIC BAR SYSTEMS

by

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ABSTRACT : Aerial photograph and field studies in the southeastern Mediterranean, involving bathymetric mapping, and concurrent and antecedent wave measurements, have been used to delineate the sequential development of crescentic bars and associated dynamics. The bar sequence includes multiple parallel or wavy bars, ridge and runnels, oblique/transverse bars, single crescentic and double crescentic bars, and occurs during a calming down of wave activity from 2.5 to 0.5 m waves. The concomitant wave data, including wave directions, energy spectrum, significant wave height, and length of the calm period, showed strong correlation with the bar stages.

An increase in total bar occurrence during summer is related to a major wave energy decrease in the spring, when significant wave heights ($H_s$) $\leq$ 1 m sharply increase to 70-85% in April-May. Inner single crescentic and initial double-crescentic bars are largely restricted to the calmest wave months of May/April to October/November, which reflects their sensitivity to wave energy. The aseasonal occurrence is best shown by the mature double crescentic type, which apparently is the final stage in the crescentic bar development sequence.

Two bar developmental sequences were delineated: one shore-normal and the other initially oblique, but gradually rotating to shore-normal in the mature stage. Out of phase relationships between inner and outer bar systems resulted from the lag in response of the outer bars behind changes in wave direction. Among the inner crescentic bars and shore rhythms, phase-correlation was the rule.

Crescentic bars are well developed on this coast because of the dissipative conditions and the distinct wave climate. High waves in the winter remove the existing bars, and extended calms allow the full development of the crescentic bar sequence. Similar bar types occur on different coasts in different sequences and in different proportions of time. Thus, it is suggested that these differences are attributable to global differences in the occurrences of threshold wave height conditions.

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INTRODUCTION : During the past 15 years, several studies have attempted to define the specific dynamic conditions promoting the development of crescentic bars (e.g. Bowen & Inman, 1971; Greenwood & Davidson-Arnott, 1975; Owens, 1977). A global bar classification was proposed (Greenwood & Davidson-Arnott, 1979) including ridge and runnel, cusp, multiple parallel, transverse and straight bars, as well as sinuous to crescentic bars.

Recently it was shown that crescentic bars occur within a bar developmental sequence on both high wave energy macrotidal coasts (Short, 1979; Wright et al., 1979) and moderate wave energy microtidal coasts (Goldsmith et al., 1982). On the high wave energy Australian coast, Short (1979) observed that as wave heights decreased from 3 m to 1 m, the accretional bar stage sequence went from a parallel bar and channel to crescentic bars, megacusps, welded bar, and terminated in cusps and berm. Similarly, on the dissipative, moderate wave energy Israeli coast, Goldsmith et al. (1982) observed that as wave heights decreased from 2.5 m to 0.5 m, the accretional bar sequence went from multiple parallel bars to ridge and runnel, transverse/oblique bars, single and then to double crescentic bars. The first concern of this study is to further delineate the wide range of nearshore bars and shoal patterns along the southeastern Mediterranean microtidal coastline, and to widen our knowledge of environmental conditions of the different bar types. The second aim is to delineate the sequential stage developments of meandering-crescentic bar systems at HaHoterim coast, northern Israel (Fig. 1), and to relate this to specific wave parameters.

METHOD : The study includes all available air photos of the southeast Mediterranean taken in the period 1949-1980. Accordingly, 123 flights showing 150 clear coastal segments were available for bar pattern recognition. Also, a series of eight consecutive maps of the nearshore zone and beach at HaHoterim were made for depicting the bathymetry, rhythmic topography, and sequential bar development. Twenty-two repetitive overflights were conducted, twelve of which were taken at regular weekly intervals.

The air photos were compared to concomitant wave data, up to 60 days prior to each air photo date. The energy spectrum was computed for each digitized wave record, twice a day for one year, using a Fast Fourier Transform algorithm described in Clairbout (1976). The equations from Goda (1974) were used for height and period statistics.

THE SOUTHEASTERN MEDITERRANEAN : The 270 km long study area (Fig. 1) is a relatively smooth coast, with beaches generally narrowing to the north (Goldsmith, in press). Submerged and eroded eolianite remnants occasionally compose rocky outcrops in the inshore and along the water line. Haifa Bay is the northern border of the quartz sedimentary province of the Nile delta (Goldsmith & Golik, 1980). Well-sorted medium beach sand decreases in size from Egypt northwards to Tel-Aviv (Emery & Neev, 1960). Calcium carbonate is 6-8% in southern Israel, and is 65% of the sediment at HaHoterim, south of Haifa. At HaHoterim the beach sand is medium size (1.82 $\phi$), moderately to well-sorted (S.D. = 0.45 $\phi$), slightly negatively skewed and mesokurtic (Gwirz, 1982).

