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The Sharon Escarpment (Mediterranean Coast, Israel): Stability, Dynamics, Risks and Environmental Management

Ithamar Perath and Gideon Almagor

Geological Survey of Israel
Ministry of National Infrastructures
30 Malchei Yisrael Street
Jerusalem 95501, Israel

ABSTRACT

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The Sharon Escarpment between Giv'at Olga and Tel Aviv connects two regional land levels: the Coastal Plain, and the level of the Mediterranean beach and continental shelf, both of which consist of shore-parallel eolianite (kurkar) ridges and intervening troughs. The escarpment is up to 45 m high and is 75–90° steep. It terminates the westernmost coastal ridge along its seaward side, parallel to the ridge crest. The seaward face exposes two layers of crossbedded eolianite topped by paleosols, and it is usually capped by a 1–3 m ledge of hard calcarenite. Over the years, the escarpment moves evenly eastward by discontinuous collapse and slumping on the seaward side. Slabs of friable sandstone, commonly about 2 m thick and several meters long, become separated from the face of the cliff along tensional fissures. As they slide downward they crumble almost completely and come to rest as 30–55° aprons of loose sand which are removed in seasonal stages by wave swash. No further rockslides occur as long as this talus protects the cliff's foot. The frequency of rockslides, averaged over several years and along the entire length of the escarpment, is uniform and independent of cliff height or differential rock properties.

The escarpment's catchment area is small but steep, and runoff erodes deep primary gullies. Downwashed sand collects in low-angle fans in front of the talus and is removed with it by wave swash. Even though erosion causes visible degradation (especially where connected to more inland systems and to artificial catchments, where it causes great damage), the volume of sediment thus removed from the escarpment is negligible compared to the volumes removed by slumps and rockslides, and this erosion by runoff scarcely influences the rate of cliff retreat.

Talus-free sections along the escarpment, where the next expected event is a rockfall, were defined as Risk A sections. Sandslides from wave-cut talus aprons mainly involve horizontal mass distribution (including blocks of detached calcarenite that ride atop the talus), and these sections were defined as Risk B. Non-truncated talus was defined as Risk C (no event expected before the onset of sand removal).

A slump cycle starts from the Risk A situation. After a rockfall, a Risk C situation is obtained, which through a sequence of B-C-B-C events, becomes Risk A. According to observational estimates over the last decade, Risk C lasts 1 to 2 years, Risk B several years, and Risk A up to 10 years and possibly more. The rate of retreat for the total escarpment is constrained by the overall strength of the cliff and by the wave climate (*i.e.* the frequency of beach clearance of all talus). The rate of retreat is not perturbed by cliff height, by cliff angle or by cliff-top activity, as claimed by some authors, although one-time events may have a temporary or local effect on the short-range rate of retreat.

The Sharon Escarpment provides environmental benefits which may be irreversibly damaged by road building, sand quarrying, uncontrolled drainage, slope grading, and general tampering with the topography. The effects of such tampering are described and evaluated, and guidelines for durable cliff maintenance are recommended.

SUGGESTED INDEX WORDS: *Israel, Mediterranean coast, Sharon Escarpment, eolianite, kurkar, rock sliding, environmental risk, beach management, cliff retreat.*

BACKGROUND

The 190-km-long Mediterranean coastline of Israel serves as western borderline to the most intensively settled part of the country, and from the fifties onward it is increasingly exploited as an environmental resource. Along the thinly sand-covered water line, large areas have been sequestered for ports, power plants and industry. Along the remainder (10–20% of the total coast length) marinas, private beaches and hotels compete for space with bathing beaches.

Artificial changes along the shore have, for the most part, been harmful. Damage is either irreversible, or only repairable at excessive cost. The disruption of natural systems (water balances, geological substrate, drainage patterns, shoreline dynamics, ecosystems) proceeds without reliable predicting or monitoring, incurring risks of unknown and unestimated magnitudes.

The present study arose from the need to evaluate the risk of collapse along the Sharon Escarpment (Figure 1), whose steady landward migration causes losses to real estate and involves landslide danger along the beach. The study is based

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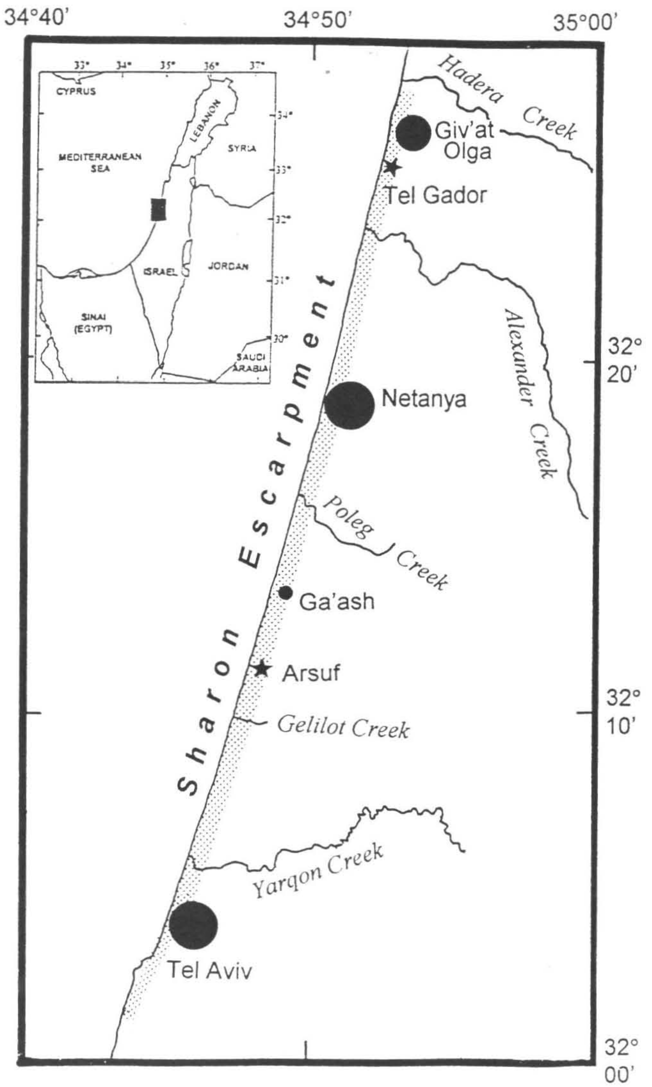

Figure 1. Location map of the Sharon Escarpment.

on surveillance of the cliff dynamics over some 10 years. Records were taken between Giv'at Olga and Tel Aviv during 1980–84 and the autumn and spring of 1991–92. Additional observations were made during summer 1995 and winter 1996. Also used were two series of overlapping diagonal aerial photographs taken in 1984 and 1992 expressly for the purpose of recording cliff morphology, and stereoscopic sets of overlapping vertical photographs taken in 1976 and 1978. Data were also collected on the frequency and extent of slumping and wave abrasion.

The paper does not deal with slope stability analysis, nor does it dwell upon the geologic history of the Israel Mediterranean coast, knowledge of which is not essential to understanding the present-day shore-sea interactions.

MORPHOLOGY

Figure 2. The Sharon Escarpment south of Alexander Creek. Note the overall rectilinearity and the slight sinuosity, expressed by the rim (Photo by Albatross).

