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GEOLOGICAL SURVEY OF ISRAEL

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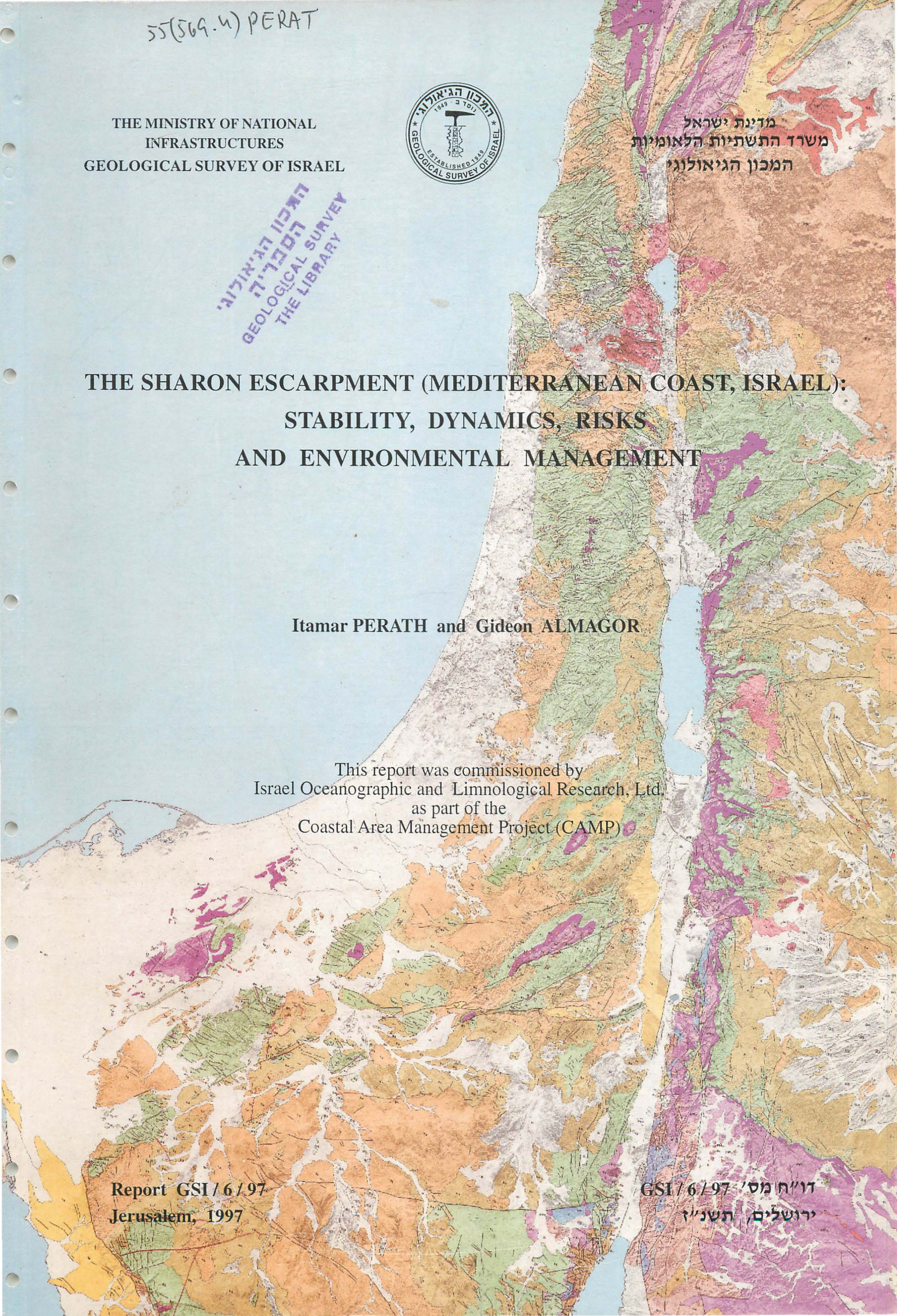

THE SHARON ESCARPMENT (MEDITERRANEAN COAST, ISRAEL): STABILITY, DYNAMICS, RISKS AND ENVIRONMENTAL MANAGEMENT

Itamar PERATH and Gideon ALMAGOR

This report was commissioned by
Israel Oceanographic and Limnological Research, Ltd.
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ABSTRACT

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 terminates the westernmost coastal ridge along its strike, parallel to the ridge crest. It is up to 45 m high and has 75-90° slopes, across layers of cross-bedded eolianite interlayered with up to 4 beds of loam, and it is capped by a ledge of hard calcarenite. The escarpment moves evenly eastward by discontinuous collapse on the seaward side. Rock slabs, commonly about 2 m thick and several metres long, become separated from the face of the cliff along tensional fissures, slide downward, and come to rest as 30-55° aprons of loose sand which are removed in seasonal stages by wavewash. No rockfalls occur as long as this talus protects the cliff's foot. The frequency of rockfalls, 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. 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 rockfalls, and this erosion hardly influences the rate of cliff retreat.

Talus-free section 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 riding blocks of detached calcarenite), 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 slide 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 inexpert tampering with the topography. The effects of such tampering are evaluated, and a policy of cliff maintenance is recommended.

INTRODUCTION

The coastal plain and continental shelf of Israel consist of a system of subparallel longitudinal carbonate-cemented quartz sandstone (locally termed kurkar) ridges separated by longitudinal shallow depressions (Picard, 1943; Avnimelech, 1952; Itzkhaki, 1961; Neev *et al.*, 1976; Almagor, 1979; among others). The broadly concave shoreline cuts this ridge-and-depression system at a slight angle (Fig. 1). Consequently, Israel's northern shoreline, from Mount Carmel to Taninim Creek, includes a continuous backshore ridge, whereas the coastal ridge along the central shoreline, from Hadera Creek to Yarqon Creek, is abraded, forming a prominent backshore cliff. In this 40-km-long stretch, known as the Sharon Escarpment, the cliff (and ridge) is at its highest (10-45 m). Southward, the ridges are not clearly aligned, causing irregular and widely spaced cliff sections.

BACKGROUND

The 190-km-long Mediterranean coastline of Israel is western borderline to the most intensively settled part of the country, and is increasingly exploited as an environmental resource. From the fifties onward the Mediterranean coast and the zone immediately east of it are utilized as urban substrate and a farming region, a recreation zone and a main traffic belt, a source of building materials and a region of waste disposal, as an outlet for sewage and as a groundwater recharge area. Along the thinly sand-covered water line, large areas have been sequestered for ports, power plants, industry, and the military. Along the remainder (10-20% of the total coast length) marinas, private beaches and hotels compete for space with bathing beaches. The intensive usages often interfere with each other, and together they put a heavy pressure on the natural environment with its pristine landscapes, biotopes, historical sites and archeological remnants which, even if not destroyed outright, are heavily burdened by accumulations of man- and seaborne garbage.

Man-made 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. Human interference with the Sharon Escarpment, is only one case in point.

The present paper arose from the need to evaluate the risk of collapse along the Sharon Escarpment (Fig. 2), whose steady landward migration causes losses to real estate and involves landslide danger along the beach. The spatial variability of the eolianite sandstone yhat composes the cliff does not enable representative sampling. For this reason previous geotechnical studies of the coastal cliff (Gavish and Friedman, 1969; Wiseman and Hayati, 1981; Greenberg, 1976; Bakler

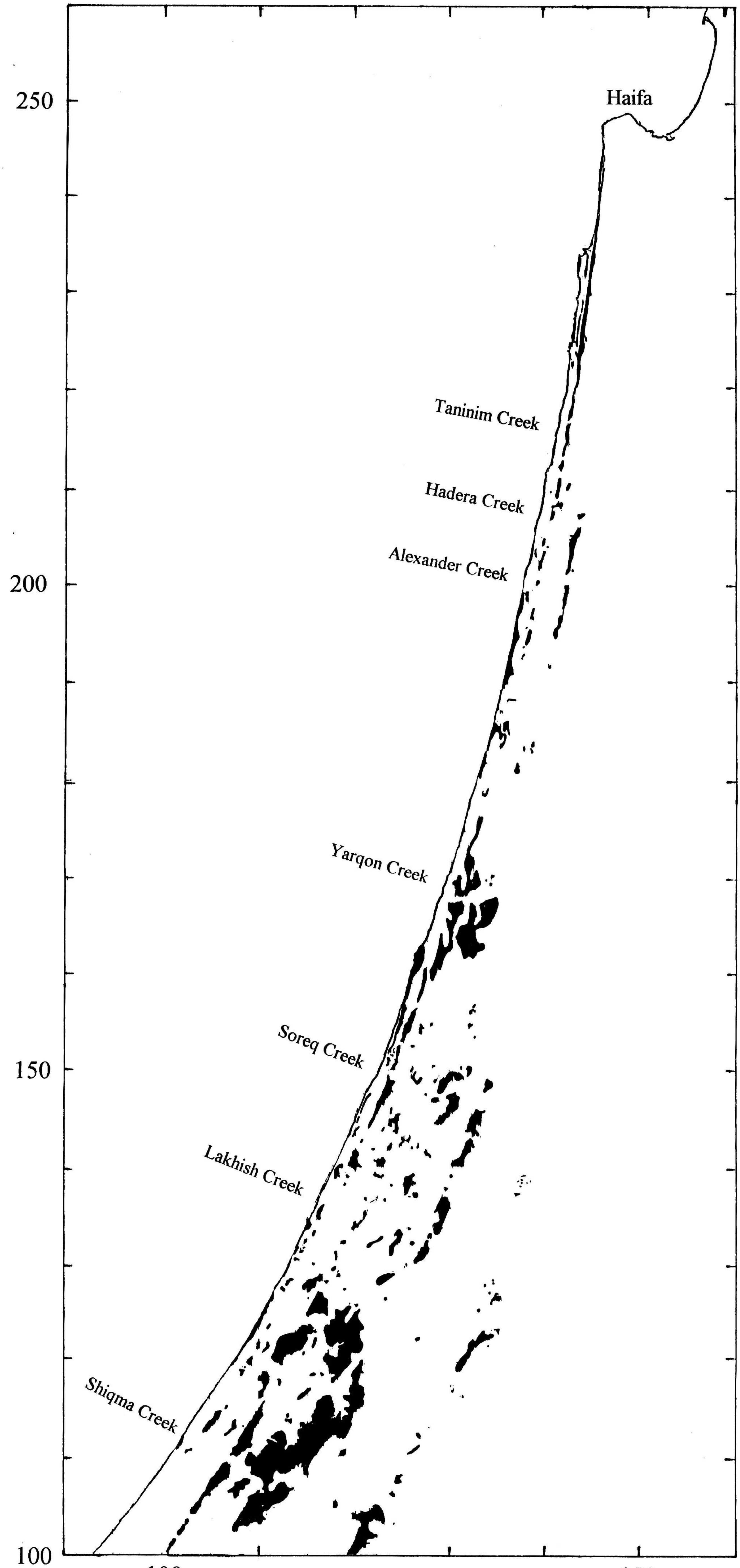


Fig. 1. Kurkar ridges in the Coastal Plain (After Sneh *et al*., 1966a-d).

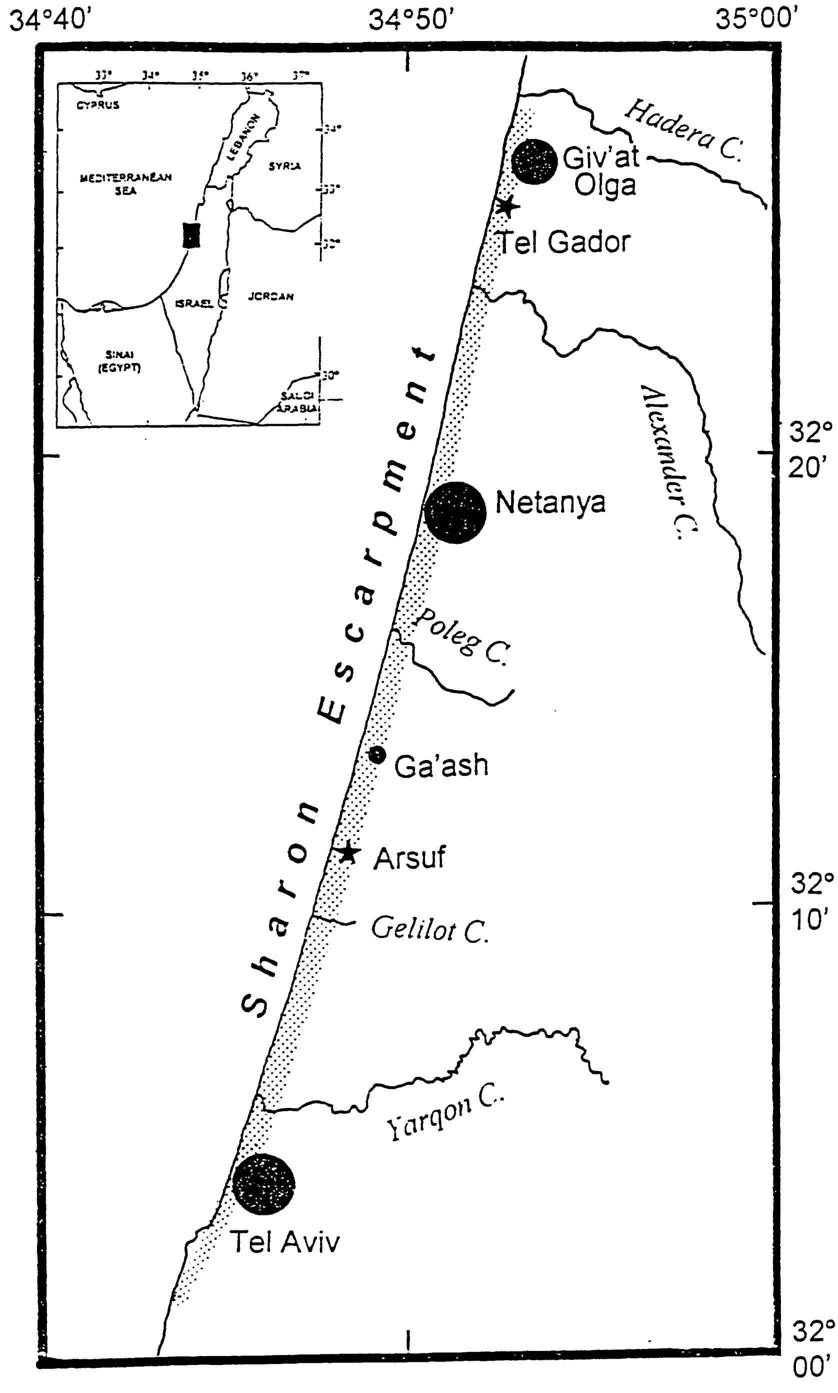


Fig. 2. Location map of the Sharon Escarpment.

the coastal cliff (Gavish and Friedman, 1969; Wiseman and Hayati, 1981; Greenberg, 1976; Bakler *et al.*, 1972; Nedavia *et al.*, 1979; Wiseman *et al.*, 1981; Frydman, 1982; Komornik and Hayati, 1983; Arkin and Michaeli, 1985) could not be used as a data base. No correlation could be established between previous laboratory tests of the rock and the calculated slope stability based thereon, and predictable field behavior. Existing geodetic and photogrammetric data (Ron, 1982; Nir 1989; 1992; Ben-David, 1995) were similarly unusable for quantifying cliff behavior over time, due to inaccuracy and lack of control.