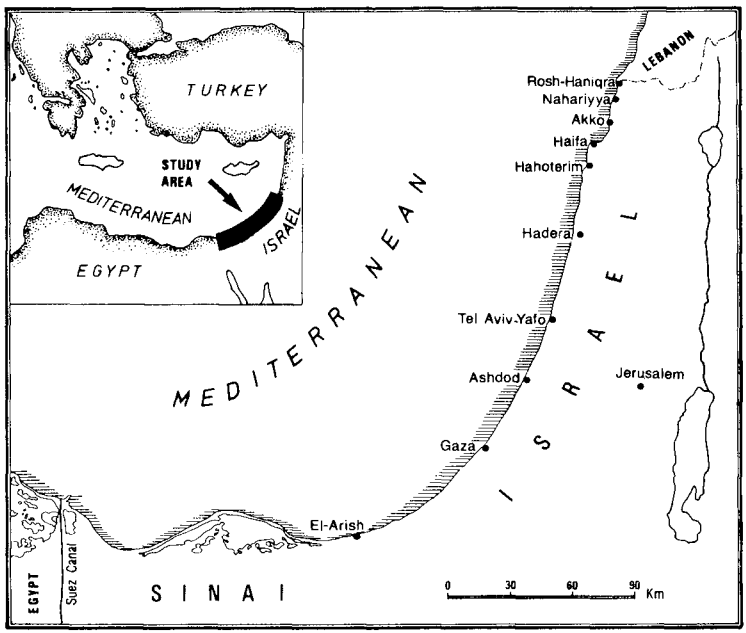


Figure 1. Location of study area in the southeastern Mediterranean.

The wave climate consists of three wave seasons (Goldsmith & Sofer, 1983): the highest wave months are December-March ($\bar{H}_s$ = 1.0 to 1.5 m); the lowest wave months are May, September-October ($\bar{H}_s$ = 0.6 to 0.8 m); and the intermediate wave months are June-August. The winter wave months are dominated by storm fronts passing at an average of 5-7 day intervals. Maximum winter significant waves reach 5 m and 13 sec, although only about 10% of $H_s$ are $\geq$ 2 m high.

The same nearshore slope gradient of 0°20' to 1° dominates the nearshore. However, the slopes of the offshore facing bar flanks are considerably steeper, ranging from 1° to 5°. The Israeli coast, in spite of its low to medium wave height, and because of its high wave steepness and low mean beach gradient, falls mainly within the dissipative regime with $\varepsilon >> 33$ (Bowman & Goldsmith, in press). Field evidence for the extremely dissipative character is provided by the relatively wide (100-300 m) barred inshore, segmented into longshore sub-regions of troughs and shoals, and by the rhythmic beaches, abundant bar-types and dominant spilling breakers.

BAR MORPHOLOGY : The bars observed along this coast may be grouped within three distinct "families" (Bowman & Goldsmith, in press).

1. Non-rhythmic parallel bars. During severe storms (i.e., $H_s \geq 2.5$ m), it appears that the crescentic and other bars are destroyed. As the storm waves decrease, multiple parallel bars are discerned first by the multiple breaker lines, and then they are observed directly. These bars may be straight or meandering. Since during severe wave conditions the whole nearshore zone is filled with breaking waves, it is very difficult to determine the bar patterns. Nevertheless, it is clear that pre-existing bar patterns are completely removed. Observations made by helicopter appear to indicate that the multiple parallel bars form and migrate shoreward only when waves decrease to $H_s \leq 2$ m and when the strong rip current systems ameliorate. The rip current systems were observed to migrate in the longshore direction. During less severe storms ($2 > H_s \geq 1$ m), pre-existing crescentic bars are modified, but not totally removed.

As the waves decrease, the bars migrate shoreward. As the most landward bar approaches shore, it tends to migrate onshore non-uniformly in the form of a ridge and runnel, and portions of the ridge weld onto the beach, resulting in non-uniform widening of the beach.