The Sharon Escarpment forms a sharp dividing line between the coastal plain to the east, and the beach and upper shelf to the west. It rises up to about 40 m above the beach, and usually slopes about 75–90° in a laterally variable profile. The escarpment is formed by truncation of the seaward side of a longitudinal sandstone ridge (the westernmost of a series of linear Holocene dune ridges) immobilized by grain cementation, with natural gaps through which several creeks flow seaward. Walking along the rim one moves over a gentle eolian landform, 10 to 40 m above the beach.

Viewed meridionally from overhead, the cliff's rim forms an almost straight, slightly sinusoid line, projecting a waveline front with a horizontal frequency of several hundred meters, and swinging no more than 20 m landward or seaward (Figure 2). Slump scars cause seaward-concave serration along the rim. The foot of the cliff is nonserrated and aproned by sandy talus over long stretches. Most of the rim is west of the ridge crest and truncates the west slope with a sharp nickpoint.

The cliff cuts two layers of cross-bedded, carbonate-cemented quartzose dune sand (the Lower and Upper Kurkar), each topped by a fossil loam (the Beige Paleosol and the Upper Hamra) (Figure 3). The Upper Hamra is overlain by a hard ledge of calcarenite that usually forms the top of the cliff. A blanket of stratified sand (unlithified dune) overlies the calcarenite, but is rarely preserved along the rim. The

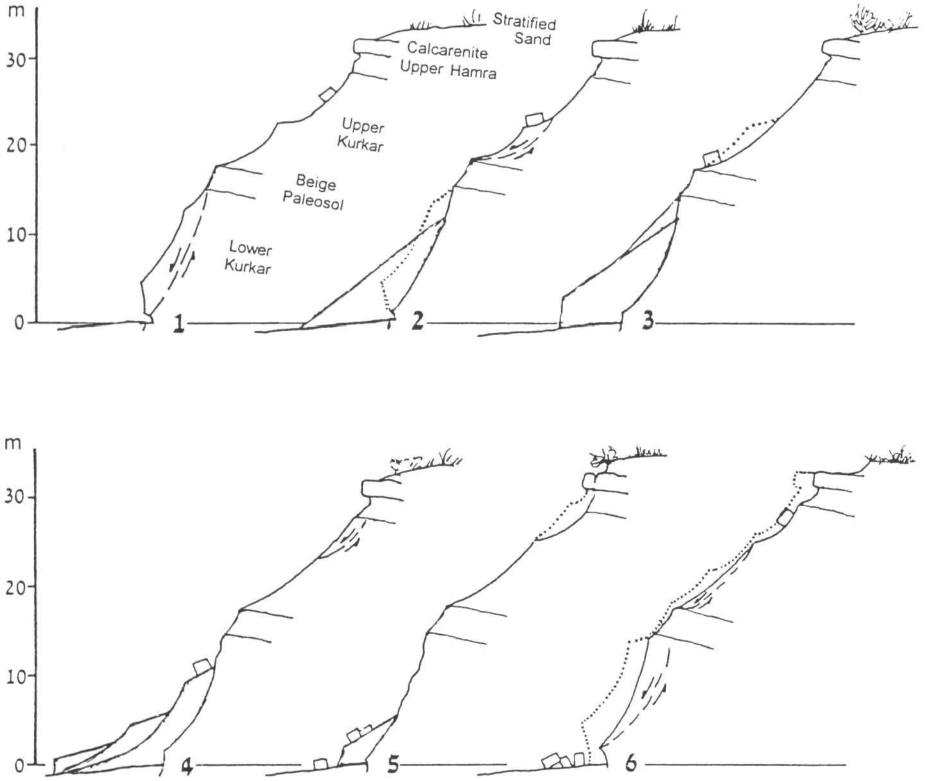

Figure 3. Cycle of cliff retreat. (1) Talus-free cliff with wave-cut notch at its base (Risk A). (2) Slumping of Lower Kurkar and deposition of talus apron (Risk C). (3) Toe of talus apron is cut by wave swash (Risk B); slumping of Upper Kurkar. (4) Compound step faulting across talus apron; calcarenite block riding on talus. (5) Apron cut by wave swash (Risk B); slumping of Upper Kurkar and Upper Hamra; detachment of calcarenite. (6) Talus-free cliff, lag boulders of calcarenite, wave-cut notch (Risk A). Dotted line—rock volumes lost by slumping, representing amount of cliff retreat per cycle.

Figure 4. Calved-off block of calcarenite, riding the talus apron.

Table 1. **Geotechnical parameters of the Sharon Escarpment's sedimentary units.**

Unit	Color	Thickness	Slope	Age	Components				
		(m)	(°)	(yrs BP)	Quartz sand (%)	Biogenic sand (%)	$CaCO_3$ cement (%)	Clay (%)	Heavy minerals (%)
Stratified sand	Light to dark gray	0–5		6–3,000	80–95	0–20	—	Negligible	Negligible
Calcarenite	Yellow ↑ White ↓	0–10, commonly 1–5	90	12–5,500, Neolithic to Early Chalcolithic	10–40	60–90	20	1–3	0.5
Upper Hamra	Red to brown	0–10, commonly 1–6	20–90	20–10,000, Epipaleolithic	65–95	1–3	—	10–40	0–1.5
Upper Kurkar	Yellowish, gray-white	0–38	30–50	50,000	30–90	5–10	5–10	1–2	0–2
Beige Paleosol	Beige, dull brown	0–5, commonly 1–3	55–90	Paleolithic	50–90	10–30	—	10–20	0.5–5
Lower Kurkar	Yellowish, gray-white	0–38, base not exposed	55–90, usually 75–90	60,000	40–60	0–10	20–60	1–2	1

Main sources:

Cliff slopes measured by Wiseman and Hayati (1971) and by Levin (1995).

Age: (a) Ages of dune stabilization (Lower and Upper Kurkar, Calcarenite) by Porat and Wintle (1994) by use of Infrared Stimulated Luminescence (IRSL). (b) C^{14} dating using vegetation and skeletal debris by Gavish and Friedman (1969), Arad *et al.* (1977), Kaufman (in Bakler *et al.*, 1977) and Neev *et al.* (1987). (c) Prehistory according to Gophna (1977; 1990), Ronen (1977), Gophna and Ayalon (1980), Herzog (1981) and Gifford *et al.* (1989).

Geotechnical, petrographical and mineralogical data evaluated by Dan and Yaalon (1966; 1968; 1990), Greenberg (1971; 1976), Yaalon and Laronne (1971), Bakler *et al.* (1972), Bakler (1977 and unpublished data), Nedavia *et al.* (1979), Arkin and Michaeli (1985), Gavish and Bakler (1990) and Ritte (1996).

Strength parameters tested by Zolkov and Wiseman (1965), Wiseman and Hayati (9171), Wiseman *et al.* (1981), Frydman (1982), Komornik and Hayati (1983) and Arkin and Michaeli (1985).

Lower Kurkar almost invariably forms a steeper slope (usually 75–90°, not smaller than 55°) than the Upper Kurkar (32–50°) (Wiseman and Hayati, 1971; Levin, 1995). A convex nickpoint marks the contact between the two.

The foot of the escarpment is at most times covered by 30–55° talus aprons over much of its total length. These consist of free sand mixed with irregular blocks and shards of kurkar, and are in places covered by riding slabs of calcarenite (Figure 4). Rock slumping produces talus half-cones which may combine to form long prism-shaped aprons. Most sand aprons exist for several years, during which time they may become vegetated and gullied. Sand aprons may appear also higher up the cliff face, resting on halfway ledges of kurkar. The height of an apron never exceeds that of the remaining cliff face above it, except in the rare cases of compound slumping or artificial dumping.