The present study is therefore not based on previous studies, but on field work only, and periodic surveillance of the cliff dynamics over some 10 years. Records were taken between Giv'at Olga (the northern edge of the escarpment) and Tel Aviv during 1980-84 and the autumn and spring of 1991-92. Auxiliary observations were made during summer 1995 and winter 1996. Among the recordings are 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. Also used are partly analyzed data on the frequency and extent of slumping and wave abrasion, collected in the course of the field work.

The paper does not deal with slope stability analysis, nor does it dwell upon the geology, history and tectonics of the Israel Mediterranean coast, which are not essential to understanding the present-day coast dynamics or risk factors. Various geological aspects have been partly dealt with by many authors (Avnimelech, 1950; 1952; 1960; Issar, 1961; 1968; Itzkhaki, 1961; Dan and Yaalon, 1966; 1968; 1990; Yaalon *et al.*, 1966; Karmeli *et al.*, 1968; Gavish and Friedman, 1969; Bakler *et al.*, 1972; Bakler, 1977; Neev and Bakler, 1978; Horowitz, 1979; Perath *et al.*, 1981; Perath, 1983; 1993; 1994; Gavish and Bakler, 1983; 1990; Gvirtzman *et al.*, 1984; 1995; Neev *et al.*, 1987; Gvirtzman, 1990; Katzav, 1994; Katzav and Gvirtzman, 1994; Netser, 1995).

MORPHOLOGY

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 begins rather abruptly south of Hadera Creek and continues southward as a distinct landform, with local interruptions, as far as north Sinai. The present study was confined to the northern stretch where the cliffs are the highest, and which includes areas of intensive coastline development.

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 the Alexander, Poleg and Yarqon creeks flow seaward (the Gelilot Gap is artificial, even though quite ancient; the nature of Olga Gap is not quite understood). Walking along the rim one moves over a gentle eolian landform, 10 to 40 m above the beach (not counting the gaps).

Viewed meridionally from overhead, the cliff's rim forms an almost straight, slightly sinusoid line, projecting a wave-line front with a horizontal frequency of several hundred meters, and swinging no more than 20 m landward or seaward (Fig. 3). Indentation and embayment are slightly more pronounced along the northern section of the escarpment (Fig. 4), yet the overall linearity of the cliffline is preserved. Slump scars cause seaward-concave serration along the rim. The foot of the cliff is nonserrated, shaped by wave notching and collapse, 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 combination of sigmoid linearity and serration occasionally produces small local headlands and inlets along the upper part of the cliff. Back-cutting erosional gullies, however, intensify the serration, and in places produce a belt of badlands (see below, 2. Erosion, paragraph 5).

The cliff cuts through a vertical sequence of eolianites (locally named kurkar), horizontal to wavy, which consist of 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) (Fig. 6). The Upper Hamra is partly alluvial, and along most of the cliff it is overlain by a hard ledge of the Calcarenite (cemented carbonate skeletal sand). A blanket of stratified sand (stabilized but not lithified dune) overlies the Calcarenite. This layer is rarely preserved along the rim. The 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 kurkar layers, at approximately the top of the Beige Paleosol horizon. Since the paleosol makes the cliffs intersection with an undulant (eolian) land surface, the break in slope may be high or low on the cliff face, absent where the paleosol submerges below beach level, or it may be sliced away altogether by slumping.

The stratigraphic units of the cliff have been variously named by various authors (*e. g.* Avnimelech 1960; Wiseman and Hayati, 1971; Bakle *et al.,* 1972; Neev and Bakler, 1978; Perath *et al.,* 1981; Gvirtzman *et al.,* 1984). The present paper employs the mappable lithologic units.

The steeper profile of the Lower Kurkar may be due to stronger cementation. The possibility cannot be ruled out that by nature of the mechanism of cliff retreat (see below, 1. Rockslides and slumping, paragraphs 3 and 4) the Lower Kurkar is oftener affected by slump events than the

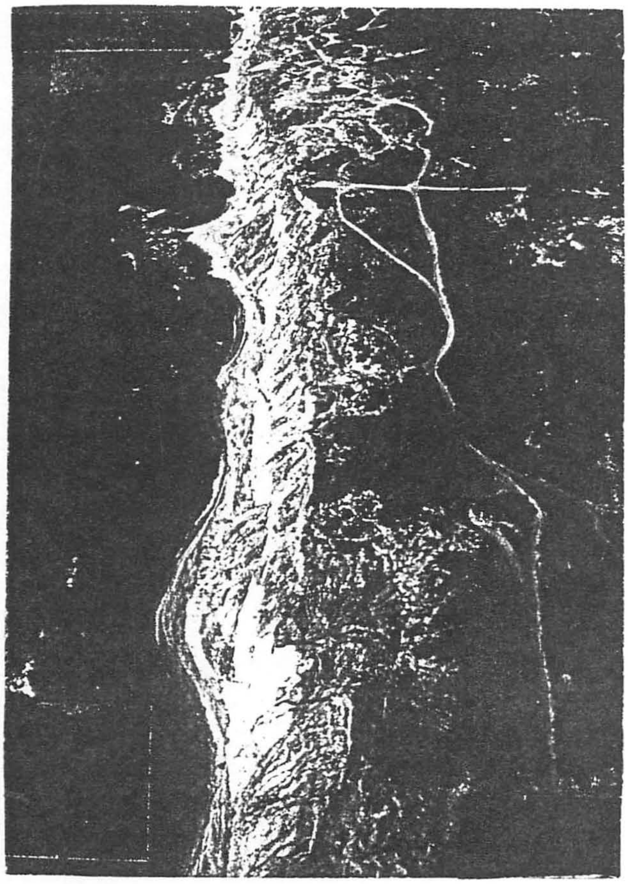


Fig. 3. The Sharon Escarpment, north of Ga'ash. Note the overall rectilinearity and slight sinuosity expressed by the rim ("Albatross Air Photography").

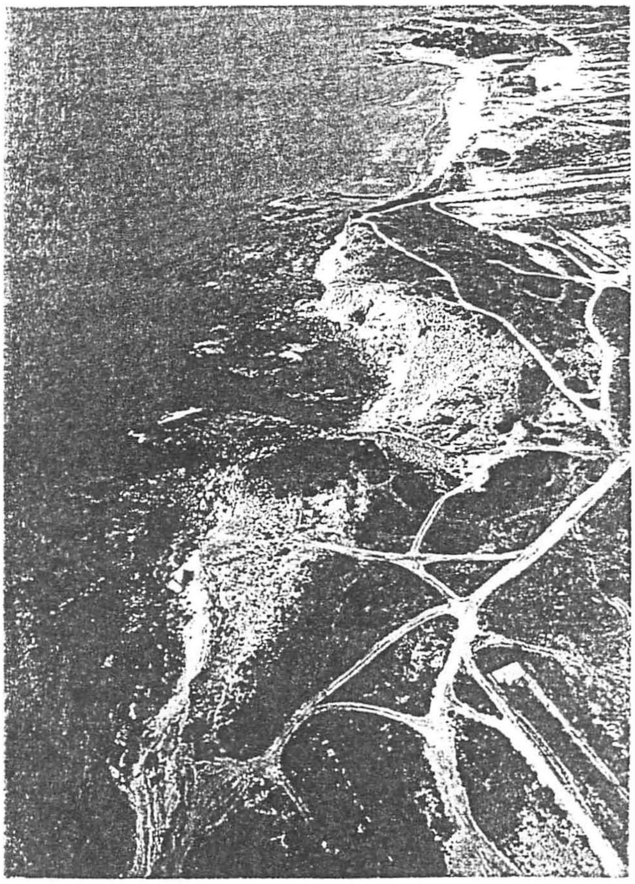


Fig. 4. The Sharon Escarpment between Tel Gador and Hadera Creek. Note headlands and embayments ("Albatross Air Photography").

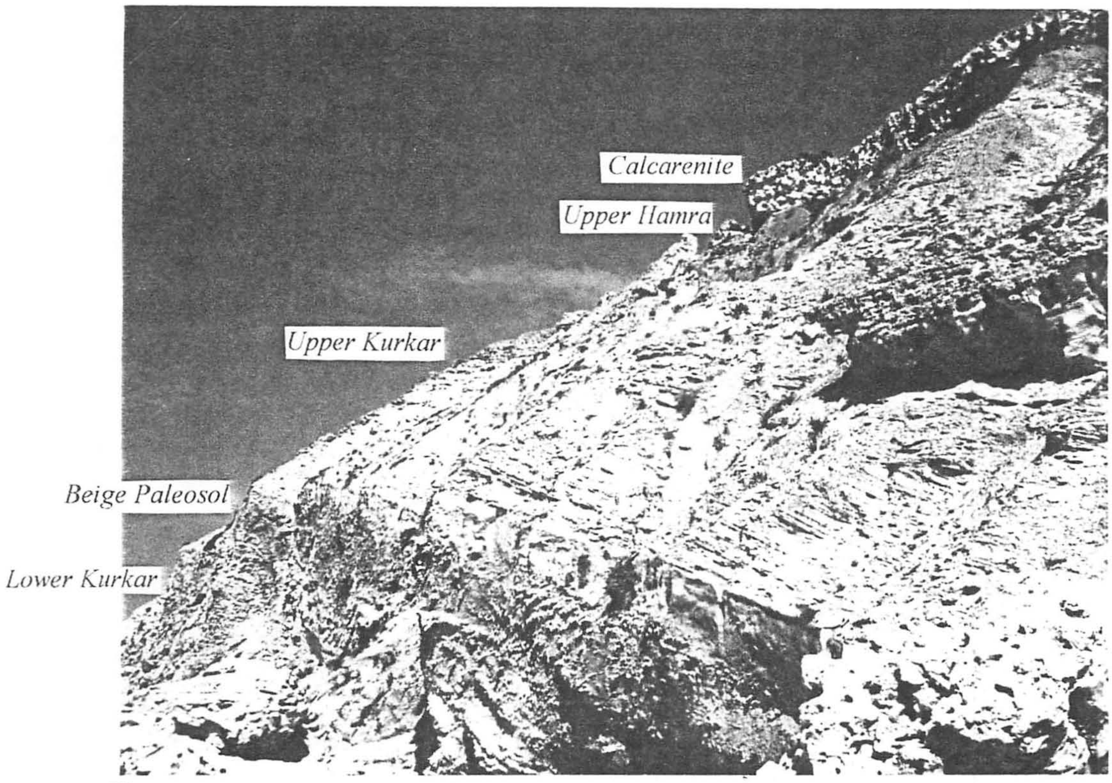


Fig. 5. Stratigraphic units of the Sharon Escarpment. The Lower Kurkar topped by the Beige Paleosol forms a steeper slope (commonly 75-90°) than the overlying Upper Kurkar and Upper Hamra (32-50°).

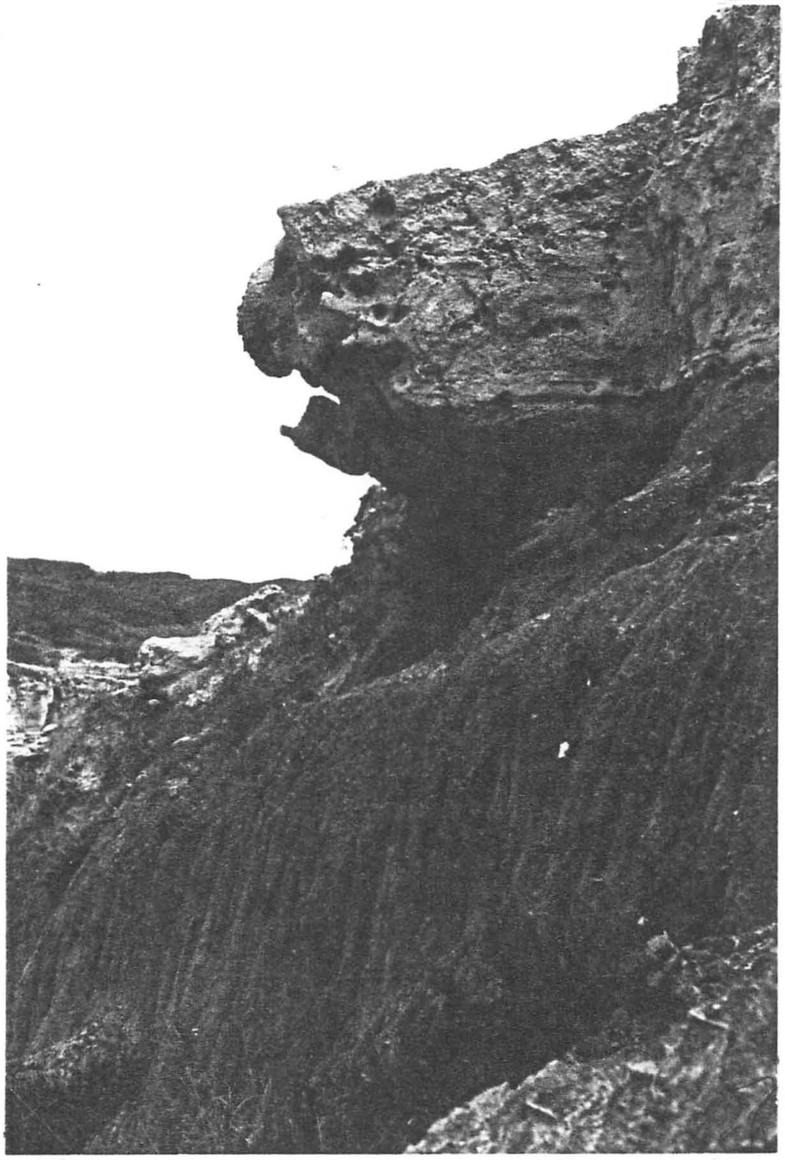


Fig. 6. The calcarenite ledge overlying the Upper Hamra. Washout of hamra causes overhang. Note parallel rills on the hamra surface, and eolian pitting of the calcarenite.

Upper Kurkar, and therefore its exposures do not have sufficient time to develop mature gentle slopes - a situation analogous to bank formation in side-cutting creeks.

The hard calcarenite ledge that usually forms the rim slumps less often than the Upper Hamra underlying it, which is prone to liquefaction and flushing. For this reason the calcarenite often stands out as a protruding ledge, which when overstressed breaks off in great slabs rather than calving off in rotational slumps like the kurkar. In recent years, man-made excavations have caused local disequilibria with the natural morphology, causing runaway damage that affects the cliff and even more the areas back of it.

On the whole, the sandy formations building the Sharon Escarpment are rather weak and friable, intensely sculpted by erosion and deflation. The foot of the escarpment is at most times covered by talus aprons over much of its total length (Fig. 3). The aprons, 30-55° steep, consist of free sand mixed with irregular blocks and shards of kurkar, and are in places covered by riding slabs of calcarenite. A single slump event produces a half-cone talus apron, several meters wide at the base, but contiguous half-cones combine to form a long prism-shaped apron. Slumps from the lower part of the cliff also tend to form prismatic rather than half-conical aprons (Fig. 7A). The life expectancy of a sand apron is several years, during which time it may become vegetated and gullied. Sand aprons may appear also higher up the cliff face, resting on a sockle of Lower Kurkar or Beige Paleosol (Fig. 7B). The height of an apron never exceeds that of the remaining cliff face above it (Fig. 7C), except in the rare cases of compound slumping or artificial dumping.