2. Single crescentic bars. Initially oblique and transverse bars form, resulting from the non-uniform widening of the beach. Within a few days, and with wave heights $H_s < 1$ m, the seaward ends of the bars connect to form crescentic bars, while simultaneously, the landward ends of the oblique/transverse bars become detached from the shore (Fig. 2). The beach is usually in phase with bar cyclicity, forming a dominantly cuspoidal shoreline.

3. Double crescentic bars. Double crescentic bars form when low wave heights persist for several weeks after the single crescentic bars are formed (Fig. 2). The inner system consists of embryonic crescents

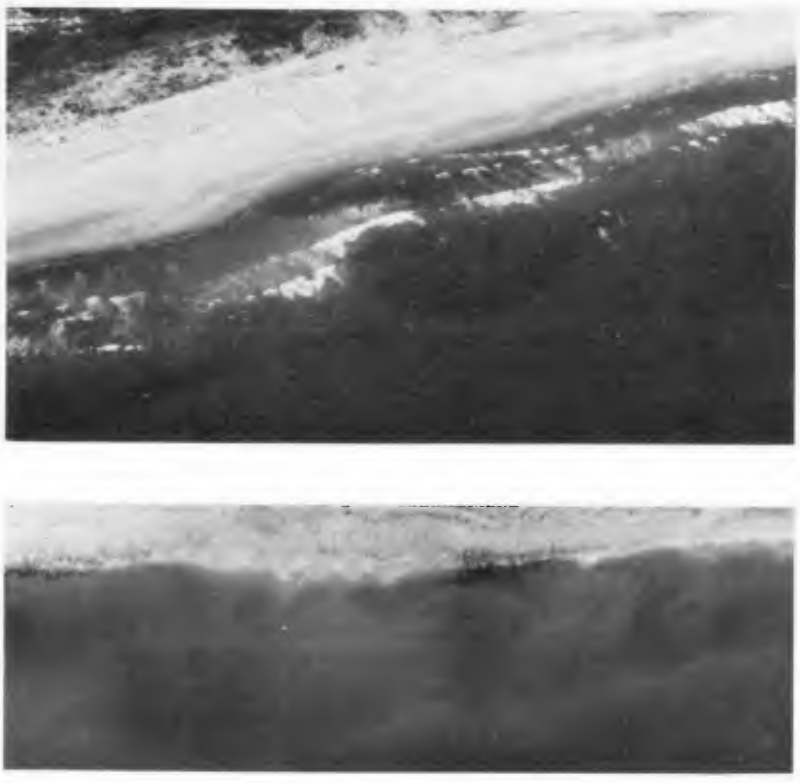

Figure 2. Single crescentic (top) and double crescentic (bottom) bar systems along the Israeli coast.

extending across the seaward end of recurring small rip channels. Wave data indicate that the formation of these inner double crescentic bars is preceded by a short energy pulse of $1.0 > H_s > 0.5$ m of a few hours to a day duration. In the mature stage they extend more than half way across the inshore width (i.e., between the shore and the initial single crescentic bars).

Phase correlation between the inner and outer bar systems is usually not evident. Since the inner crescentic bars form at a different time and under different wave conditions than the outer crescentic bars, one set may be either skewed or symmetric, differently than the other set. Groins and other coastal structures interfere mainly with the inner bar systems, whereas the outer bars often remain continuous and undisturbed.

BAR SEQUENCES : The sequence of bar developments, which was observed by mapping, overflights, and study of the historical aerial photographs, is summarized in Figure 3. The sequence includes, in order: multiple bars, ridge and runnels, transverse/oblique bars, outer crescentic and nested inner crescentic bars. The detailed sequence is discussed in Goldsmith et al. (1982).

In the storm stage, the shoreline is irregular, and the rip heads extend 200-300 m from shore. In the post-storm stage, the outer and inner meandering bars block the former rips and feeders, indicating circulation atrophy (Fig. 3, Seq. B). Three main levels of inshore bathymetry are discerned: 1) the deepest, which are the entrenched, stagnant rip channels; 2) shoals, which are the shallowest; and 3) the main accumulative bodies, which are the meandering and oblique bars.