Altogether, the Sharon Escarpment is shaped entirely by slump scars. Erosion is secondary to slumping as a cliff-sculpting factor, and achieves no mature landforms beyond a series of deep narrow gullies that may change downhill into cylindrical scour pipes, which become hanging valleys as the back-cutting slumping overtakes them.

GEOTECHNICAL PROPERTIES AND SLOPE STABILITY

The cohesion, shear strength and abrasivity of the kurkar are all functions of the interstitial calcite that cements the sand grains, 60% to 90% of which are quartz with some heavy minerals, the rest consisting of calcareous bioskeletal debris (Table 1). The carbonate cement is obtained by recrystallization of calcareous bioclastics. Both the quartz and the bioclastics are marine, the former deriving from the Nile delta and the latter from the inner littoral.

Cohesion in Lower Kurkar was found to be about 30 kPa, and nearly zero in the Upper Kurkar which upon sampling behaves as free, non-cohesive sand. The angles of internal friction are 33–43° and 35–37°, respectively (Table 1). Thus, most of the cliff is in a state of instability (*i.e.* even a small-magnitude event may effect change), and the strength of kurkar is extremely variable over short distances. The prediction of slope failure based upon slope stability analysis or upon geotechnical properties of samples is therefore unrealistic.

Mass movements starting on the upper reaches of the cliff, usually built of weak Upper Kurkar, trigger slumping along the way, thus precluding the buildup of large instabilities.

Table 1. **Continued.**

Grain size		Sorting		Porosity	Specific Gravity of Solids	Bulk Density	Moisture Content			
Grain Size (mm)	Median diameter M_d (mm)	Average S_o	Range S_o —	p (%)	G_s —	γ (kg/m^3)	Before Rain w (%)	After Rain (%)	Cohesion c' (kPa)	Angle of Internal Friction ϕ' (°)
0.200									0	38–45
Quartz: 0.062–0.250 Biogenic: 0.500–1.000	.191	1.15	1.10–1.19	30–50	2.77	1.55–1.70	0.5		170–600	35
0.062–0.250	.162	1.33	1.17–1.67		2.60–2.70	1.82–1.86	2	8–23	10	35–37
0.130–0.310	.137		1.11–1.16	4–32	2.66–2.67	1.50–1.65	0.3	8	0	
0.088–1.250					2.68–2.70		1.5		Considerable	33–43
0.130–0.310				2–23	2.69	1.55–1.70	0–2	7.5	30	

Slope failures are somewhat clustered in winter and spring, which points to rainfall as a major destabilizing factor.

The clayey paleosols have little cohesion, about 10 kPa, and their internal angles of friction are larger than 35° (Table 1). In spite of low cohesion the paleosols develop quite steep slopes, several meters high, and maintain semi-vertical profiles through several seasons.

High degrees of cohesion (170–600 kPa) were measured for the upper ledge of calcarenite (Table 1), which shears under its own weight where the underlying Upper Hamra has been removed by slumping or flushing. Shearing begins with the formation of rim-parallel crevasses which appear about 2–3 years before full detachment. The breaching of a slab does not provide enough impetus to send the block rolling downslope, and constitutes no direct hazard—the bigger the slab, the greater the friction that slows its downslope sliding (Figure 4).

NATURAL PROCESSES THAT SHAPE THE SHARON ESCARPMENT

Rockslides and Slumping

Rapid landward translation of the coastal cliff is deduced from: (1) the many fresh slump scars along the cliff's face, (2) from commonly observed slumping along the slopes and the renewal of talus aprons, (3) from discernible retreat of the rim as revealed (though not measurable) by comparing aerial photographs and topocadastric records, (4) from the permanently youthful drainage pattern and its basal amputation (Figure 5), (5) from the presence of a submerged and abraded reef of eolian kurkar that reaches as far as 250–300 m seaward of the cliff's present base, and (6) from the remnants of ancient seaside buildings transected by the cliff's rim or scattered among the scree's lag gravels (Figure 6).

Cliff retreat is activated by wave-shore interaction, possibly sustained by a slow rise of sea level (*e.g.* FLEMMING 1968; FLEMMING *et al.*, 1968), or by pulses of recent tectonism (NEEV *et al.* 1973; 1987). The multiannual rate of cliff retreat is controlled by the rock's overall strength (a lithologic constant) and the frequency of apron clearance by wave swash (a climatic constant), and cannot be slowed or accelerated without modifying of these constants. Local cliff retreat may be irregular, but on a multiannual scale the ribbon delimited by the line that connects the escarpment's headlands and the line that connects its bights moves eastward at an even rate (Figure 7).

Although the evidence indicates that cliff retreat is rapid, disagreement exists concerning the overall rate, and different approaches to measurement have yielded different results. Migration rate of the rim has often been taken as a measure of overall cliff retreat, but the available photographs are on too rough a scale to determine small (less than 1 m) changes, or even to determine the exact position of the rim (actually recorded as the pre-noon border between sun and shadow, which is sharp only where the rim is sharply angular). Moreover, repeat photographs are never identical, and photographs on both dates must undergo the same photogrammetric correction procedure in order to obtain reliable quantitative results—a technique which until lately has not been available. Comparative geodesy has been applied to selected short stretches of rim by Nir (1989), Ron (1992) and by Ben-David (1995), who—from debatable data—extracted rates of retreat of 30–40, 0–78 and 16–155(!) cm/year, respectively. Perath (1982) calculated the rate of retreat for the entire cliff front (*i.e.* not only the rim at a particular locality) on the basis of the volume of scree removed by wave swash along 20 km, and found multiannual rates of 15–22 cm/year. Geodesy by

Figure 5. An erosional gully, ending as a hanging valley due to slumping and removal of its basal part.

the present authors (unpublished) along 500 m of rim north of Netanya has yielded maximal local rates of 5–40 cm/year. For methodological reasons, greater credence is accorded to the more conservative rates.

Rock slumping involves the following cycle of events (Figure 3):

(a) Creation of a wave-cut notch at the talus-free base of the cliff. This takes place during the few hours per winter that wave swash from storm swells comes into contact with the cliff. The actual mechanics of notching have not been recorded, but it has been repeatedly observed that waters reaching the cliff base have spent most of their turbulent energy, and can do little mechanical work. Cement dissolution possibly plays a role comparable to mechanical abrasion. The notch, initially 15–30 cm high and of indeterminate width, may undercut the cliff as far as 1 m, rarely more, and grow several meters upward by subsequent roof collapse, creating a conspicuous overhang (Figure 8).

(b) Slope failure is initiated, with the notch causing basal instability, setting off upward-translated events of slumping at unpredictable times and places. An average slump is moderately concave, up to several meters wide, detaching a slab several tens of centimeters thick and usually no more than a few cubic meters in volume. Rockslides that nibble the rim are maximally 4–6 m wide and rarely more than 2 m thick. These rim-biting rockslides are the largest, often affecting the entire face of the cliff and involving a cascade of slumpings that produces an exceptionally large talus apron (Figure 9). Repeated counting of slump scars along representative stretches of the rim found that yearly slumps are spaced 19 to 63 m apart, with average distance usually 38–44 m. Repetition time is 5 to 13 years for a random rim locality, the longer periods corresponding to stronger rock.