Altogether, the Sharon Escarpment is shaped entirely by slump scars. Erosion is secondasry to slumping as a cliff-sculping factor, and achieves no mature landforms beyond a series of deep narrow gullies that may change downhill into cylindric scour pipes (Fig. 8), which become hanging valleys as the back-cutting slumping overtakes them (Fig. 9).

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). Both the quartz and the bioclastics are marine, the former deriving from the Nile delta (Emery and Neev, 1960; Goldsmith and Golik, 1980) and the latter from the inner littoral.

Cohesion in Lower Kurkar samples was found to be about 30 kPa, nearly zero in the Upper Kurkar which geotechnically behaves as free, non-cohesive sand. The internal angles of friction are 33-43° and 35-37°, respectively.

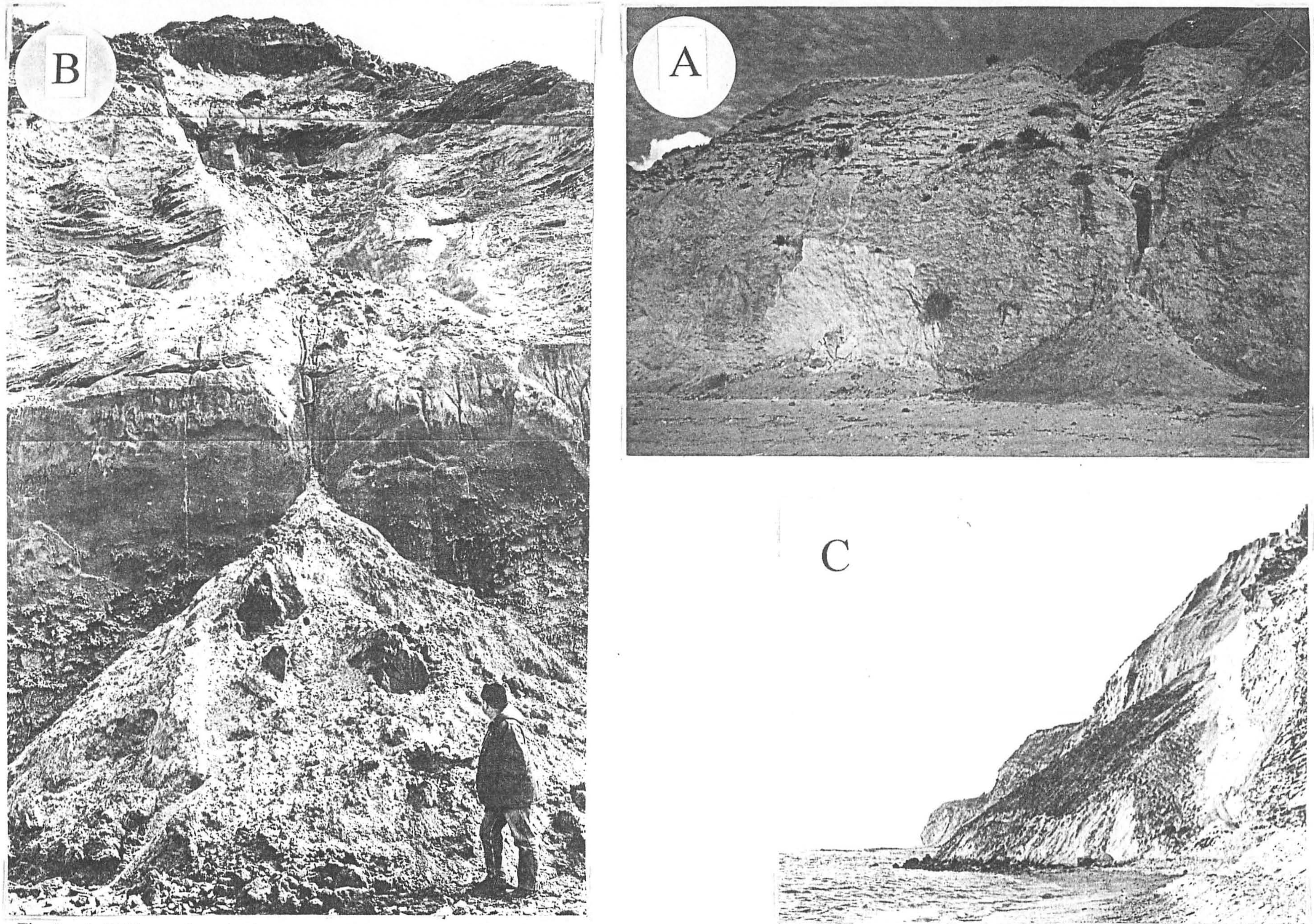


Fig. 7. A. Halfcone-shaped talus apron produced by sand funneling through erosional gully (right), and prism-shaped talus apron produced by slumping of the Lower Kurkar. Note the fresh slump scar (left).
B. Conical talus apron perched on a sockle of Lower Kurkar.

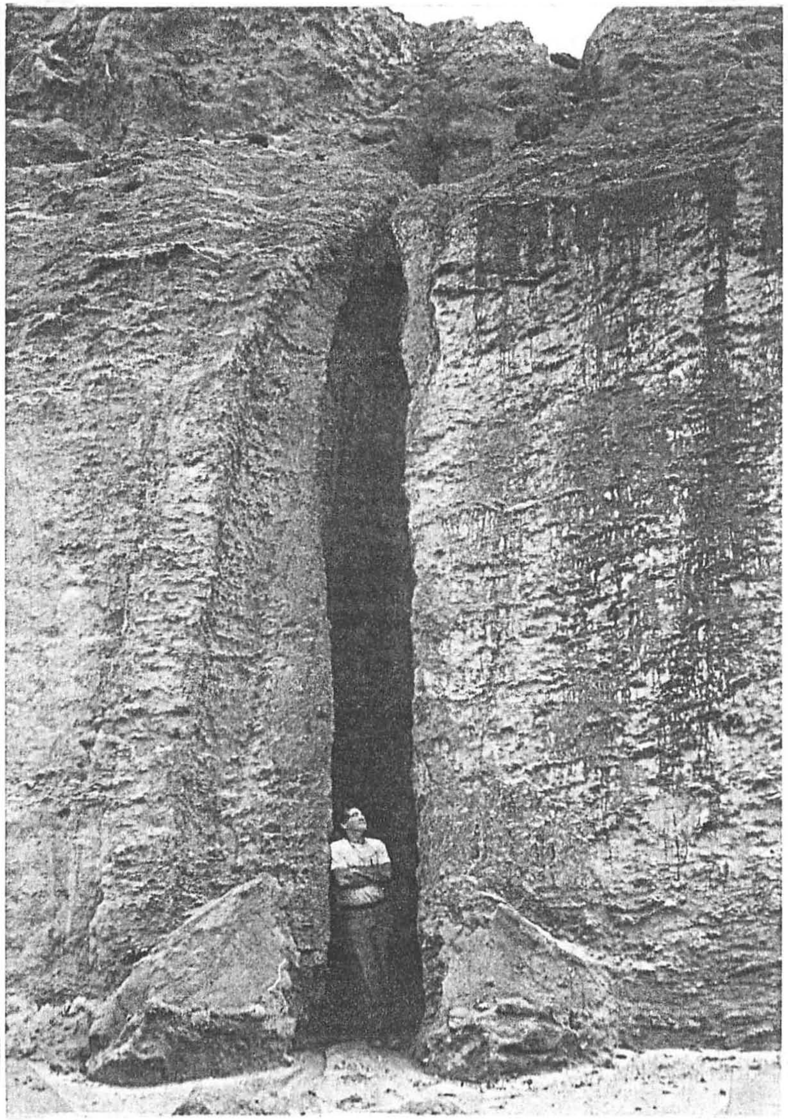


Fig. 8. A cylindrical scour pipe.

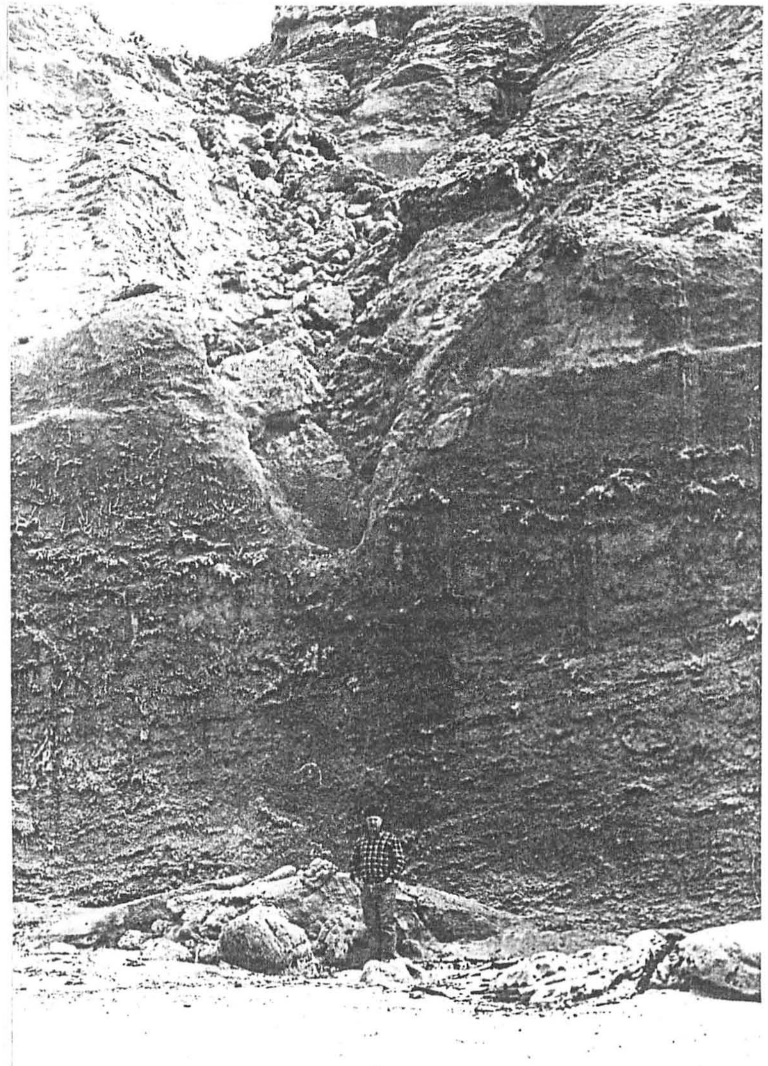


Fig. 9. A deep gully ending at hanging valley due to recent slumping.

Table 1. Geotechnical parameters of the Sharon Escarpment sedimentary units

Unit	Color	Thickness	Slope	Age	Components: Quartz sand	Components: Biogenic sand	Components: $CaCO_3$ cement	Components: Clay	Components: Heavy minerals	Grain size: Grain size	Grain size: Median diameter M_d	Sorting: Average S_o	Sorting: Range S_o	Porosity p	Specific gravity of solids G_s	Bulk density γ	Moisture content w: Before rain	Moisture content w: After rain	Cohesion c'	Angle of internal friction ϕ'
		(m)	(°)	(yrs BP)	(%)	(%)	(%)	(%)	(%)	(mm)	(mm)	-	-	(%)	-	(kg/m³)	(%)	(%)	(kPa)	(°)
Stratified Sand	Light to dark gray	0 - 5		6 - 3,000	80 - 95	0 - 20	-	Negli-gible	Negligible	.200									0	38 - 45
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	Quartz: .062 - .250 Biogenic: .500 - 1.000	.191	1.15	1.10 - 1.19	30 - 50	2.77	1.55 - 1.70	0 5		170 - 600	35
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	.062 - .250	.162	1.33	1.14 - 1.67		2.60 - 2.70	1.82 - 1.86	2	8 - 23	10	35 - 37
Upper Kurkar	Yellowish, gray-white	0 - 38	30 - 50	50,000	30 - 90	5 - 10	5-10	1 - 2	0 - 2	.130 - .310	.137		1.11 - 1.16	4 - 32	2.66 - 2.67	1.50 - 1.65	0.3	8	0	
Beige Paleosol	Beige, dull brown	0 - 5, commonly 1 - 3	55 - 90	Paleolithic	50 - 90	10 - 30	-	10 - 20	0.5 - 5	.088 - 1.250					2.68 - 2.70		1.5		Consider-able	33 - 43
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	.130-.310				2 - 23	2.69	1.55 - 1.70	0 - 2	7 5	30	

The table was prepared using published data. Important data are missing, and the existing data often cover wide range, and are sometimes conflicting.

Main sources:

1. Cliff slopes measured by Wiseman and Hayati (1971) and by Levin (1995).
2. 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) Ancient civilizations by Gophna (1977; 1990), Ronen (1977), Gophna and Ayalon (1980), Herzog (1981) and Gifford *et al.* (1989).
3. Geotechnical, petrographic 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).
4. Strength parameters tested by Zolkov and Wiseman (1965), Wiseman and Hayati (1971), Wiseman *et al.* (1981), Frydman (1982), Komornik and Hayati (1983) and Arkin and Michaeli (1985).

The carbonate cement is a recrystallization product of the calcareous component of the eolianite, its amount and commensurate strength depending on the on-the-spot availability of bioclastics. The general rule which applies on the horizontal scale is (a) that the kurkar becomes more calcareous northward (due to diminishing of the Nile-derived quartz component), and (b) that dune immobilization due to grain cementation has been more rapid in the north than along the beaches south of Tel Aviv where the dune ridges, due to the lower rainfall, have traveled far inland before lithifying. The Lower Kurkar, being older, had more time for cementation and may for this reason be somewhat more resistant. Cementation probably explains the morphologic difference between north and south: slump events in harder kurkar are more widely time-spaced in the north, and embayments persist longer after removal of the talus aprons than in the south. Indentations are deeper from Tel Gador northward, even though the multiannual rates of retreat is the same as in the south (compare Figs. 3 and 4). Kurkar strength depends both on cementation and on the amount of carbonate sand grains (which form a strong bond with the cement than do quartz grains) as well as on irregular variabilities such as porosity, clay content and others (Frydman, 1982). Therefore, outside the above geographic trend, the strength of any patch of kurkar is unpredictable, as can be concluded from the available analytical data (Table 1). Altogether, less than a few hundred samples have been analyzed from about 40 km of cliff, but even these indicate that a technically meaningful sampling grid is not feasible.

Slope stability analysis and the prediction of slope failure based upon geotechnical properties is therefore unrealistic, since most of the cliff is in a state of instability (*i.e.* even a small-magnitude events may effect change). It appears, however, that slope failures are somewhat clustered in winter and spring, which would point to wetting as a major triggering factor.

Since overall strength in the Upper Kurkar is smaller than in the Lower Kurkar, unstable steep slopes cannot build up there, and any slope failure affecting the top of the Lower Kurkar usually activates failure in the slope above it. Mass movements starting on the upper reaches of the cliff usually set off slumping along the way, thus precluding the buildup of large instabilities.