The early stages of crescentic bar development are documented in a box core obtained in a shore-attached oblique bar at a distance of 80 m from shore, at a water depth of 1 m (Fig. 4). Five distinct units are shown. The lowest unit (A) represents an onshore-migrating bar. Unit B displays offshore-dipping foresets, indicating a rip current. Unit C, the thickest and largest unit, displays approximately one-half of a mega-trough, which may indicate a longshore channel or wave orbital scouring. The upper unit (E) again indicates onshore bar migration. The wave history shows that a severe storm ($H_s = 3$ m) occurred three weeks prior to obtaining the box core. Such storms tend to destroy all bars. This suggests that this entire core was formed during a post-storm sequence, although the depth of activity was not documented. The top unit, landward-dipping planar bedding, reflects the asymmetrical shoaling waves, which may correlate with the low waves prior to sampling.

During the extended calm, the sediment fill "blurs" the stagnant rip channel (Fig. 3, post-storm, Seq. B). Nested "micro" transverse bars and cusps, in phase with embryonic rips, dominate the foreshore and the shallow inshore. Also during extended-calm, a new, shore-normal inner microsystem grows out of the former shoals and embryonic rips. The inner system shows discontinuous crescents that match the shoreline microembayments. The inner system becomes less complex, and both bar systems, separated by a trough, are in phase with the shoreline and the trans-

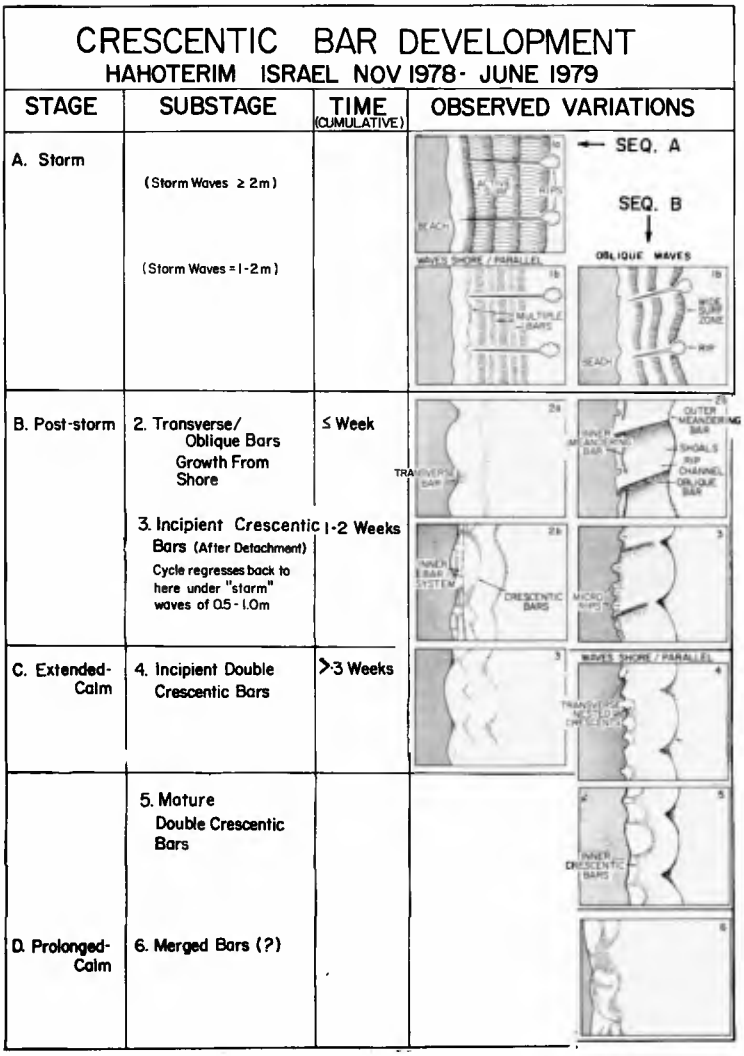


Figure 3. Crescentic bar development and concomitant waves in the south-eastern Mediterranean.