(c) The talus apron is removed in stages by wave swash. Collapsed waves running up the beach approach close to the cliff at high tides, and wash away the toe of the talus apron. A vertical step is formed across the base of the apron (Figure 10), initially stable because of capillary water and carbonate bonding, but soon drying out and collapsing (Figure 11). Subsequent toe removal causes repeated series of step faulting across the apron, with repeated collapse until all talus is removed, after which the base of the cliff is again exposed to wave action and notching (event a), as described above.

Erosion—Effects of Runoff and Interstitial Waters

In spite of large amounts of seasonal rainfall and heavy rainstorms (540 mm multiannual average, 16 days with more than 10 mm per day—BITAN and RUBIN, 1991), the narrow catchment area of the Sharon Escarpment does not receive much runoff. The maximum daily average may reach 2.8 m^3 for one meter of cliff front. Runoff is fed only from rain that falls on the west slope, between the ridgeline and the foot of the cliff—a ribbon less than 100 m across. At localities where the ridgeline has been cut away by the advancing cliff, the rim serves as water divide and the only catchment area is the cliff's face.

Much of the rain is absorbed by the stratified sand—insofar as not quarried away—that caps the cliff. The rainwater that is not absorbed or evaporated flows downcliff as a sheet wash, attaining high velocities due to the steep grade. Loose sand is washed out of the substrate, and straight primary gullies and rills are eroded to a depth of 1 m and more, whether in kurkar, paleosol or talus. Only a small percentage of the gullies cut back of the cliff's rim, and only very few gullies have short side branches—the first buds of a trellis system. Loose sand, the main erosion product, is spread in the form of a low-angled fan at the base of the gully (Figure 12), or at the base of its continuation down the talus cone. These fans are washed away by wave swash during the same winter season (fans older than a year are rare). The gullies also serve as a conduit for dry material slumping from the middle and upper parts of the cliff.

Percolating rainwater dissolves carbonate and enlarges fissures in the calcarenite, and causes partial liquefaction and

Figure 6. Slabs of cemented masonry lining the defensive moat of the 13th century castle of Arsuf. The detached slabs slumped onto the beach in late winter 1994.

flow of the Upper Hamra, forming concave notches below the ledge. Flushed-out clay stains the slope a reddish brown, superficially disguising it as hamra. Much water that flows through the gullies may be swallowed up by fissures or porous pockets along the way. Vertical or near-vertical sections along the flowpath of many gullies bear resemblance to breached solution pipes. These pipes are several meters long and may reach from the base of the cliff to its very rim. In places they grow into wide funnels and chutes, which guide sandy avalanches down the gully.

Some of the larger gullies, when they breach the rim and cross the saddles of the kurkar ridge, begin to collect runoff from the eastern slope and from the trough beyond. Within several years these ridge-crossing gullies develop into steep gorges with tributaries of their own, bigger by an order of magnitude than those that remain west of the ridgeline (Figure 13). Yet, if not tampered with, even these large V-shaped gorges do not significantly affect the shape and frontal integrity of the escarpment, although causing great havoc in the eastern catchment area.

It should be emphatically pointed out that erosion, in spite of its considerable intensity and its highly visible effects, plays no role at all in determining the rate of cliff retreat, as can be concluded from the following:

(a) The great majority of cliff-front gullies have not developed beyond the earliest stage of erosion, *i.e.* series of parallel channels that do not coalesce, and do not have tributaries.

(b) A gully grows in width and depth while a slump scar does not change its original shape. Yet, the volume of lost rock represented by the slump scar is always larger than the volume eroded by its gullies. Nowhere have gullies eroded away even half the scar surface.

(c) Slump scars hardly ever carry traces of gullies that existed before the slumping. Only in the lowermost scars near the foot of the cliff, where the gullies are at their deepest (Figure 5), some pre-slump gullies may be temporarily preserved as small hanging valleys in the upper part of the scar.

(d) Along any length of beach, the volume of slump talus is many times greater than the volume of alluvial fan material. In all cases (except for gorges that have crossed the ridge line) the fan represents material that would in any case have been removed by the next slumping event. In other words: whatever the rate of erosion, it is part of, and not an addition to, the volume of cliff material destined for wave-induced collapse and removal.

Gullies of types (a) and (b) indicate that erosion must attain double its rate or more in order to supersede slumping. Hanging gullies of type (c) indicate that the position and shape of the cliff's base is entirely determined by slumping. The situation represented by (d) indicates that cliff retreat is entirely determined by the rate of rock slumping, and that erosion plays no more than an ornamental role.

Whatever the inland effect of erosion, it has no effect on the rate of cliff migration. The multiannual rate of precipitation has to more than double in order to exert decisive influence on cliff retreat. No such climatic fluctuations are recorded in the Holocene history of the region.

Wind and Vegetation

The cliff is swept by moderate to strong, very humid sea breezes, replete with salt aerosol. Sandblasting by these breezes scours the exposed kurkar, producing a sharply corrugated surface texture of resistant laminae. Strong breezes

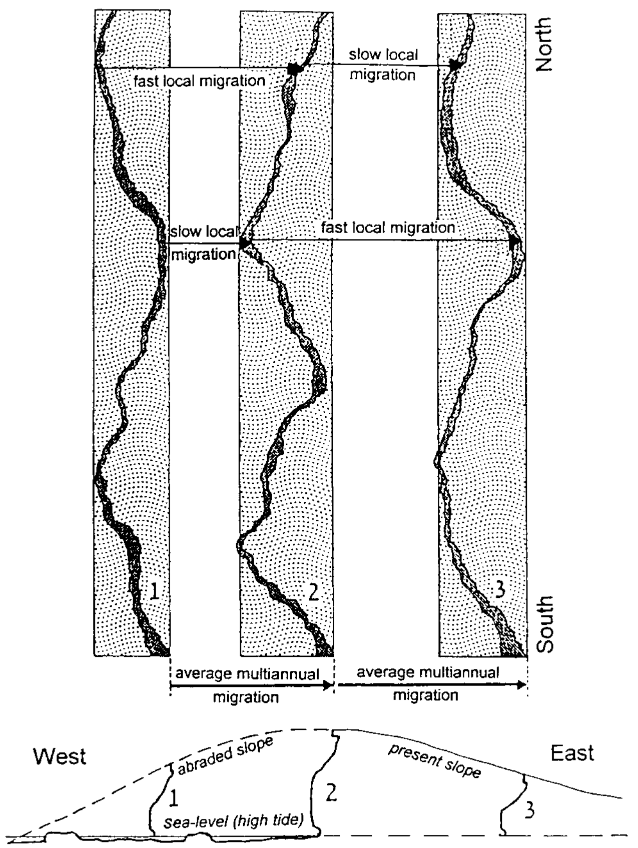

Figure 7. Cliff retreat through continuous uneven abrasion of the western Kurkar ridge. Above: planar projection, showing how rates of migration may be haphazard, but on a multiannual scale the belt that is delimited by the straight line connecting the escarpment's headlands and the straight line connecting its bights preserves an even width, and migrates eastward at an even rate. Below: cross section. (1) Abraded and submerged kurkar reefs—remnants of the western part of the ridge. (2) Present-day situation—the Sharon Escarpment coincides roughly with the ridgeline. (3) Future situation—the eastward-migrating cliff will reach the inland trough.

blow talus and beach sand upward along the cliff face (sand chuting down the gullies was observed to be blown back in upward-whirling plumes). The amount of sand that is blown beyond the rim is irrecordably small, except where the cliff is very low, or breached by ridge-crossing gullies. The cliff is therefore a dune barrier, and the stratified sands of its uppermost unit cannot but be a relic of pre-cliff times, or the eolian deposit of winds considerably stronger than those blowing today.