The paleosols, which are secondarily enriched in eolian clay - of continental (eastern) provenance - have little cohesion, about 10 kPa, and their internal angle of friction is larger than 35°. In spite of their low cohesion the paleosol horizons may develop quite steep slopes, several meters high (Fig. 6), and may display a semi-vertical profile through several seasons.

High degrees of cohesion (170-600 kPa) were measured for the upper ledge of calcarenite. The ledge shears by its own weight only 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 broken slab gains no impetus to roll downslope, and constitutes no direct hazard - the bigger the slab, the greater the friction that slows its downslope sliding (Fig. 10).

NATURAL PROCESSES THAT SHAPE THE SHARON ESCARPMENT

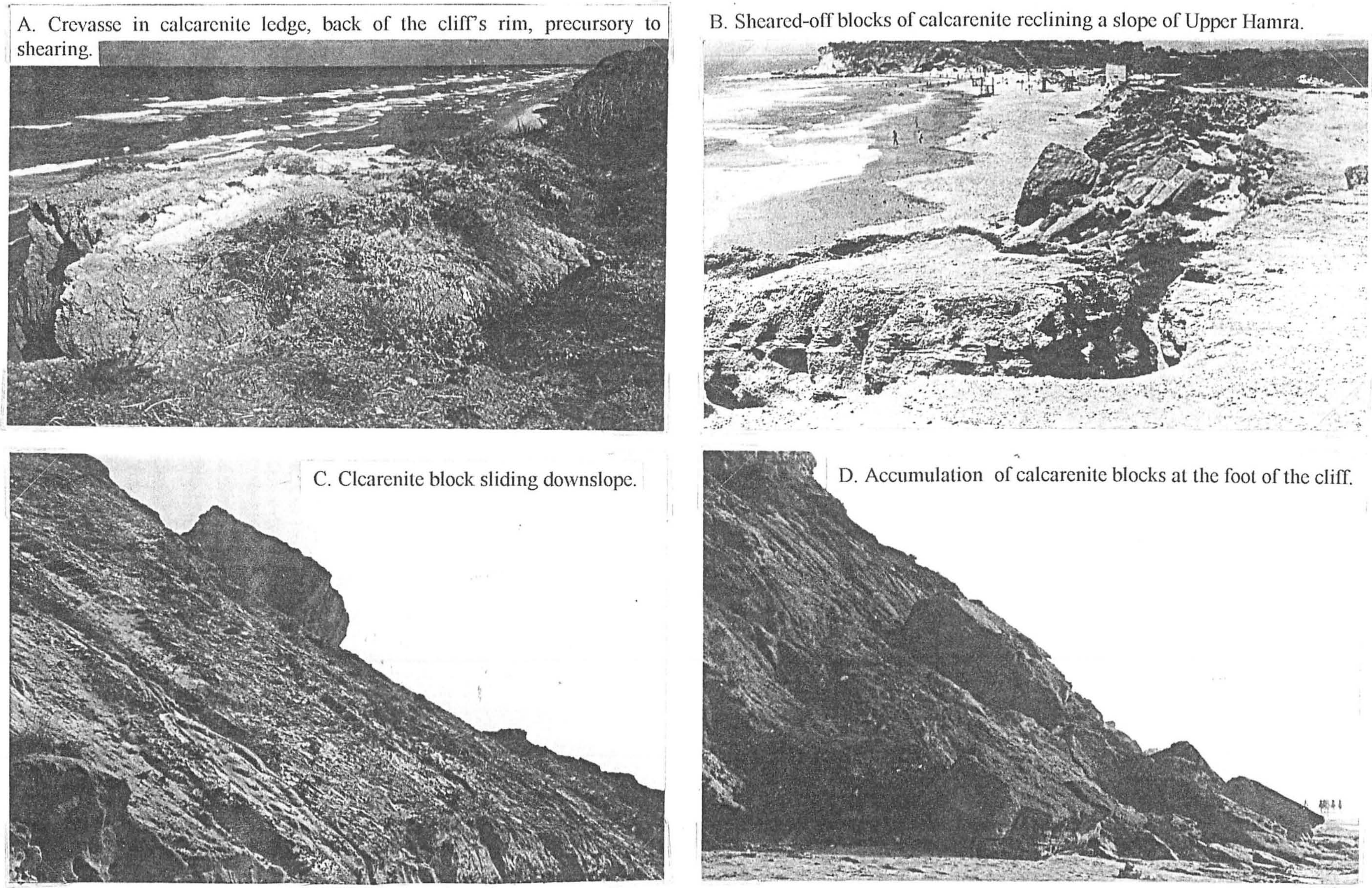
1. Rockslides and slumping

Rapid landward translation of the coastal cliff is deduced from: the many fresh slump scars along the cliff's face, from commonly observed slumping along the slopes and the renewal of talus aprons (Fig. 3 and 7) from discernible retreat of the rim as revealed (though not measurable) by comparing aerial photographs and topocadastric records, from the permanently youthful drainage pattern and its basal amputation (Fig. 9), from the presence of a submerged and abraded reef of eolian kurkar, the sockle of the eolianite ridge, that reaches as far as 250-300 m seaward of the cliff's present base (Fig. 4), and from the remnants of ancient seaside buildings transected by the cliff's rim or scattered among the scree's lag gravels (Fig. 11).

The driving force activating the events that lead to cliff retreat is 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). Not enough evidence is provided by the Sharon Escarpment to allow conclusive settlement of the question. 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 haphazard, 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 (Fig.12).

Rock slumping involves the following cycle of events:

(a) <u>Creation of a wave-cut notch at the talus-free base of the cliff.</u> 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 observed. There may be a delay between cliff-base wetting and kurkar disintegration. 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 a handspan 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 (Fig. 13).



A. Crevasse in calcarenite ledge, back of the cliff's rim, precursory to shearing.

B. Sheared-off blocks of calcarenite reclining a slope of Upper Hamra.

C. Clcarenite block sliding downslope.

D. Accumulation of calcarenite blocks at the foot of the cliff.

Fig. 10. Process of Calcarenite block detachment and downslope sliding.

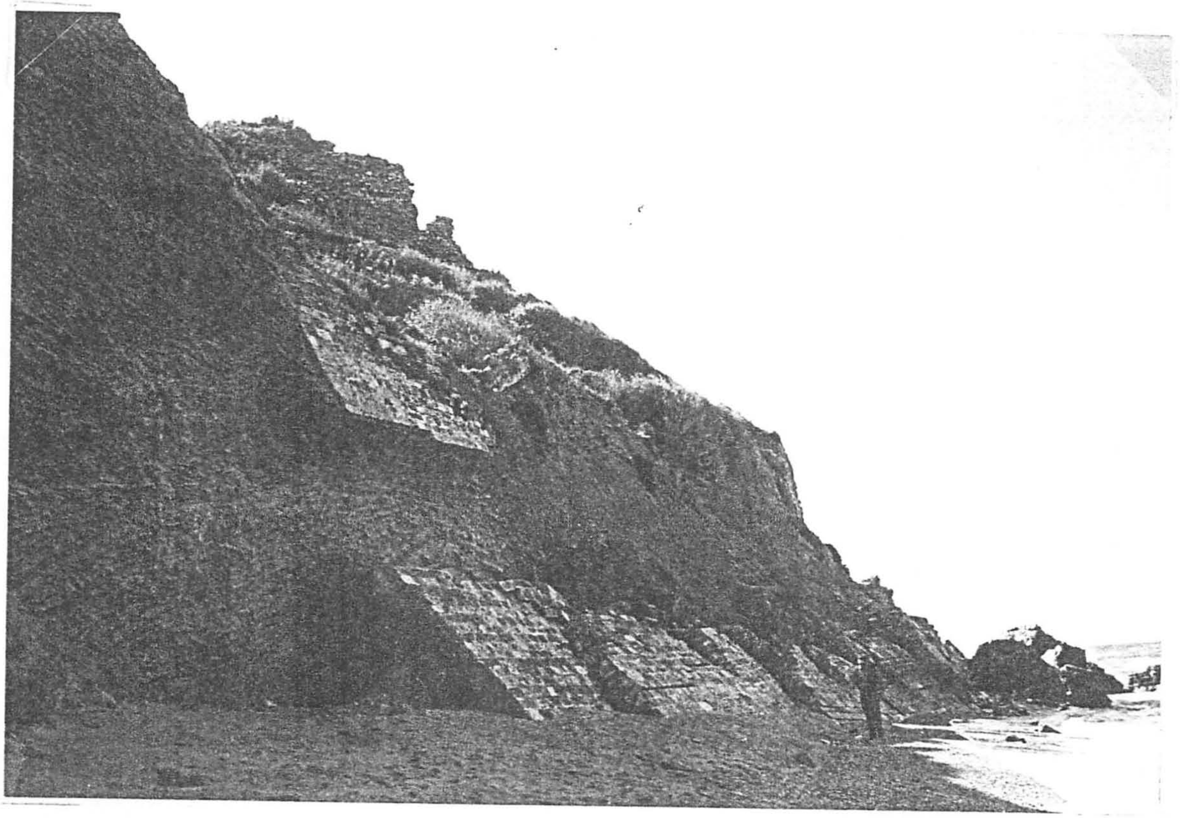


Fig. 11. Slabs of masonry from the defensive moat of the 13th century castle of Arsuf which slumped in 1994.

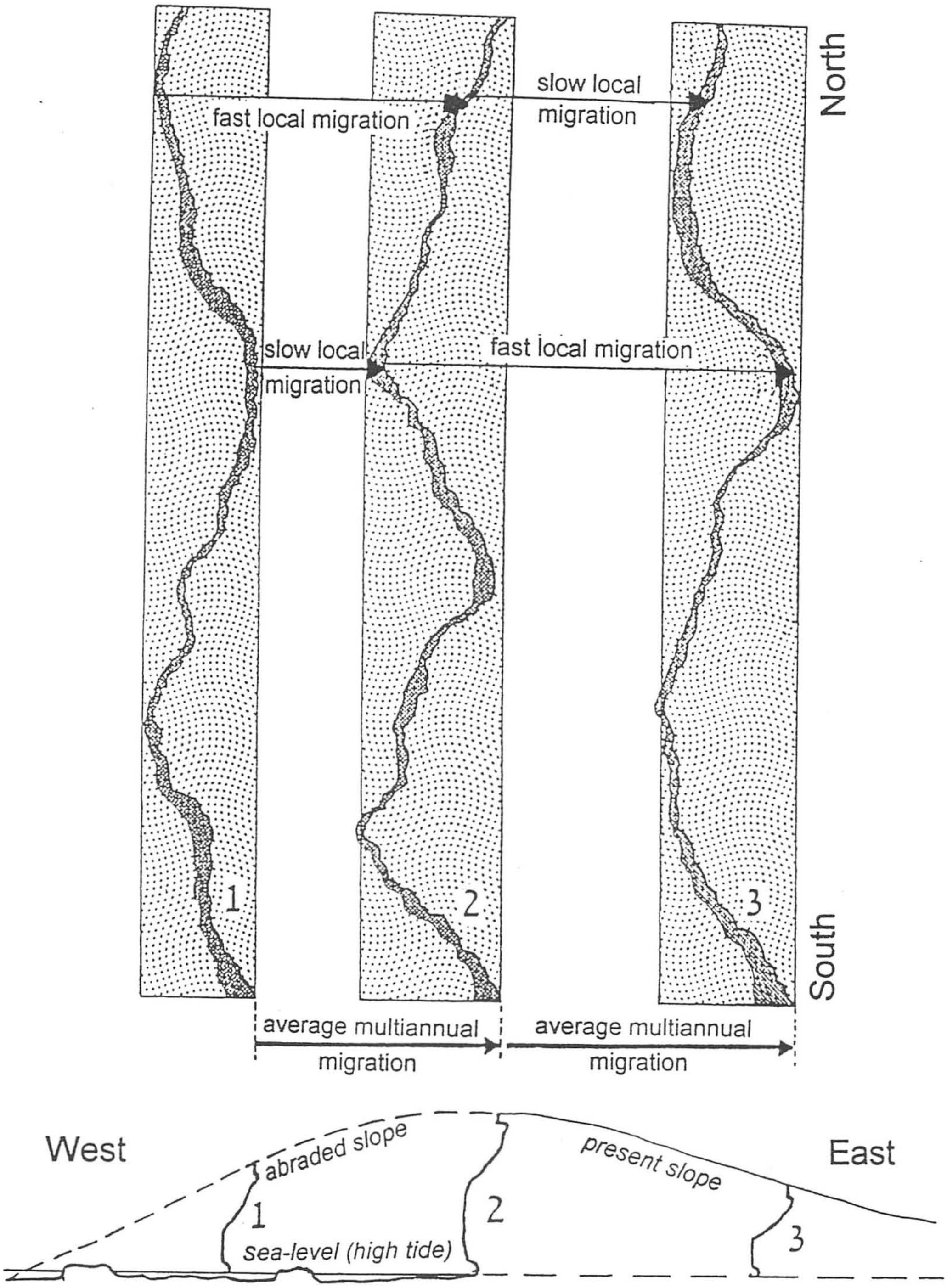


Fig. 12. Stages of the process of cliff retreat.

Cross Section: (1) Past - submerged and abraded kurkar reefs - remnants of the western part of the ridge; (2) Present - the Sharon Escarpment approximately coincides with the ridge line; (3) Future - ridge abrasion will reach the western trough.

Planar projection: Local retreat of the escarpment (darkly dotted) may be haphazard, but on a multiannual scale, the ribbon delimited by the line that connects the escarpment's headlands and the line that connects its bights (lightly dotted) moves eastward at an even rate.

(b) Slope failure is initiated, with the notch as basal instability, setting off upward-translated events of slumping at unpredictable times and places. An average slump is up to several meters wide, slightly listric, detaching a slab of several tens of centimeters thickness and usually no more than a few cubic meters in volume (Fig. 7). Rockslides that nibble the rim (the only ones that register as visible cliff retreat) are maximally 4-6 m wide (measured across the scar) and rarely more than 2 m thick. These rim-affecting 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 (Figs. 7C and 14). A repeated census of slump scars along representative stretches of the rim found that yearly slumps are spaced 19 to 63 m apart, wit average distance usually 38-44 m. Repetition time is 5 to 13 years for a random rim locality, the longer periods usually corresponding to sections of stronger rock.

(c) The talus apron is removed in stages by wave swash. Collapsed waves running up the beach get 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, initially stable because of capillary water and carbonate bonding, but soon drying out and collapsing (Fig. 15). 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, as described above.

2. 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. The entire slope receives water only from rain that falls on the west slope, between the ridgeline and the foot of the cliff - a ribbon that measures less than 100 m across. At localities where the ridgeline has been cut by the 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, percolates through pores and fissures of the sandstone layers, and penetrates into desiccation cracks of the Upper Hamra. Arkin and Michaeli (1985) measured seasonal increases of humidity from 1.5% in summer to 23% in winter for cliff exposures of the Upper Hamra, and 1-2% in summer to 7-12% for the Upper Kurkar.