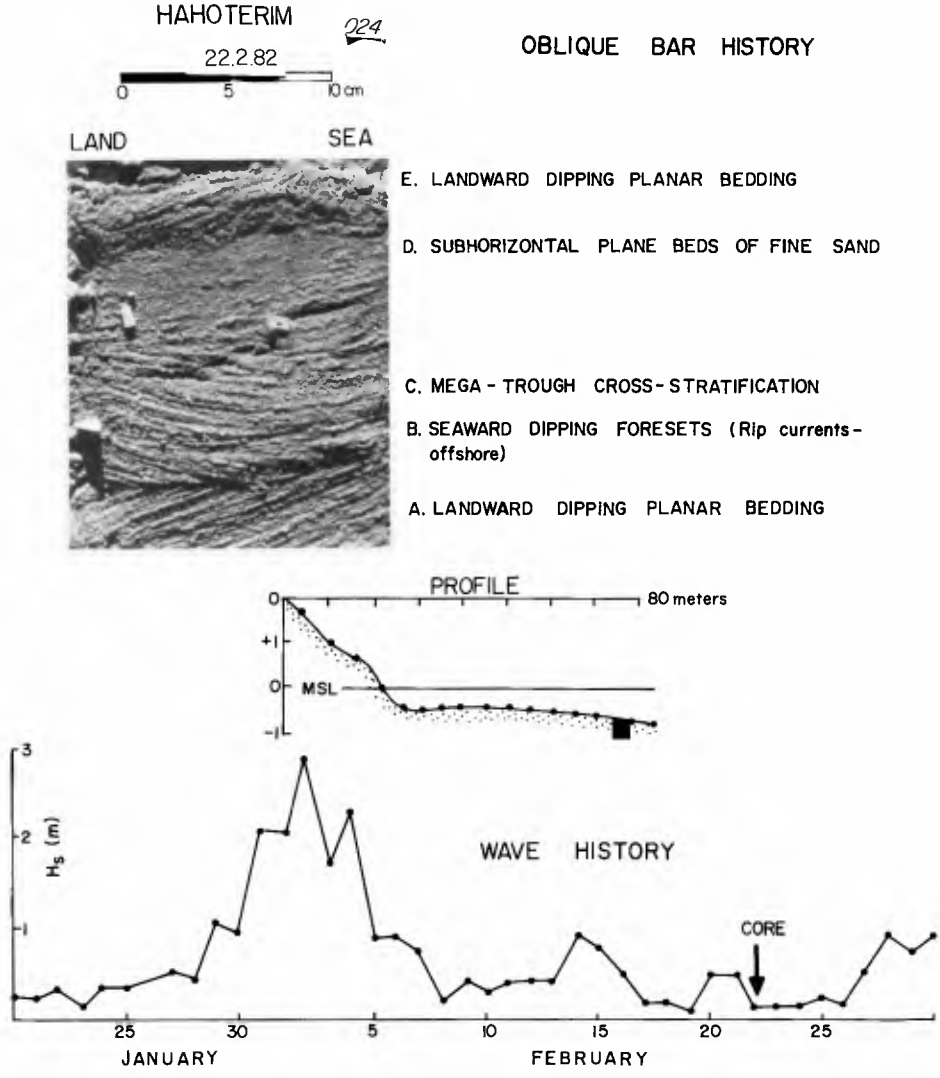


Figure 4. Sedimentation and wave history on an oblique bar, HaHoterim.

verse bars. The outer bars did not evolve during the inner crescentic low energy regime, but persisted from the moderate storms, and should be regarded as inherited. Their "memory" results in out-of-phase relationships between the outer and inner crescentic systems, i.e., the center of the outer crescentic bar corresponded to an inshore shoal, and the outer horns pointed toward an inshore rip channel. Sequence B (extended calm, Fig. 3) indicates the complete removal of the antecedent morphology under the influence of low waves. Phase correlation between the inner bars and the cuspate shore rhythms usually dominates this mature double crescentic stage.

The following wave characteristics were defined coincident with bar stages:

1) Storm, above threshold conditions for bar formation; spilling-plunging breakers, $H_s > 1.0$ m, main range of spectral density $> 10^{-1}$ $m^2$/Hz. These conditions typify stage A.

2) Wave energy conditions decrease below threshold; collapsing-surging breakers, $H_s < 0.5$ m, main range of spectral density $10^{-2}$ to $10^{0}$ $m^2$/Hz. These conditions indicate the start of crescentic development.

3) Calm, $H_s < 0.3$ m, main range of spectral density $< 10^{-2}$ $m^2$/Hz indicating the double crescentic bar stage. Minor storms in the range of $10^{-2}$ to $10^{-1}$ $m^2$/Hz did not modify the double crescentic bar pattern.