Wind never triggers talus movement, but together with rain and microscopic salt growths in pores, wind action contributes to the visual aging of fresh scars. This, however, does not seem to have any effect on the longevity of a surface.

Vegetation, consisting of grain-bonding algal coatings, bacterial and fungial filaments (DANIN *et al.*, 1989), and ephemeral and multiannual psammophile scrub, is time-related, and a cliff feature can be roughly dated by the maturity and extent of its plant cover. Vegetation causes bonding of the talus and reduces the frequency of its slumping, but since almost no vegetation grows at the wave-wetted toe of the apron, sand removal is not prevented and the vegetation confers no greater longevity on the talus. Nowhere have trees taken hold.

It is not clear whether vegetation causes bonding or weakening of the paleosols and kurkar layers, but it slows or prevents sheet wash and dissipates the stream energy that carves gullies. At localities where wave-cliff interaction is artificially prevented, the cliff is preserved for a long time by apron-covering vegetation. Notable cliff cover is provided by carpets of *Portulaca* ("Ice-plant"), escaped from domestic gardens.

DIRECT AND INDIRECT HUMAN INTERFERENCE WITH CLIFF RETREAT AND CLIFF MORPHOLOGY

Drainage, Road-Building and Back-Cliff Excavations

Drainage includes the downcliff channeling of sewage, industrial runoff, and/or artificially collected rainwater, either in open-flow channels or in pipes.

Sewage and runoff cascading from the cliff's rim erode funnels and grooves much larger than the naturally-formed gullies, either because of the greater amounts of water involved or because of their greater cement-dissolving acidity.

Piped drainage affects the cliff indirectly if the pipe is housed in an artificial groove or trench which may serve as a conduit for rainwater. If the pipe's trench—even if filled-in with rubble or loose sand—connects with areas that otherwise do not drain beachward, intensified erosion soon transforms the trench into an artificial ridge-crossing gully, cutting great gaps in the cliff face and yawning wider as the cliff retreats at its natural rate (Figure 13). Nevertheless, even though these drainage gaps disfigure the cliff front and endanger the integrity of the back-cliff areas, they have—for the time being—the same negligible influence on the rate of cliff retreat as the natural erosion processes.

Vastly greater damage (in per cent of cliff-front destruction) is caused by (a) road building, and (b) the quarrying of sand, calcarenite and hamra in back-cliff areas.

(a) Steep roads descend from the ridge to the beach at several localities. Some are hewn parallel to the cliff face, others roughly normal to it. The latter kind, especially when connecting to a back-cliff catchment area, behave during rainfall like artificial torrents which accelerate the maturation of the local erosion system (Figure 14). Grooves excavated by the recently popular "sport" of uphill climbing by cross-country vehicles have similar effect (Figure 15). Roads are often connected to broad parking terraces, bulldozed in the cliff side or within its top. These parking lots, paved by crushed kurkar or tarmac, transform the heavy *in situ* precipitation into wholesale runoff. Re-excavation and repaving of the seasonally destroyed sites has created rapidly widening gorges, increasingly erosion-efficient, which by now surpass all the previous natural erosion systems in magnitude. Amazingly, in spite of the formidable cost of repair and the growing damage to the cliff front, no preventive engineering (replanning of roads, harnessing of runoff, blocking of incipient gullying) has

Figure 8. Wave-cut notch at the base of the cliff, slightly enlarged by roof collapse. Note Tel Malha in background, a Roman-Byzantine site truncated on its seaward side by slumping.

Figure 9. A large, hemiconical talus apron, formed by slumping of the entire cliff front. Note the compound scar that reaches up to the rim. The toe of the apron has been bulldozed to enable beach traffic. No change is expected in the situation (Risk C) before the waves start removing the talus (Photo Y. Nir).

Figure 10. Wave-cut step, truncating the toe of a sandy talus apron (Risk B). The step is maintained at this high angle by capillary forces in the moist sand. Desiccation results in collapse, as has happened to the apron in the foreground.

been applied to date, except on some privately-owned property.

(b) In its natural state, stratified sand is stabilized by the presence of clay and humic substances, and overlain by extensive patches of mobile dune. Throughout the year it is overgrown by a luxuriant multiannual heath of psammophile vegetation of admirable seasonal variability (an environmental asset by itself) and a permanent mesh of roots. This substrate totally absorbs all seasonal precipitation and prevents the development of surface runoff. In spite of more than 500 mm of yearly rain, and even though it consists entirely of non-consolidated sand, no hydrographic network develops on it, and its morphology is entirely eolian.

However, the sands are a much-sought building material. Sand poaching is most intensive along the cliff's rim, which north of Tel Aviv has been stripped down to the calcarenite

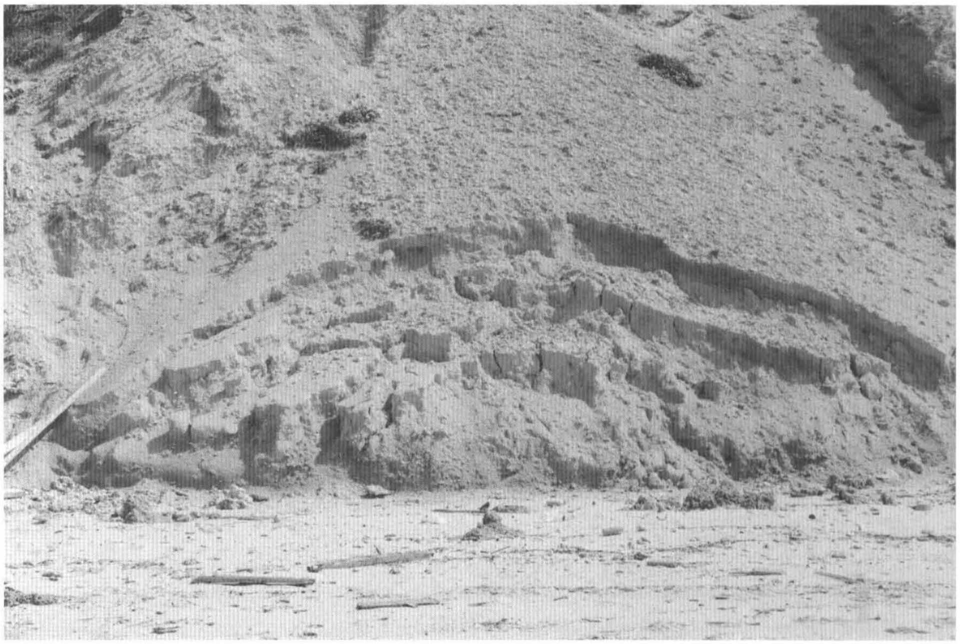

Figure 11. Serial step faults cutting across a hemiconical talus apron, the result of the collapsing of the wave-cut step formed by removal of the toe.

Figure 12. Low-angled alluvial fan, its toe truncated by wave swash. Note small new cone in front of wave-cut step.

along approximate 90% of its length. At many localities the calcarenite—an equally useful material—has been quarried through, and wide pits have been excavated in the Upper Hamra, also in high demand as landfill and garden soil.