The rainwater that is not absorbed or evaporated, flows as a sheet wash over the cliff, 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

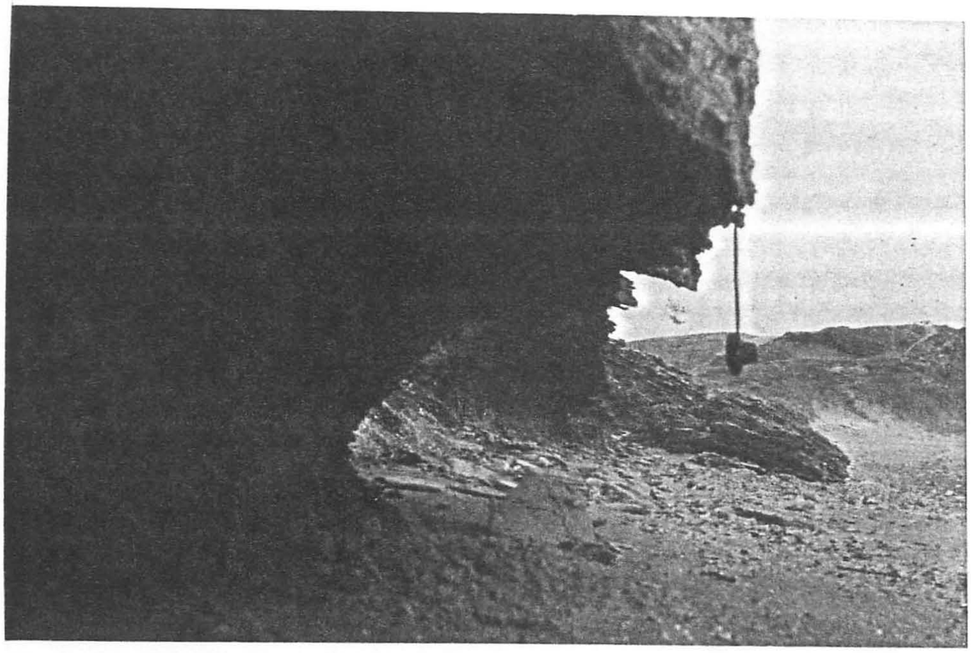


Fig. 13. Wave-cut notch in kurkar at the base of the cliff.

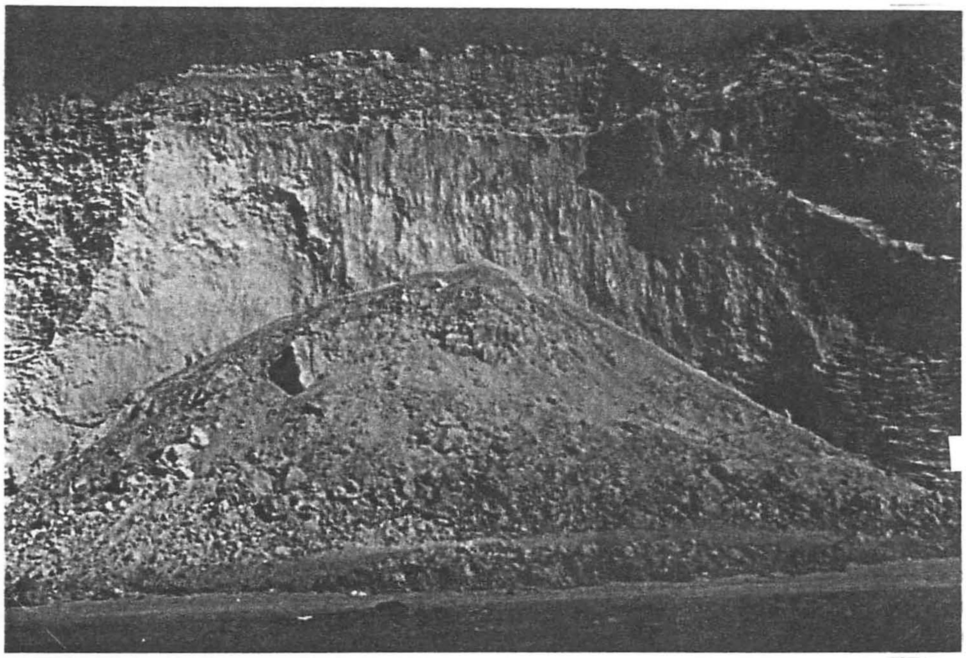


Fig. 14. Very large slump involving the entire cliff front. The toe of the talus apron was bulldozed to enable beach traffic.

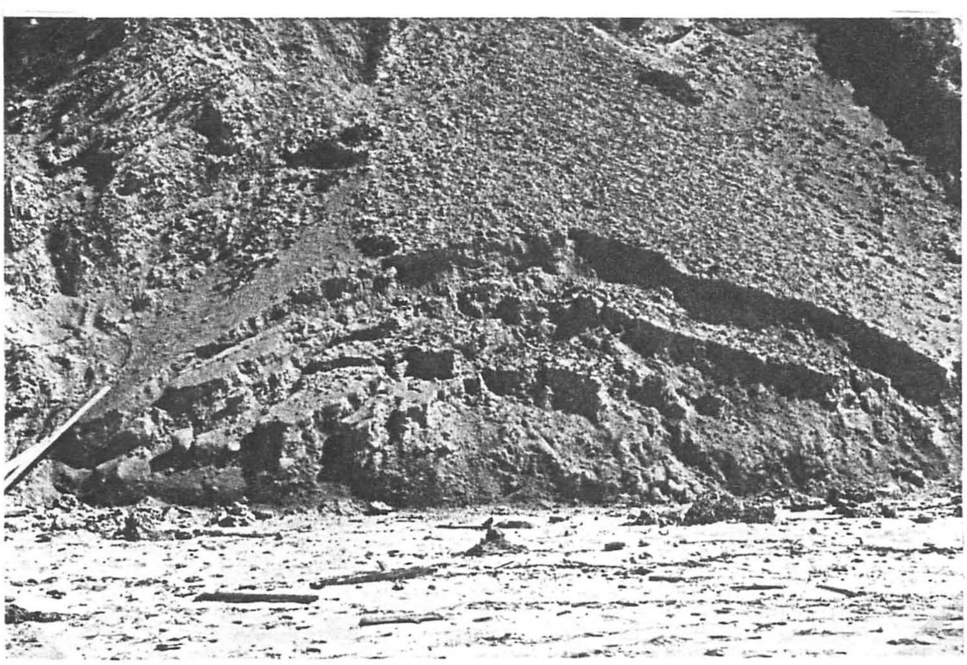


Fig. 15. Repeated removal of the apron toe causes serial step faulting across the apron.

talus. Only a small percentage of the gullies cut back of the cliff's rim, and some of the gullies have short side-gullies - the first buds of a trellis system. The gullies may become a conduit for material slumping from the middle and upper sections of the cliff (Figs. 7A-B and 16). Loose sand, the main erosion product, is spread in the form of a low-angled fan at the base of the gully (Fig. 17), or at the base of its continuation along the talus cone. The fans are washed away by wave swash during the same winter season (fans older than a year are rare) (Fig. 18). Clayey sediment is spread in thin brown crusts over the slope and beach. After desiccation it pulverizes and blows away.

Percolating rainwater dissolves carbonate and enlarges fissures in the calcarenite. Seasonal wetting of the Upper Hamra causes partial liquefaction and flow, forming concave notches in the hamra paleosol. below the calcarenite ledge. Small amounts of clay are flushed out and stain the slope a reddish brown. Where the calcarenite ledge is missing, surface erosion may round the sharp edge of the rim. A considerable amount of 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 superficially resemble breached solution pipes. The pipes are several meters long and may reach from the base of the cliff to its very rim. They may be up to 1 m across, and may grow peripherally and develop into wide funnels and chutes, which guide sandy avalanches down the gully.

Some of the larger gullies that reach the rim have crossed the saddles of the kurkar ridge. They collect runoff not only from the west slope, the catchment area of the Sharon Escarpment, but also from the eastern slopes and from the trough east of it. These ridge-crossing gullies develop within several years into steep gorges with side gullies of their own, bigger by an order of magnitude than those flowing off the cliff from the ridgeline (Fig. 19). Yet, if not tampered with, these V-shaped gorges do not significantly affect the shape and frontal integrity of the escarpment - even though causing great havoc in the eastern catchment area (see below, 1. Drainage, road-building and back-cliff excavations).

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) Wherever observed, cliff-front gullies represent no more than the earliest stage of erosion, *i.e.* series of parallel channels that do not coalesce, and do not have tributaries.

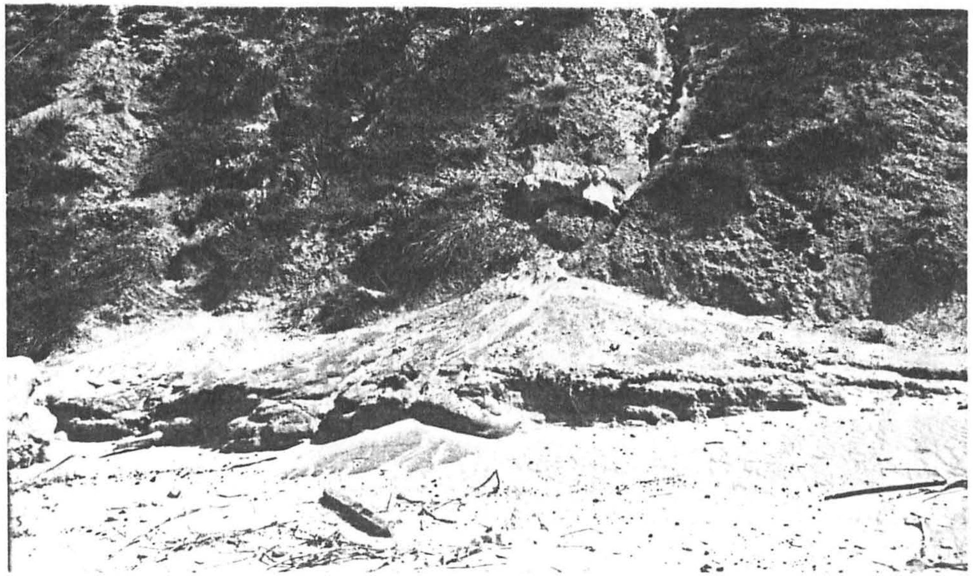


Fig. 17. Wave-stepped alluvial fan.

Fig. 18. Storm waves in the process of abrading the front of an alluvial fan.

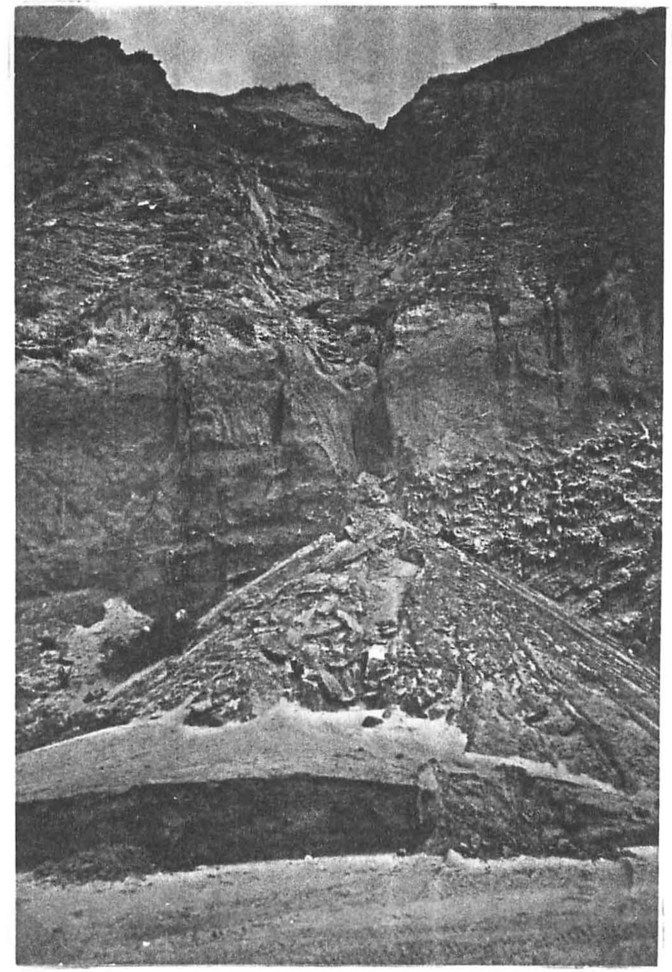


Fig. 16. A wave-cut, low-angled alluvial fan at the mouth of a gully which serves aslo as a chute to the coarse debris. Gullies serve as talus chutes only after they have reached considerable width.

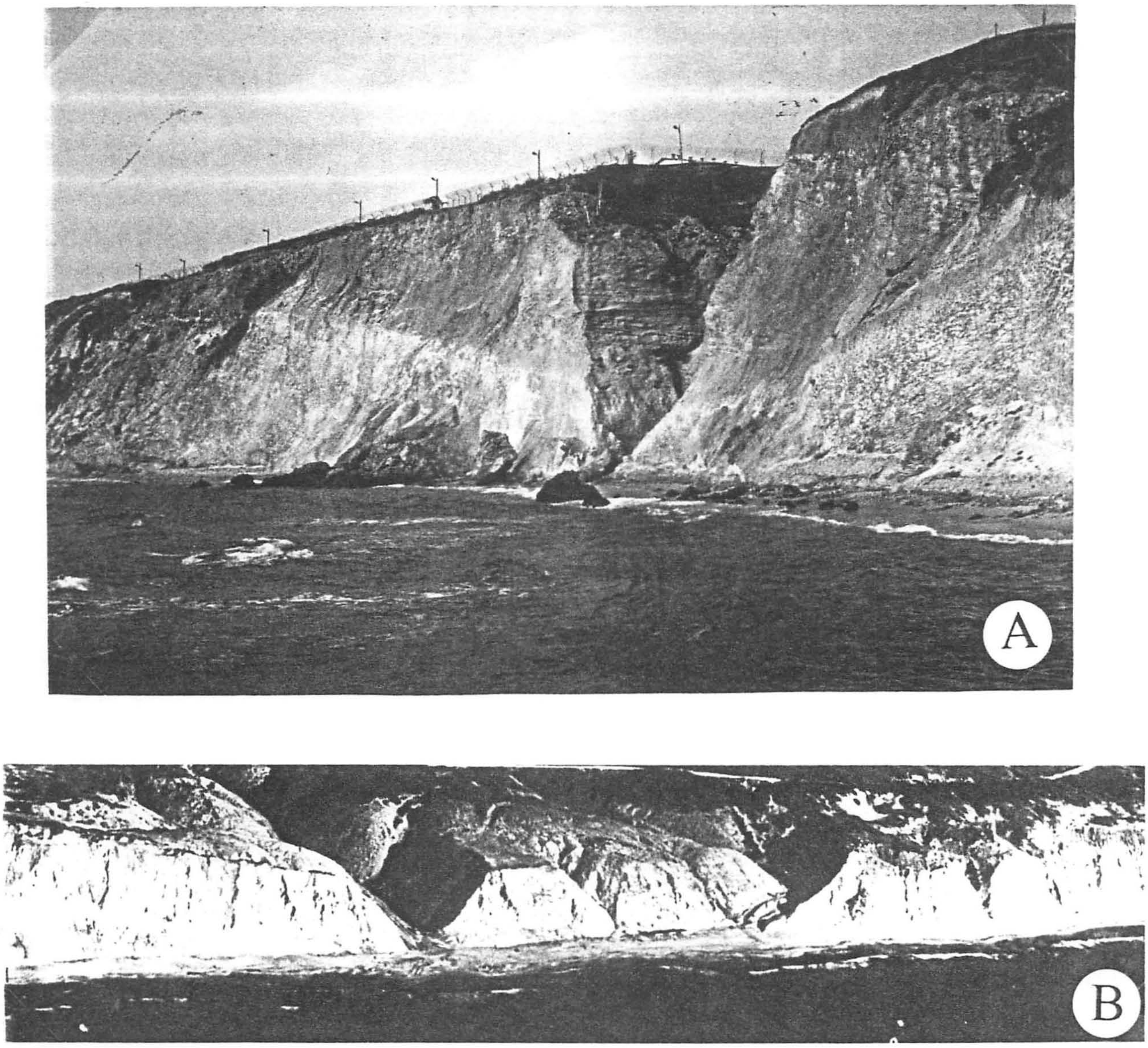


Fig. 19. A. A V-shaped gap of ridge-crossing gorge.
B. V-shaped gaps of ridge-crossing gorges (Photograph by R. Erde, from Nir, 1989).