BAR AND WAVE SEASONALITY : Although the 150 observations of bars during the 1948-1980 period were spread throughout all months of the year, there is a definite tendency for more bars to occur during the six lowest wave months, June through November (62%), than the remaining six months (Fig. 5A). This tendency is explained by the monthly frequency of low waves ($H_s \leq 1$ m) during the 1948-1978 period (Fig. 5B). The parallelism between months of low waves and the annual distributions of bars is quite striking. Most notable is the increase in bars related to a major wave energy threshold in the spring, when the frequency of $H_s \leq 1$ m sharply increases from 58% in the winter months to 70% frequency in April and 85% in May. The calmer and barred summer composes an uninterrupted period of lower waves, explaining the observed seasonal stability of some of the bar types. Summer shows two peaks of low wave activity (Fig. 5B). May to June composes one low wave peak which, when one allows for the lag time needed for bar formation, is clearly related to the high occurrence of bars in June. July is stormier, and therefore both July and August have fewer occurrences of bars. August and September compose a second summer low wave peak, and this is mainly related to the bar-richest month of September. Thus peaks of bar occurrence and wave energy do not match perfectly, but rather indicate a lag in the adjustment of bars to wave power, also observed by Short (1979).

The mature double crescentic bars occur throughout the year, lacking seasonality (Fig. 6). The single crescentic and the initial double crescentic bars are the most energy-sensitive types, being non-existent during winter but abundant from May to November. Non-rhythmic morphologies also seem to occur most of the year (Fig. 6). The major excep-

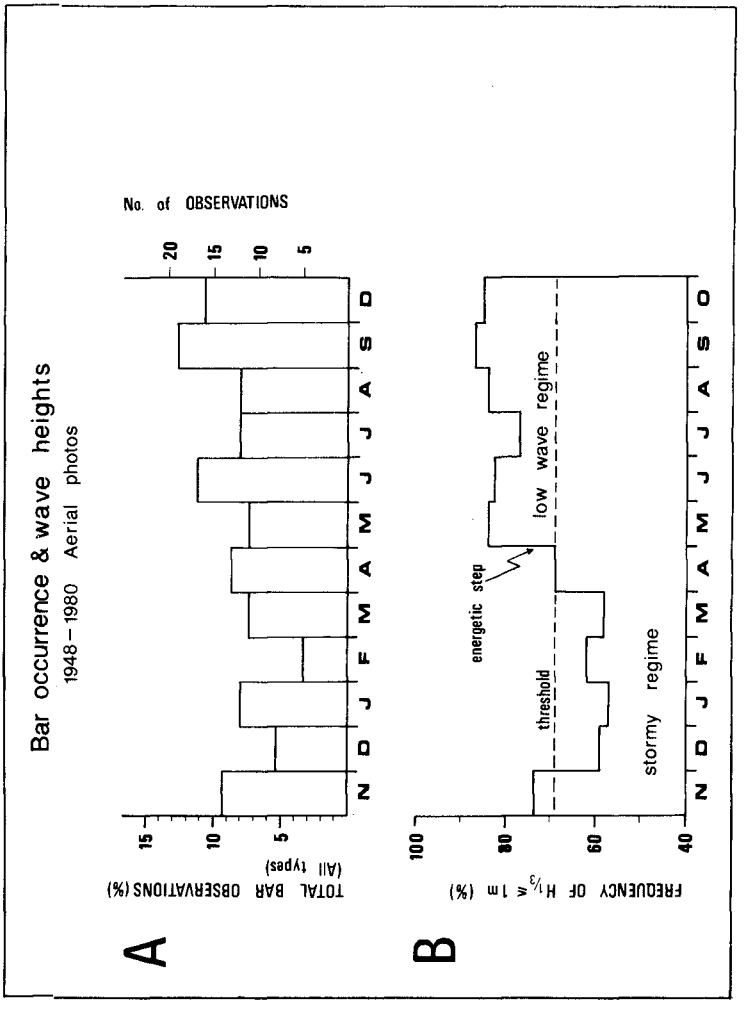


Figure 5. Monthly distribution of (A) bar frequency and (B) wave heights ($H_s$), 1948-1980.

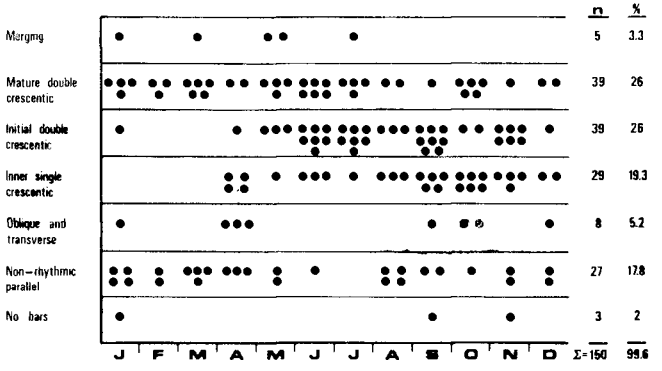


Figure 6. Seasonal distribution of bar types in the southeastern Mediterranean, 1949-1980.

tions are the months of May to July, when the crescentic families dominate. Because July has higher waves, August shows the reappearance of noncyclic systems. This antiphase relationship between non-rhythmic and crescentic bar families continues in September/October.