Removal of the sand cover threatens the stability of the entire erosional regime. A new element, surface runoff, is introduced into the system. Channels and gullies appear where there were none; ridgetop areas and catchments beyond it become part of a beachward erosion system that did not exist, but which grows with increasing efficiency due to the heavy rainfall, the erodibility of the clayey hamra substrate (Figure 16) and the stripping of the vegetation cover. Along some of the denuded areas the cliff's rim has been serrated by badland formation in the Upper Hamra, and the cliff front is becoming a series of contiguous erosional V's. Natural cliff retreat is much more destructive when affecting the thin interfluvial divides.

The effect of man-caused erosion through removal of the porous ground cover poses a threat to the regional infrastructure (undercutting of roads and buildings, exhumation of pipe systems, flooding of low areas, loss of soil from the inland trough, destruction of the sand biotope, reduction of groundwater recharge, degradation of the coastal cliff, rapid changes in the topography) that is not counterbalanced by the utilization—lawful or not—of cheaply obtained groundfill and aggregate.

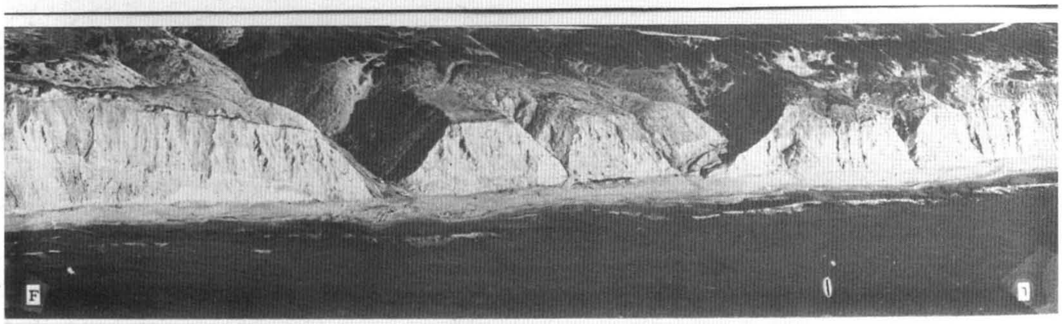

Figure 13. V-shaped gorges, crossing the ridgeline and draining the inland trough east of it. Note the difference in magnitude between these gorges and the V-shaped gullies that merely nibble at the rim. Note also that both the gullies and the gorges are truncated above beach level, terminating as hanging valleys (Photo R. Erde, from Nir, 1989).

Figure 14. Artificial road gap, hewn at right angles to the cliff, repeatedly eroded, re-excavated and re-eroded.

It should be emphasized that we are not dealing with the acceleration of a pre-existing natural process, but with an entirely human-caused phenomenon which, if not counteracted, may attain disastrous dimensions. The most efficient and proven remedy is refilling of the denuded back-cliff areas with sand or with chemically inert porous rubble material, readily available from building sites and well-aged garbage dumps. The refill material must be sufficiently porous to prevent the development of surface runoff, sufficiently heavy to resist erosion, and sufficiently non-cohesive to prevent undermining.

Beach Maintenance

Human activities along the cliff-front beach that may potentially affect cliff behavior include (a) offshore structures, (b) the removal of beach sand and beachrock, and (c) the removal of talus aprons.

(a) Offshore structures interfere with the balance of marine sand supply and removal (NIR, 1976; 1982). Where the alongshore supply is intercepted by structures normal to the shoreline, the beach beyond the obstacle is stripped of sand cover, sometimes down to its kurkar substrate. Narrowing of the sandy beach heightens the frequency and turbulent energy of wave swash that reaches the talus aprons and the base of the cliff, increasing the potential of cliff retreat.

Offshore structures are a young feature, nowhere more than a few decades old and not yet closely spaced. In several observed cases, artificially-caused sand starvation has led to accelerated slumping from coastal cliffs within one or two seasons of the disturbance, and was later arrested by artificial supplies of sand and artificial cliff tampering. To date, the random sinuosity of the cliff front displays no deviations that can be correlated with the presence of offshore structures. The effects may be too slow or too small to enable early detection.

(b) Sand removal does not necessarily cause narrowing of the beach, but lowers its surface and promotes more contact between cliff and wave swash, in the same way as would sand interception. There are no reliable records whether the wholesale beach sand removal up to 1964 (5 million m^3 since the late 1940's—NEEV *et al.,* 1963; 10 million m^3 since the beginning of this century—A. GOLIK, *personal communication*), when it was stopped by law, has caused accelerated cliff retreat. Unlike back-cliff sand poaching, tight control has effectively prevented sand removal from the beach during the last decades.

Beachrock ledges in the lower intertidal belt act as a sand trap and favor the conservation of beach sand; on the other hand they form a potential barrier to marine sand supply. Over the centuries beachrock has supplied building stone to shore settlements and today it is removed from bathing beaches, but whether or not this has any influence on the frequency of cliff-sea interaction—the effect is too small or too slow to have affected the multiannual rate of cliff retreat.

(c) During the last decades, talus aprons are bulldozed away from bathing beaches and from stretches of narrow beach to facilitate along-beach traffic. This shortens the time span during which the base of the cliff is protected from wave swash, and accordingly should speed up the rate of local cliff retreat. Since the talus apron stage is the shortest in the cycle (See above: "Rockslides and Slumping", p. 211), the effect is not—as yet—notably influential, but it may be crucial for the life expectancy of specific structures on the overhead cliff.

Garbage Dumping

In recent decades, great volumes of urban rubble and industrial refuse have been transferred from regional disposal sites to fill up some of the cliff's larger erosional gorges. In addition, whole clifftop areas have been piled over with garbage to the very edge. By now the process of cliff retreat has reached these deposits, which usually overlie the calcarenite *in lieu* of the removed stratified sands, and they are becoming an increasingly significant component in the talus.

The packing and mass cohesion of piled garbage (even though maturated, and containing little or no perishables) are chaotic. Unlike the sandy formations its talus is neither regular nor stable. Among the components are netted fabrics that entangle heavy, non-disintegrating blocks, much more

Figure 15. Deep ruts, destined to become erosion channels, made by motorized sport vehicles ploughing into a moderate-sloped section of the Sharon Escarpment.

Figure 16. The Upper Hamra that has been stripped of the stratified sands and calcarenite, is attacked by sheet wash and transformed into badlands that destroy the back-cliff zone.