(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) Almost none of the slump scars carry traces of gullies that existed before the slumping. In some cases pre-slump gullies remain as small hanging valleys in the upper part of the scar. Even so, this is observed only in the lowermost scars near the foot of the cliff, where the gullies are at their deepest (Fig. 14).

(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 gullies and gorges that are fed from the eastern slope of the ridge or from the trough beyond) the fan consists of 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 lost by slumping.

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.

3. Wind and vegetation

The cliff is swept by moderate to strong, very humid sea breezes, with a high salt aerosol content. Sandblasting by these breezes thoroughly scours the exposed kurkar, producing the deflated, sharply corrugated surface texture of resistant lamina (Fig. 5). Strong breezes 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). Concave pitting of the face of the calcarenite ledge appears to be caused by eolian scooping and sandblasting (Fig. 6). 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.

Nowhere is wind observed to produce any acceleration of slumping processes by undercutting or weakening of the rock layers or by triggering talus movement. Together with rain and microscopic salt growths in pores, wind action contributes to the visual aging of fresh scars, but the rate and exact physical nature of this aging, which does not seem to have any effect on the longevity of a surface, are not known.

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 reduces stream energy that produces gullying. In areas where wave-cliff interaction is artificially prevented, the shape and dimensions of the cliff can be preserved for a long time by apron-covering vegetation (Fig. 20). Carpets of *Portulaca* ("Ice-plant"), escaped from domestic gardens, soon become dominant. Slumping breaks up the tangled patches of vegetation and favors their downward dispersal.

DIRECT AND INDIRECT HUMAN INTERFERENCE WITH CLIFF RETREAT AND CLIFF MORPHOLOGY

1. Drainage, road-building and back-cliff excavations

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

Sewage and channelled runoff cascading from the cliff's rim erode funnels and troughs much larger than the naturally-formed gullies, either because of the greater amounts of qater involved or because of their greater cement-dissolving acidity (Fig. 21). Discharge that reaches the foot of the cliff by pipe flows seaward in a shallow rivulet, which is repeatedly swept by wave swash. There is no fan buildup, no undercutting of the cliff behind the pipe (other than natural wave-notching), and any stream channel in the beach sand is rapidly obliterated.

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 trench carries no runoff from beyond the cliff's catchment area, it behaves no different from a natural gully. The water flowing through the trench would have flown through another gully, and the overall volume of erosion from this catchment area remains essentially the same. However, 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

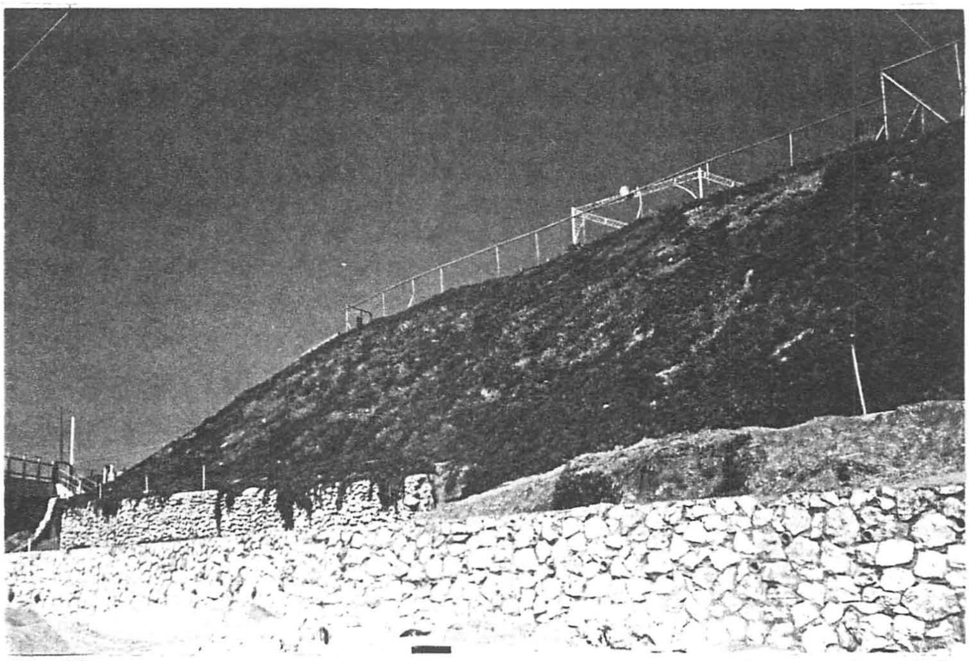


Fig. 20. A carpet of Portulaca ("Ice-plant") planted to prevent slope erosion of the graded cliff. head. Lower buttressing wall prevents notching of the cliff's base.

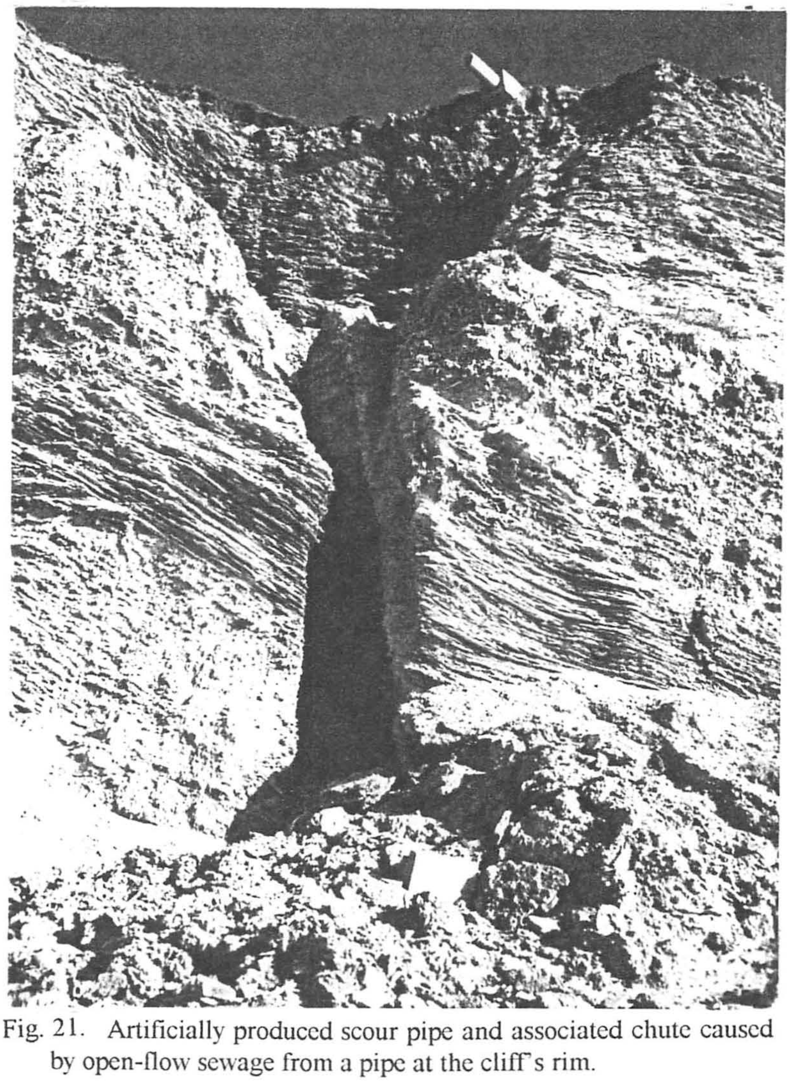


Fig. 21. Artificially produced scour pipe and associated chute caused by open-flow sewage from a pipe at the cliff's rim.

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.

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 at raintime like artificial torrents which accelerate the maturation of the local erosion system (Fig. 22). (Grooves excavated by the recently popular "sport" of uphill climbing by cross-country vehicles have similar effects - Fig. 23). 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 (Fig. 24). 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 sites) has been applied to date, except on some privately-owned property.

(b) In its natural state, the surface layer back of the cliff's rim consists of one to several meters of stratified sand, stabilized by the presence of clay and humic substances, and overlain by extensive patches of mobile dune. When undisturbed, the sand substrate 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 all along the cliff's rim, which north of Tel Aviv has been stripped down to the calcarenite 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.

Fig. 22. A. Heavy erosion of a beachward descending road excavated at right anle to the cliff.

← B. Back-cutting erosion of the road in A creates badlands and gorges back of the kurkar ridge.

Fig. 23. Deep grooving by cross-country vehicle tracks may become erosional channels at raintime.

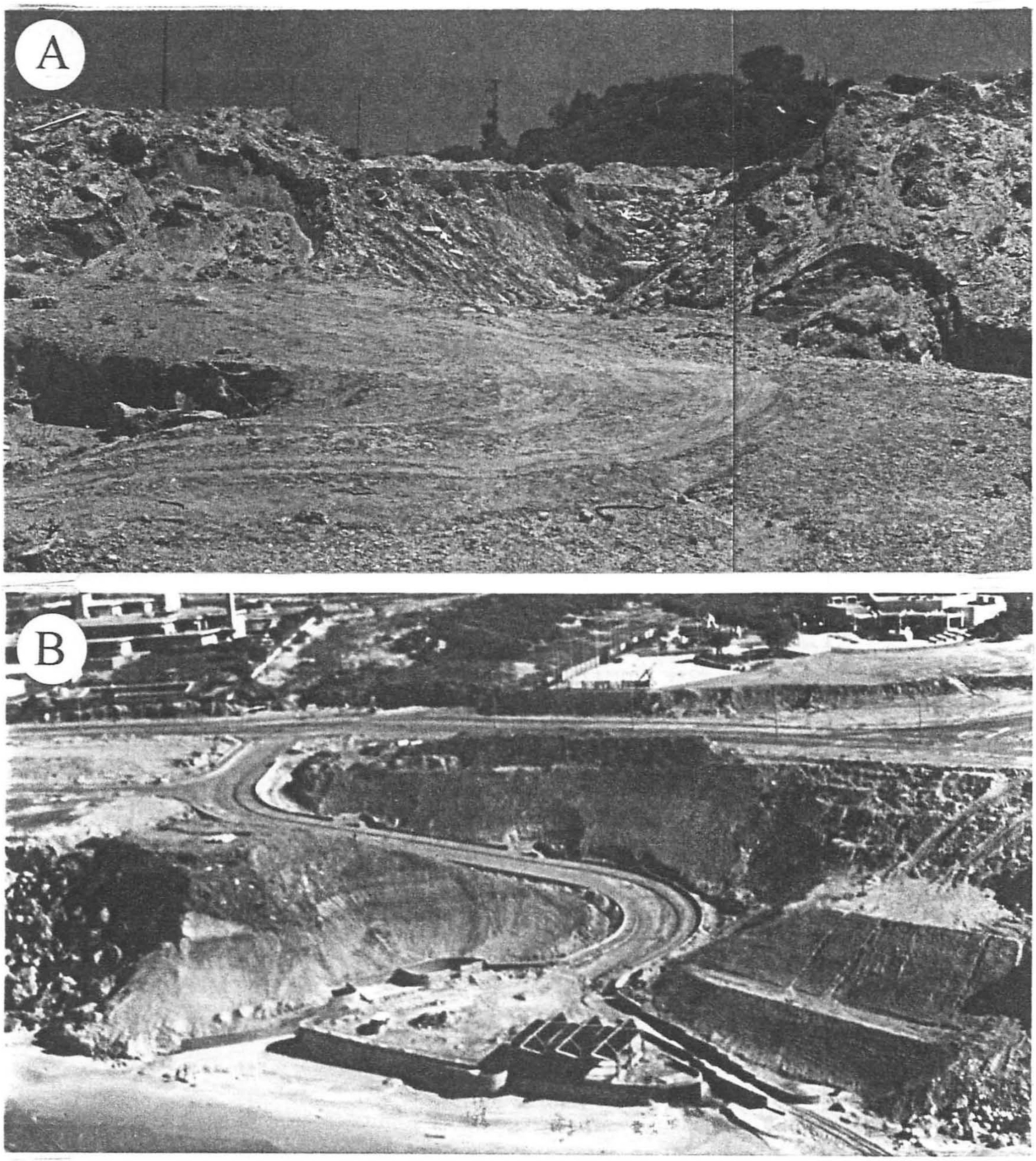


Fig. 24. A. Heavy erosional damage to artificial road and parking lots built on an artificial fill of previous erosion gap.
B. New grading and roadbuilding at the same site presently enables runoff-producing catchment areas and slopes.

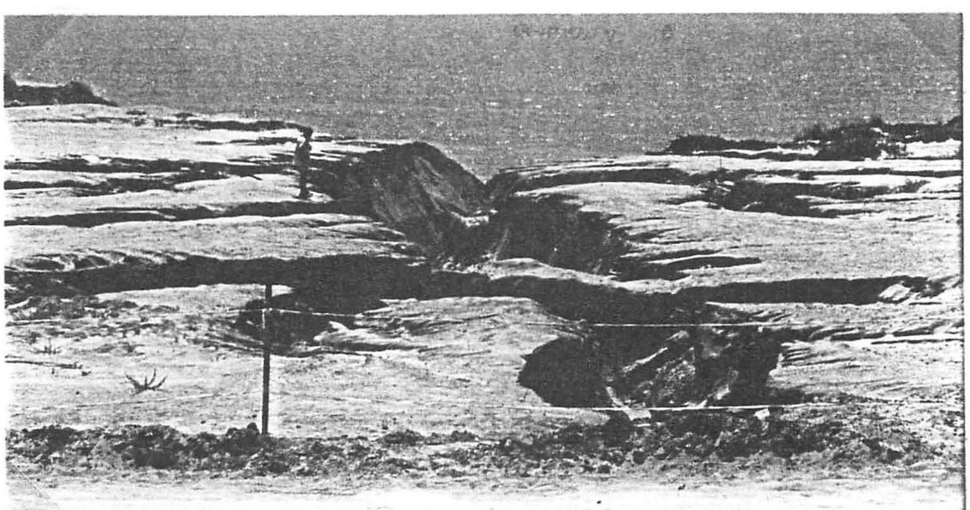


Fig. 25. Runoff erosion carving badlands into artificially exposed Upper Hamra denuded of its calcarenite and strataified sand cover.