DISCUSSION : The coast of Israel is highly dissipative, and is dominated by single and double crescentic bar families, which compose 71% of the bars. Because of the cyclicity of storm waves followed by extended times of low waves, the sequence of bar types recurs several times per year. Therefore this may well be one of the best places to study bar sequences.

Thus, this coast is different from the Australian coast (Short, 1979; Wright et al., 1979), where the inner single crescentic bars, defined as megacusps and welded bars, dominated. This may be related to the higher Australian wave energy. This, in turn, differs from the observations of Greenwood and Davidson-Arnott (1979), who reported a lack of seasonal bar changes and continuous dominance of crescentic bars.

Similar bar types occur on most coasts, despite large differences in wave climate, tidal conditions, nearshore slopes and grain size. Most importantly, bars occur successively within definite sequences. However, on different coasts the bar types tend to occur in different sequences and in different proportions of time. It is suggested that these differences are directly attributable to global differences in the occurrences of threshold wave conditions. This, in turn, may be partly due to differences in sediment size and inner continental shelf slopes, as well as to the differences in wave climate.

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REFERENCES

Bowen, A.J. & Inman, D.L. 1971. Edge waves and crescentic bars. J. Geophys. Res. 76: 8662-8671.

Bowman, D. & Goldsmith, V. In press. Bar morphology and wave energy - an empirical model for moderate energy dissipative beaches. Mar. Geol.

Clairbout, J.F. 1976. Fundamentals of geophysical data processing with applications to petroleum prospecting. New York, McGraw-Hill, 274 pp.

Emery, K.O. & Neev, D. 1960. Mediterranean beaches of Israel. Bull. Geol. Surv. Israel 26: 1-24.

Goda, Y. 1974. Estimation of wave statistics from spectral information, in Ocean Wave Measurement and Analysis, Vol. 1. Edge, W. (ed.), New York, A.S.C.E., pp. 320-337.

Goldsmith, V. In press. Dynamic geomorphology of the Israeli coast: a brief review, in Goastal Problems in the Mediterranean. Fabbri, P. & Bird, E.G.F. (eds.), Gommission on the Goastal Environment, International Geographic Union, 14 pp.

Goldsmith, V. & Golik, A. 1980. Sediment transport model of the southeastern Mediterranean coast. Mar. Geol. 37: 147-175.

Goldsmith, V. & Sofer, S. 1983. Wave climatology of the southeastern Mediterranean: an integrated approach. Israel J. Earth Sci. 32(1).

Goldsmith, V., Bowman, D. & Kiley, K. 1982. Sequential stage development of crescentic bars: HaHoterim beach, southeastern Mediterranean. J. Sedim. Petrol. 52: 233-249.

Greenwood, B. & Davidson-Arnott, R.G.D. 1975. Marine bars and nearshore sedimentary processes, Kouchibougnac Bay, New Brunswick, Ganada, in Nearshore Sediment Dynamics and Sedimentation. Hails, J.R. & Carr, A. (eds.), New York, Wiley, pp. 123-150.

Greenwood, B. & Davidson-Arnott, R.G.D. 1979. Sedimentation and equilibrium in wave formed bars: a review and case study. Can. J. Earth Sci. 16: 312-332.

Gwirz, B. 1982. A sediment transport model based on granulometric analysis of the northern Carmel beaches. Unpubl. Manuscript, Geography Dept., Haifa Univ., 47 pp.

Owens, E.H. 1977. Temporal variations in beach and nearshore dynamics. J. Sedim. Petrol. 47: 168-190.

Short, A.D. 1979. Three dimensional beach-stage model. J. Geol. 87: 553-572.

Wright, L.D., Chappell, J., Thom, B.G., Bradshaw, M.P. & Gowell, P. 1979. Morphodynamics of reflective and dissipative beach and inshore systems, southeastern Australia. Mar. Geol. 32: 105-140.