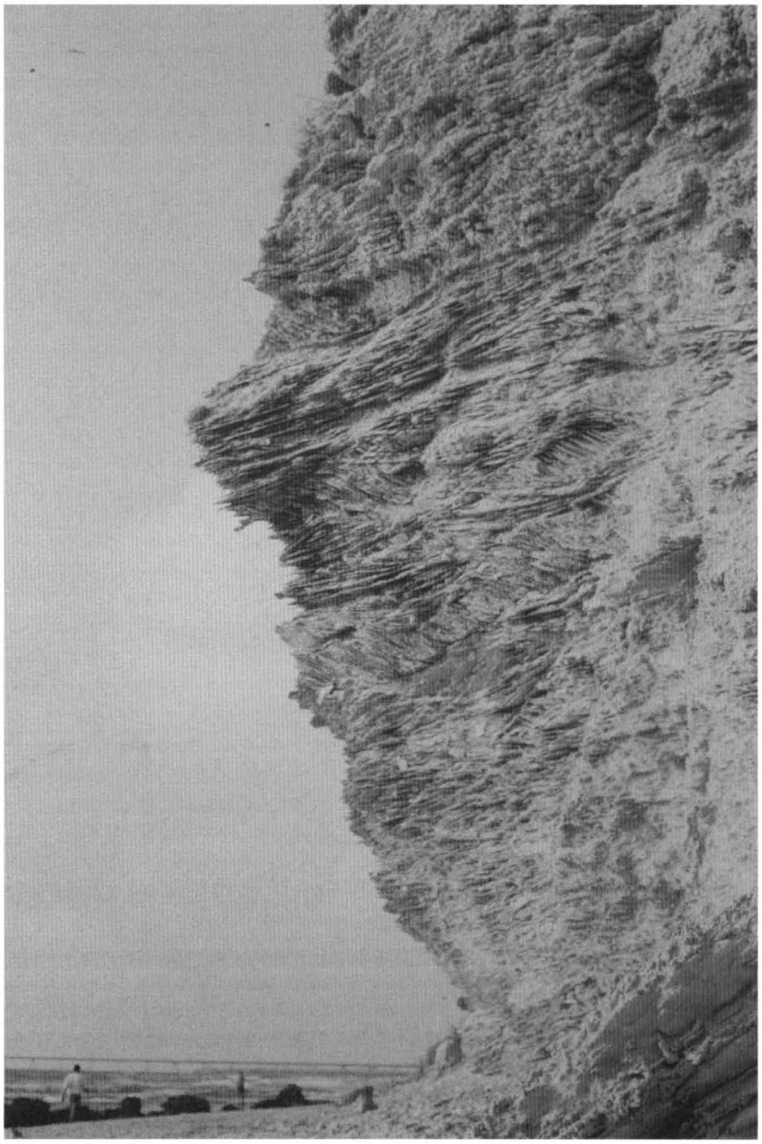

Figure 17. Talus-free cliff, with a wave-cut notch at its base (Risk A). The next event, not preceded by warning phenomena, will be rock sliding.

bulky than kurkar or calcarenite. When reclining on the beach, garbage scree is progressively winnowed and milled by wave swash, but its complete removal takes much more time than the removal of sandy talus. In the meantime, it does not adequately protect the cliff's base from wave wetting and notching.

Garbage dumping—aesthetics aside—efficiently repairs the damage of accelerated man-caused erosion. Nevertheless, garbage cliffs are different from calcarenite and kurkar, and of unknown instability. The components of garbage scree (which include metal machinery and automobile wrecks) are dangerously bulky, unstable and unpredictable—each slump is a system by itself. Perched slumps are a beach hazard, and the landed scree may have a long beach life.

At some back-cliff housing projects, large amounts of sandy debris and concrete rubble have been pushed over the rim of the cliff and smoothed over, creating an artificial cliff composed entirely of scree. In all cases, these artificial debris aprons have been spectacularly attacked by erosion before being removed (within two seasons) by wave swash, leaving an irremovable pile of concrete boulders and tangled steelwork on the beach in front of the property.

The effect of garbage dumping on the rate of cliff retreat has not been determined. The input of considerable volumes of solid material which eventually ends up as talus should prolong the time lapse between consecutive wave notchings, and thus slow the rate of retreat. On the other hand, talus composed of garbage provides poor protection of the cliff base. The role of dumped maturated garbage in the beach environment should be investigated also from these two aspects.

Slope Grading

At several municipal beach localities the entire cliff has been bulldozed to low-angled slopes, 30° and less. At these angles the position of the cliff is stabilized. Wave notching no longer induces rockslides or slumping, but leads to gradual asymptotic concave downgrading of the slope.

Technically and environmentally not much is attained by this artificial grading, except the removal at high cost of a valuable clifftop strip that natural causes would have removed free of charge over a period of several decades. The main reason for the destructive practice are architect's whims, and the expectation that a gently sloping back-beach area may offer commercial opportunities.

The grading, by eradicating the slump-generating escarpment, puts an end to the process of undercutting and slumping that would re-create the scarp morphology. Erosion remains the sole cliff-destroying factor. Moreover, the grading usually enhances erosion to unprecedented dimensions by creating a new back-beach profile and pushing the water divide far landward, often erasing it altogether. As a result, rain is collected from a strip hundreds of meters wide instead of the narrow ribbon between the cliff's base and its rim. Where grading includes a saddle of the kurkar ridge, the trough to the east is breached and starts to drain beachward. Since the grading invariably removes the surface sand cover, surface runoff is thus magnified beyond all natural dimensions. The depth and density of the gully system is such that graded sections have to be dumped over by imported landfill within one season of the grading.

Lately, cliff grading has invited the unbridled swarming of rough-terrain vehicles, which pulverize and plough up the terrain, scour deep ruts in the substrate (Figure 15), and attain within days effects which erosion would need seasons to achieve, in areas which erosion would be slow to reach.

Preservation of a graded beach slope is feasible, but requires sustained investment in counter-erosion effort. The construction of terraces with well-draining retaining walls and the planting of soil-stabilizing vegetation, may prolong its life. The effectiveness of plastic sheeting, currently applied in places, is of as yet unproven permanence.

Buttressing and Aproning

At several localities where cliff retreat constitutes an imminent danger to immovable property, practical as well as impractical measures have been taken to halt the process. The piling of heavy boulders on the beach in front of the cliff, to act as baffles to the wave swash and to dissipate its turbulent energy, has no effect whatever on cliff retreat, since the rate of talus removal depends on the yearly volumes, not the energies, of wave swash reaching the cliff's base. Much more efficient at arresting cliff retreat is the buttressing of the lower cliff with non-kurkar masonry and concrete, which are invulnerable to wave notching and thus put an end to slumping and rock sliding. Sand removal from beneath the buttressing wall can and must be prevented by deepening the foundation below low-tide level.

Cliff retreat appears to have been effectively arrested at places where the buttressing wall is aproned by concrete rubble and iron meshwork, rip-rap style. However, since the remaining beach is narrow and the cessation of cliff-front slumping closes a significant source of beach sand, this solution is less beach-friendly than the deep founding of the buttress wall.

The practical approach to the arrest of cliff retreat, even at conservative rates (15–22 cm/year—PERATH, 1983), would be either the revetment of the cliff's base by an unnotchable wall, or the absolute interception of the wave swash before it reaches the cliff's base. Protection of the cliff's base by plastic sheeting has been attempted at some localities, but the durability of this measure in a wave-swept environment is not proven. Whether applying deep-founded buttressing or unerodable aproning, or a combination of both, the part of the cliff that projects above the retaining structure will continue to slump and erode till an angle of approximately 45° is obtained (the average stable slope of the Upper Kurkar), after which the rim and cliff top remain stable. The cost of arresting cliff retreat should be measured against the actual or potential value of the cliff-top property thus preserved.

EVALUATION OF SLUMP RISK (ROCK SLIDES AND TALUS COLLAPSE) ALONG THE CLIFF FRONT

Degrees of Risk

The factors that produce the risk cycle (spatial distribution of rock strength and temporal frequency of wave swash) are known, as are the conditions that determine their magnitude and duration. Conservation of the cliff in its natural state, even if deemed desirable, involves a degree of slumping hazard. Therefore, even though the process is unpredictable on the short time scale, it can be fairly well determined where and how large an affected area will be, or when and where slumping will *not* occur. A survey was therefore carried out to define the boundaries and distribution of the various risk situations along the undisturbed Sharon Escarpment, and to assess the potential effects—and costs—of artificial interference.