Removal of the sand cover threatens the stability of the entire erosional regime. All of a sudden, 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 (Fig. 25) 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 (Fig. 19). 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.

It should be emphasized that we are not dealing with the acceleration of a pre-existing natural process, but with an entirely man-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 imperishable porous rubble material, sufficiently 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.

2. 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 (including artificial tombolos), 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. 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 reduces its slope and promotes more contact between cliff and wave swash. This affects cliff retreat 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.

It is not clear whether the removal of beachrock ledges from the lower intertidal belt affects the reach and energy of wave swash. Beachrock acts as a sand trap and favors the conservation of beach sand; on the other hand it is a potential barrier to marine sand supply. Over the centuries beachrock has supplied building stone to shore settlements, but whether or not this has had any indirect 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 public bathing beaches and from narrow stretches of 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, 1. Rockslides and slumping; and below, 1. Degrees of risk - risk B), the effect is not - as yet - notably influential, but it may be crucial for the life expectancy of specific structures on the overhead cliff (Fig. 26).

3. 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 gorges that erosion has carved into the cliff's rim and landward of it. Moreover, 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 and nor stable (Fig. 27). Many components consist of netted fabrics that entangle heavy, non-disintegrating blocks, much more 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, yet the cliff's base behind it is in the meantime not adequately protected from wave wetting and notching.

Garbage dumping - aesthetics aside - efficiently repairs the damage of accelerated man-caused erosion (Fig. 28). 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 loose sand and debris have been pushed over the rim of the cliff and smoothed over, in order to create space between the houses and the cliff's rim. In all these 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 rubble lag 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 less than absolute protection of the cliff base. The role of dumped maturated garbage in the beach environment should be investigated also from these two aspects.

4. Slope grading

At several beach municipal localities the entire cliff has been bulldozed to low-angled slopes, 30° and less. At these angles the position of the cliff is stabilized, and 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.

Morphologically the grading, by eradicating the slump-generating escarpment, puts an end to cliff retreat through the process of undercutting and slumping. Erosion remains the sole cliff-destroying factor. Moreover, the grading usually enhances erosion to unprecedented dimensions by

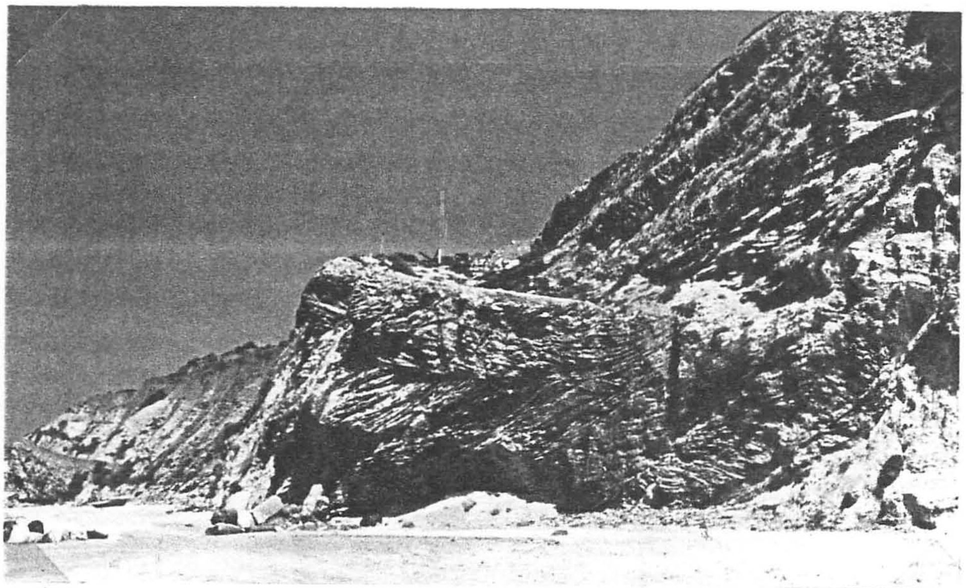


Fig. 26. Beachward descending road (constructed in 1989) has been amputated by cliff retreat accelerated by repeated talus removal.

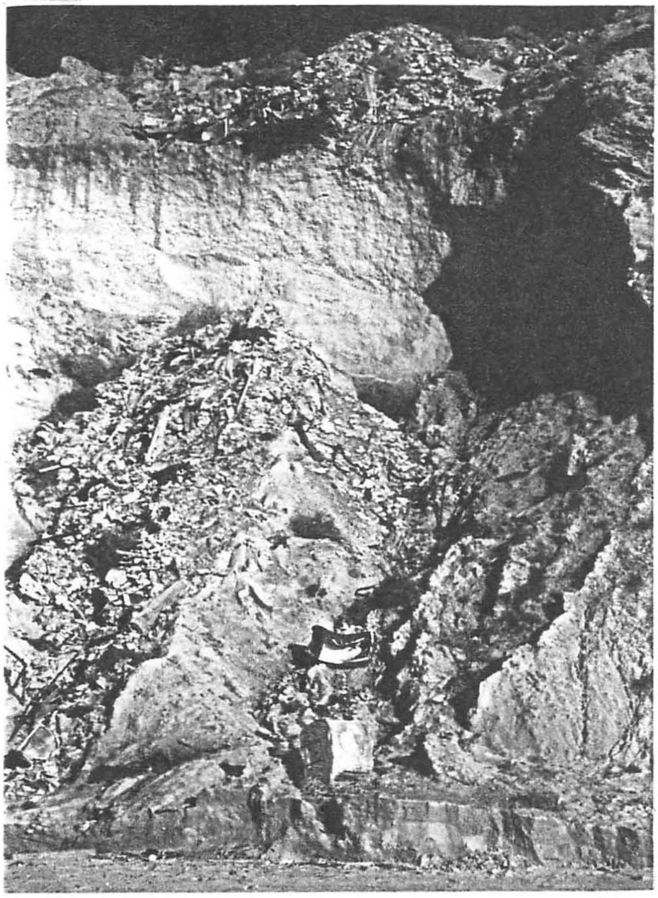


Fig. 27. Talus consisting of urban garbage.

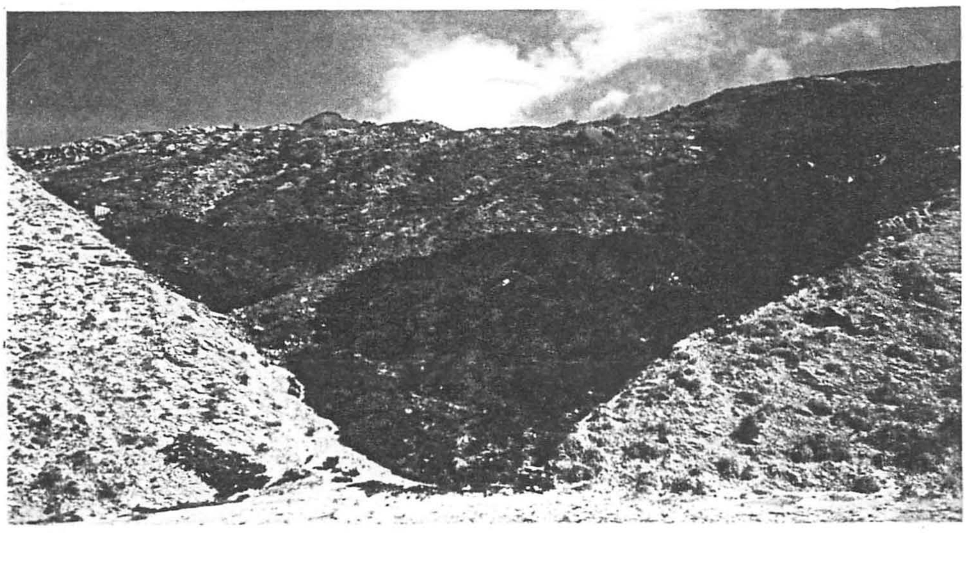


Fig. 28. Stable garbage filling in a V-shaped gorge restores the cliff. The garbage porosity prevents erosion by runoff, and supports a lush vegetation.

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 horizontal distance between the cliff's base and its rim. Where grading includes a saddle of the kurkar ridge, the western trough 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.

A ubiquitous attendant phenomenon to cliff grading is the unbridled swarming of rough-terrain vehicles, which pulverize and plough up the terrain, scour deep ruts in the substrate (Fig. 23), and attain within days effects which erosion would need seasons to achieve, in areas which erosion would be slow to reach.

The construction of terraces with well-draining retaining walls and the planting of soil-stabilizing vegetation, may prolong the existence of the graded slope, but requires sustained investment in counter-erosion effort. Plastic sheeting and blanketing with grass carpets are of unproven permanence. Control of the runoff before it reaches the graded slope, and the building of effective barriers against wave swash, are necessary if the graded slope is to be preserved for any length of time. Without this investment, graded sections will become gaps in the Sharon Escarpment, similar to the natural gaps of the Olga, Alexander, Poleg and Yarqon outlets.

5. Buttressing and aproning

At several localities where cliff retreat constitutes an imminent danger to immovable property, practical measures have been taken to halt the process. Artificial talus emplaced in front of the cliff is subjected to rapid runoff scouring and gullying, and may be completely washed away by wave swash in a short time (Fig. 29). 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 (Fig. 30), 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 (Figs. 20 and 31). 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 (Fig. 31). However, since the remaining beach is narrow and the cessation

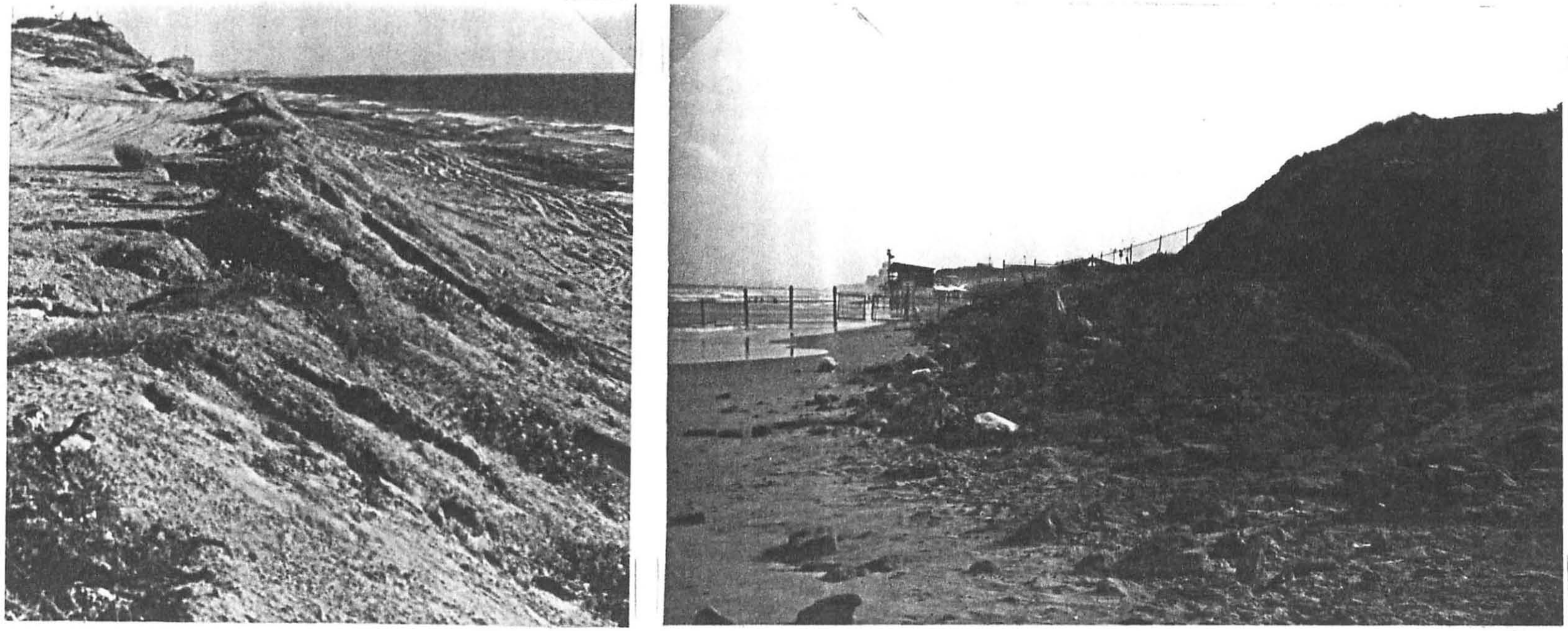


Fig. 29. A. Artificial talus, heavily scoured by rills subjected to rapid runoff gullying. B. Talus was completely removed by wave swash.

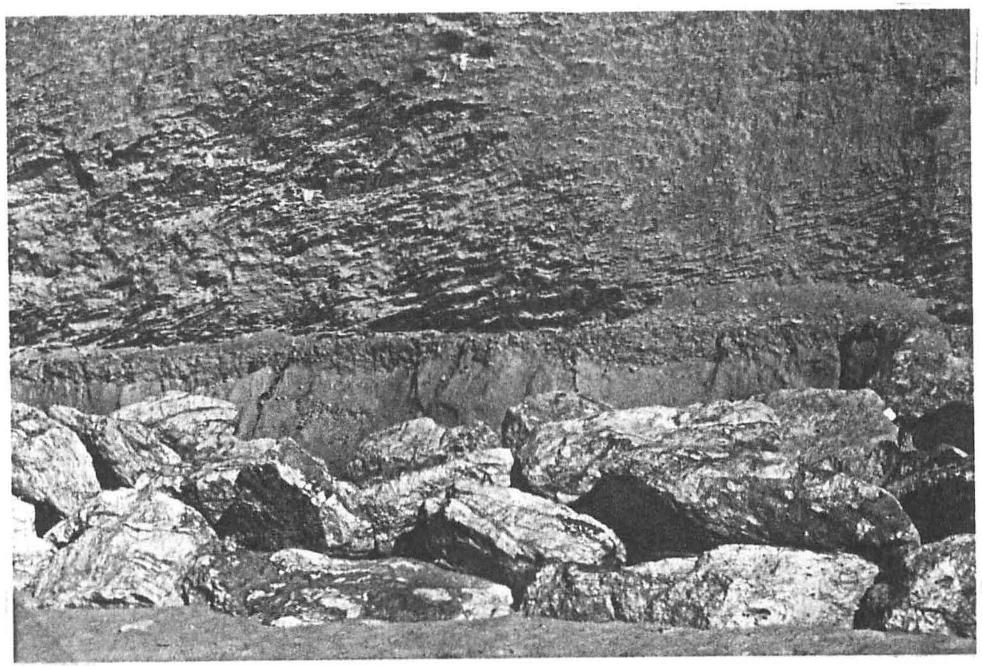
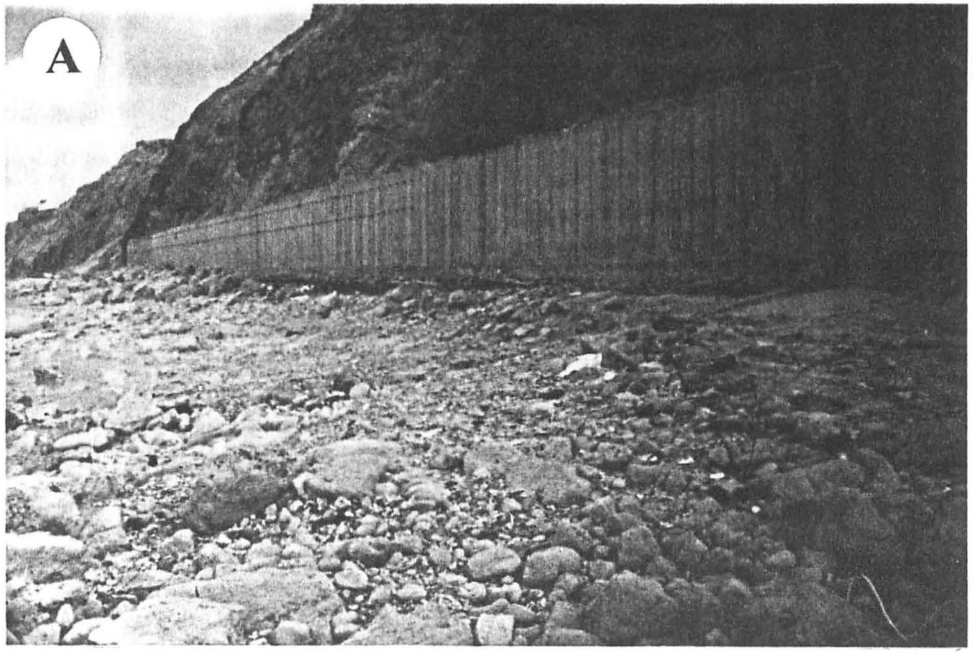