Three risk situations, A, B and C, which recur systematically in the course of natural cliff retreat, were defined in terms of severity of the next event.

Risk A, the severest, is the degree of hazard presented by exposed rock cliff, bare of talus (Figures 3 and 17), either with or without a wave-cut notch at its base[1]. In this situation the most dangerous next event is the slumping of rock. Risk B is the situation where a talus apron has lost its toe to wave swash (Figure 10), and the next event is collapse of its loose sand and riding chunks of calcarenite onto the beach in front.

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[1] Actually, the notch-free cliff presents a considerably smaller degree of risk than a notched cliff, but due to the surveying method employed—oblique aerial photography—the two situations could not be differentiated. A ground-based survey, differentiating the two situations, was carried out on sample stretches only.

Risk C is presented by cliff aproned by talus that has not been wave-swept (Figure 9); there is no dangerous next event to be expected before the apron is destabilized by the formation of a wave-swept step. Actually, Risk C is a no-risk situation.

The cycle of cliff retreat, as described above ("Rockslides and Slumping"—p. 211 and Figure 3), is also a cycle of risks. Slumping is invariably preceded, by definition, by a Risk A situation, and is immediately inherited by Risk C. As wave-swash and apron-slumping clear away the talus in stages (Figure 11), risks C and B alternate until the cliff is again bare from its base upward, returning to Risk A.

The maximal, minimal and average duration of each risk situation cannot be practically measured (it would entail daily monitoring of long stretches of cliff, over several consecutive seasons). However, observations over more than 10 years indicate that Risk A (bare cliff) may persist up to 10 years and occasionally longer; Risk B (untouched talus) for several years, and Risk C (stepped talus apron) for one or two seasons, rarely more. The talus aprons, even the largest of them, are cleared away in the course of less than ten collapses, but within this period the unstable stepped apron stage (Risk C) is the shorter-lived.

Distribution of Slump Risks Along the Sharon Escarpment

A sample of 32,710 m of cliffed beach was surveyed by oblique aerial photography and ground-based measurements (PERATH and ALMAGOR, 1996). Altogether, 372 risk sections were determined, representing a random moment in the behavior of a dynamic morphologic system. 74% of the risk sections were found to be shorter than 100 m. Some 46% were shorter than 50 m, and only about 14% were longer than 150 m, the longest reaching 950 m.

The risk situations are uniformly distributed along the Escarpment, confirming that cliff retreat is uniform even over short time intervals. The types of risk are also more or less equitably distributed (Risk A: 135 sections; Risk B: 115 sections; Risk C: 122 sections). The small but marked majority of Risk A sections can be attributed to the end of the uncommonly stormy 1992 season, when frequent wave swash had recently transmuted many Risk B and C situations to Risk A. Nevertheless, when comparing cumulative lengths, one finds that Risk C ("no risk") occurs along 40% of the surveyed beach length, Risk B (the most transient situation) along 27%, and Risk A along 33%. This however need not be true for all seasons.

Overall length values show that risk situations along the beach are most strongly influenced by the distribution of Risk C—the safer situation is the more dominant. If this distribution is found at the end of a stormy season, it may be supposed that Risk C is even more common at random times.

A definite range of lengths seems to characterize all the risk categories alike, determined by the random interplay of random wave swashings with rock of random strength distribution. It is not at all clear how the risk distributions or their overturn rate would be affected by less or more storms, stronger or weaker rock; multiannual perturbations of the sand balance, or other factors.

CONCLUSIONS AND RECOMMENDATIONS

(1) The entire Sharon Escarpment, like a waterline, a glacier or a mountain peak, should be preserved for what it is. The technology to modify or annihilate it is all too available, as are short-sighted local interests to do so. Yet, in order to preserve the environmentally desirable properties of the cliff, the most effective—and cheap—policy is one of strict non-intervention.

(2) Since the rate of cliff retreat is slow in comparison to settlement and building development, safety requires no more than a 10 m belt of no-development along its rim. Superficial structures such as roads, pavilions, playgrounds *etc.*, may well last their time at this distance. A long-range safety margin of 50 m is recommended for more permanent structures and high investments. Nevertheless, large structures built at the proper 50 m non-development distance from the rim, may within their lifetime find themselves partly isolated on headlands. Their ultimate survival depends on deep foundations that reach below low-tide level.

(3) Overhanging ledges of calcarenite, especially if displaying shear fissures, are dangerous. Since overhangs evolve randomly, a general warning on moving onto the rim and 2 m back of it should be posted. Fencing, besides being expensive, counter-scenic and largely ineffective, becomes superfluous within short years, when the overhang shears off.

(4) At localities where building close to the rim is inevitable or already *fait accompli*, buttressing of the cliff's base with a sloping concrete or a non-kurkar revetment is recommended. Grading is ineffective due to the magnified erosion hazard. Buttressing is not recommended (even if 100% effective) where its construction and maintenance costs are higher than the economic value of the 50 m safety margin beyond the top of the cliff.

(5) Descending roads should be excavated parallel to the cliff, never at an angle to it. The top of the road should never be in a local catchment area, either atop the cliff or back of it. Road maintenance should include seasonal filling-in of all incipient gullies. No parking areas or indeed any platforms should be built at any locality that drains toward the beach.

(6) Sand quarrying between the cliff and the alluvium line of the trough to the east should be prohibited. Under no condition should surface sands be removed from any area that eventually drains beachward. Stripped areas and all gullies should be filled in with porous material (sand, fine gravel, non-perishable packed rubble) that does not sustain surface flow or undermining.

(7) All conduits that carry runoff toward the beach should be made and kept leakproof down to beach level.

(8) The use of urban and industrial garbage as counter-erosion landfill and/or as stratified cliff-top deposits is recommendable, provided that (a) the garbage components are mechanically inert; (b) the deposit is not more cohesive than naturally occurring kurkar, and contains no components more massive than average blocks of sheared calcarenite; and

(c) the deposit contains no light materials that will become flotsam on the beach.

(9) A 15 m safety strip should be marked on the beach, wherever cliff is bare of talus (Risk A), and on maintenanced bathing beaches the strip should be staked off or fenced (on other beaches the fencing may interfere with beach traffic). This marking should be renewed every season, preferably in early spring, when Risk A is not expected to increase by storms sweeping the beach.

(10) Talus aprons present no hazard (not even Risk B) and should be left as they are, except to clear passages for along-beach traffic. Entrance should be strictly prohibited to all vehicular traffic (especially rough-terrain vehicles) between the water divide at the top of the cliff and the beach below.

(11) The cluttering of the beach with boulders, rip rap and other "energy-dissipating" obstacles should be prohibited, having no effect beyond fouling up the environment. The licensed removal of beachrock should be allowed at bathing beaches.

(12) The licensing of quays and groynes should be conditioned upon the buildup beforehand of a sand reserve opposite the beach section where the quay will predictably cause sand starvation (changes in the sand balance are reversible, while cliff undercutting is not).

PROGNOSIS

The natural processes that have formed and continue to form the Sharon Escarpment are still active. If they are not counteracted by artificially induced processes, the Escarpment will endure and so will its benefits, with no increase in risk.

Like so many resources and landscape features, the Mediterranean coast of Israel has reached a state where its future depends on human decisions and human actions or non-actions. Whatever the decisions, they must be based on full understanding of causes and dependable measurements of effects.

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