Fig. 30. Heavy stone revetment in front of the cliff base does not prevent talus erosion and sand removal



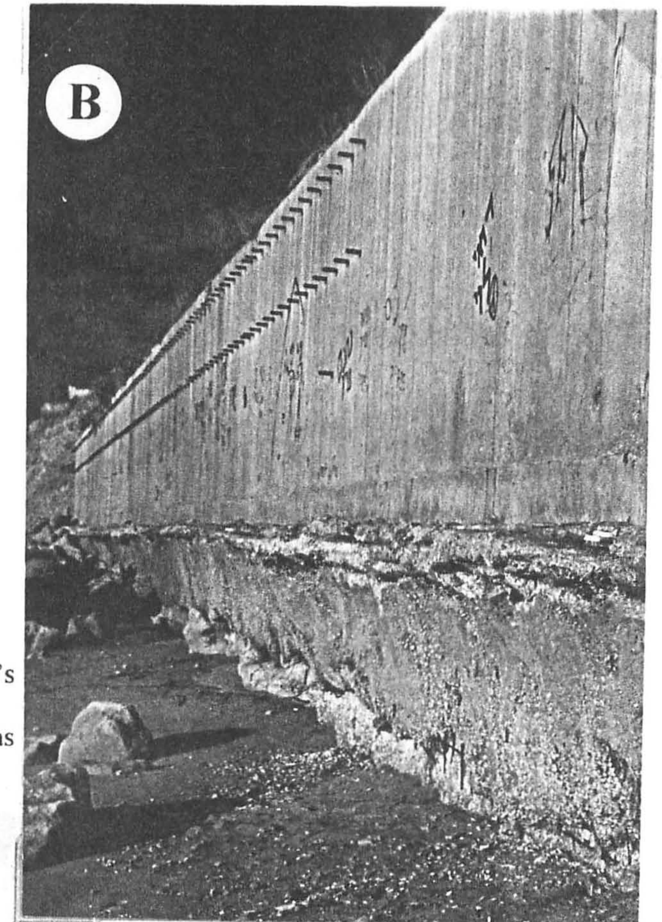


Fig. 31. A. Deep-founded concrete wall effectively prevents wave notching at the cliff's base.
B. In five years since its construction sand removal by wave swash has exposed 1.20 cm of the foundation without resulting collapse.

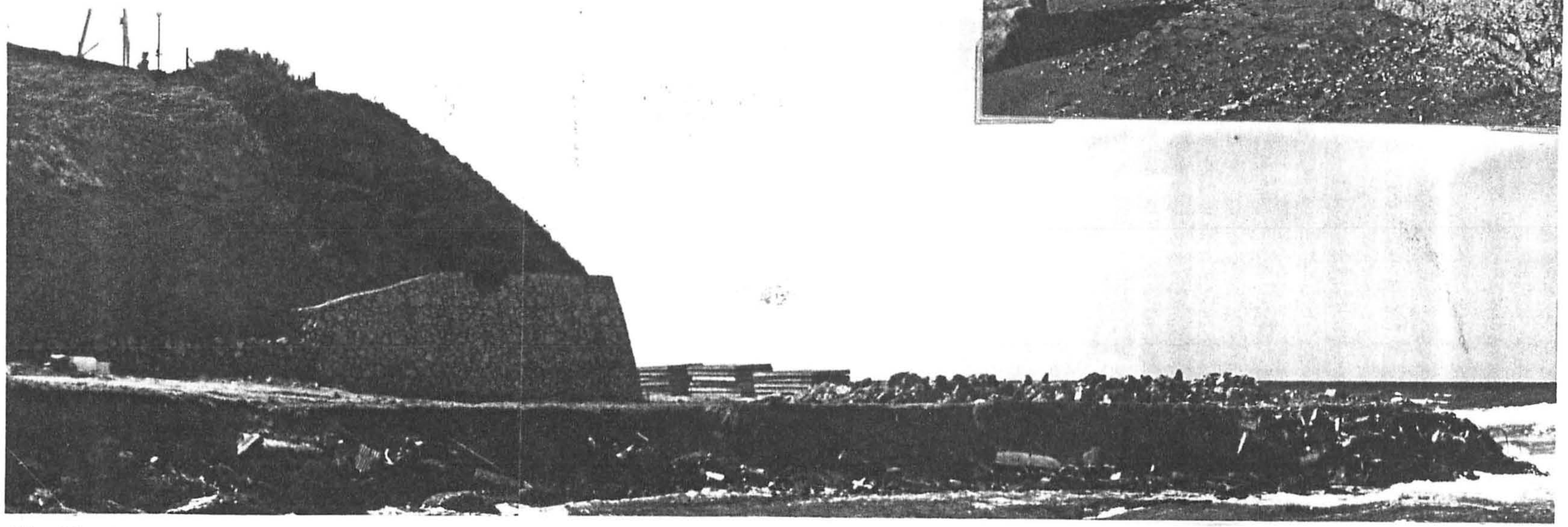


Fig. 32. Masonry revetment aproned by heavy rubble effectively arrests cliff-front slumping and retreat. Erosion of upper cliff is reduced by cliff grading and vegetation cover.

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 (Fig. 32). Cliff-base protection by plastic sheeting - as has been attempted in several localities - may be effective, even though 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.

THE SHARON ESCARPMENT AND HUMAN HABITAT

As seen above, the Sharon Escarpment is a vulnerable environmental feature, and it is important to evaluate its place within the human sphere in order to preserve its qualities and live with its risks.

Among the qualities that make the Sharon Escarpment worthy of preservation are the following:

1. The cliff top commands open seascapes, receiving day-long sea breezes throughout the hot rainless summer. Because of its immediate proximity to bathing beaches, recreation and commercial centers, land prices are among the highest in the country.

2. The cliff deflects nearground sea breezes upward, and provides a barrier against flying sand, salt spray, windblown flotsam (including windrolled tar pellets) and rotting beach refuse which plague the non-cliffed shores.

3. The cliff forms a functional barrier between two zones of activity that should not interfere with each other: The bathing beach (sports and recreation, children's area, lifesaver facilities, no motorized traffic) which is bounded by the sea, and the urban sea front (boulevard traffic, hotels and restaurants, shops and parks) which is bounded by the city center.

4. The cliff preserves relics of the natural, pre-settlement maritime environment: unique landscape forms, sculptures of nature, endemic phyto-communities with rich winter-spring blooms, and cliff-adapted wildlife.

5. The cliff contains and reveals historical relics and remnants of ancient shore civilizations - the only data from which to study extinct environments and cultures.

On the other hand, the existence of the cliff presents discomforts and even risks, which can be remedied at a cost. The cost can be very substantially reduced if the extent and degree of the risks are accurately known. They include:

6. Hazards of falling off the cliff's rim (unrelated to rock slumping).

7. A belt of potential slumping risk, about 2 m wide, back of the rim (liability to existing or planned structures).

8. A belt of danger from falling rock and sliding talus, up to 12 m wide (calculated by Perath and Almagor, 1996), prohibiting human use and incurring partial (though temporary) obstruction of beach traffic.

9. Difficulties in beach access due to the cliff's steepness. This curtails to some degree the full utilization of the *ca.* 10-20% of total Mediterranean beach length that is available to the public (as mentioned above, the rest is taken up by ports and marinas, power stations, industry, military areas and private beaches).

The risk situations are fairly well mixed and heterogeneous, caused by strictly local point events. No along-beach trends or sequences are discerned; the cliff-forming processes are neither propagated nor guided in lateral directions. For the same reason, no artificial intervention with cliff retreat can be laterally effectual beyond its locus of application. In any planning that involves either tampering or non-tampering with the cliff, the above nine points, duly weighted for local conditions, should be evaluated.

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

1. Degrees of risk

The most serious risk incurred by conservation of the cliff in its natural state is the slumping hazard (point 8 above). Although the process is chaotic and unpredictable on the miroscale, it can be fairly well determined where and how large the stricken area will be, or when rock sliding and talus slumping will **not** occur. A survey was carried out to define the boundaries and distribution of the various risk situations along the undisturbed Sharon Escarpment.

Three risk situations, A, B and C (Fig. 33), which recur systematically in the course of natural cliff retreat, were defined in terms of severity of the next event.

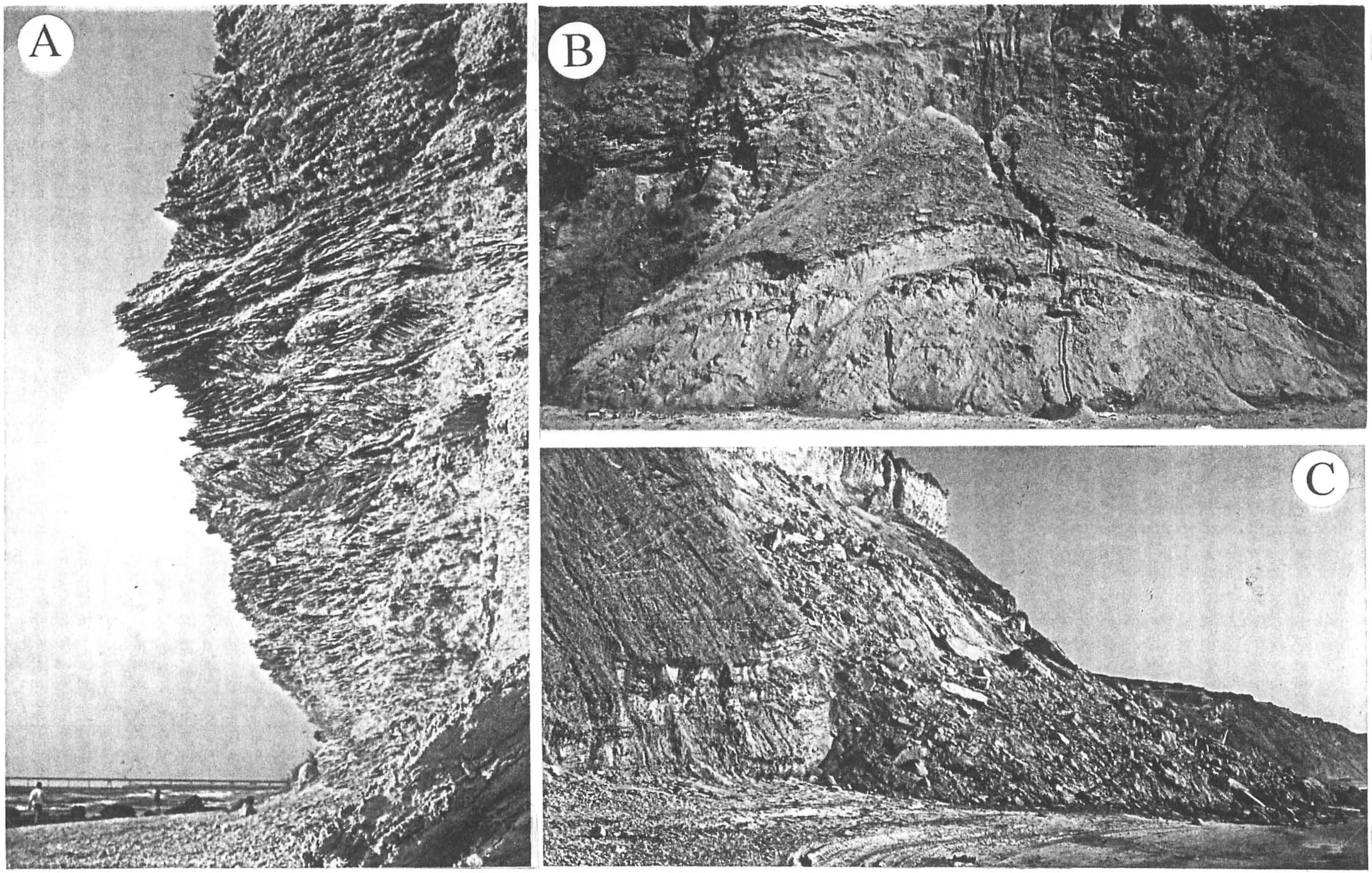


Fig. 33. A. Risk A - Pre-slump situation: steep, exposed cliff notched at its base.
B. Risk B - Pre-slump situation in talus: wave-cut, vertically stepped apron toe.
C. Risk C - No-risk situation: talus apron protects the cliff's base.

Risk A, the severest, is the degree of hazard presented by exposed rock cliff, bare of talus, 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, and the next event is collapse of its loose sand and riding chunks of calcarenite onto the beach in front (Figs. 6 and 10). Risk C is presented by cliff aproned by talus that has not been wave-swept (Fig. 7C); 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.

Cliff retreat proceeds through a periodic risk cycle (see above, 1. Rockslides and slumping) (Fig. 34). Slumping is invariably preceded, by definition, by a Risk A situation, and is immediately inherited by Risk C. As wave-sweeping and apron slumping clear away the talus in stages , risks C and B alternate until the cliff is again bare from its base upward, returning to Risk A. The risk situations are contiguous along the Sharon Escarpment without any gap and without any compounding or overlap. At any point along the cliff the certainty of the next event is unique and absolute, while the probability of its happening increases with time. The distribution and length percentage of each risk along the cliff's length are proportional to their frequency of occurrence and/or to their persistence in time - two parameters that vary within naturally-set limits.

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), nor can the expected time until the next event be determined, except roughly by observing the state of erosion and the maturity of the vegetation. By comparing photographs and field observations taken over more than 10 years it could be established 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) occurs more briefly.

The causal relations that produce the risk cycle are known, as are the conditions that determine their magnitude and duration (spatial distribution of rock strength and temporal frequency of wave swash), yet these are insufficient to define exactly when and where along the escarpment the next event will happen. Nevertheless, an analysis of the risk distribution pattern provides sufficient insight for determining the present-day trends, and for predicting effects - and possible costs - of artificial interference.

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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, differentiationg the stwo situations, was carried out on sample stretches only.

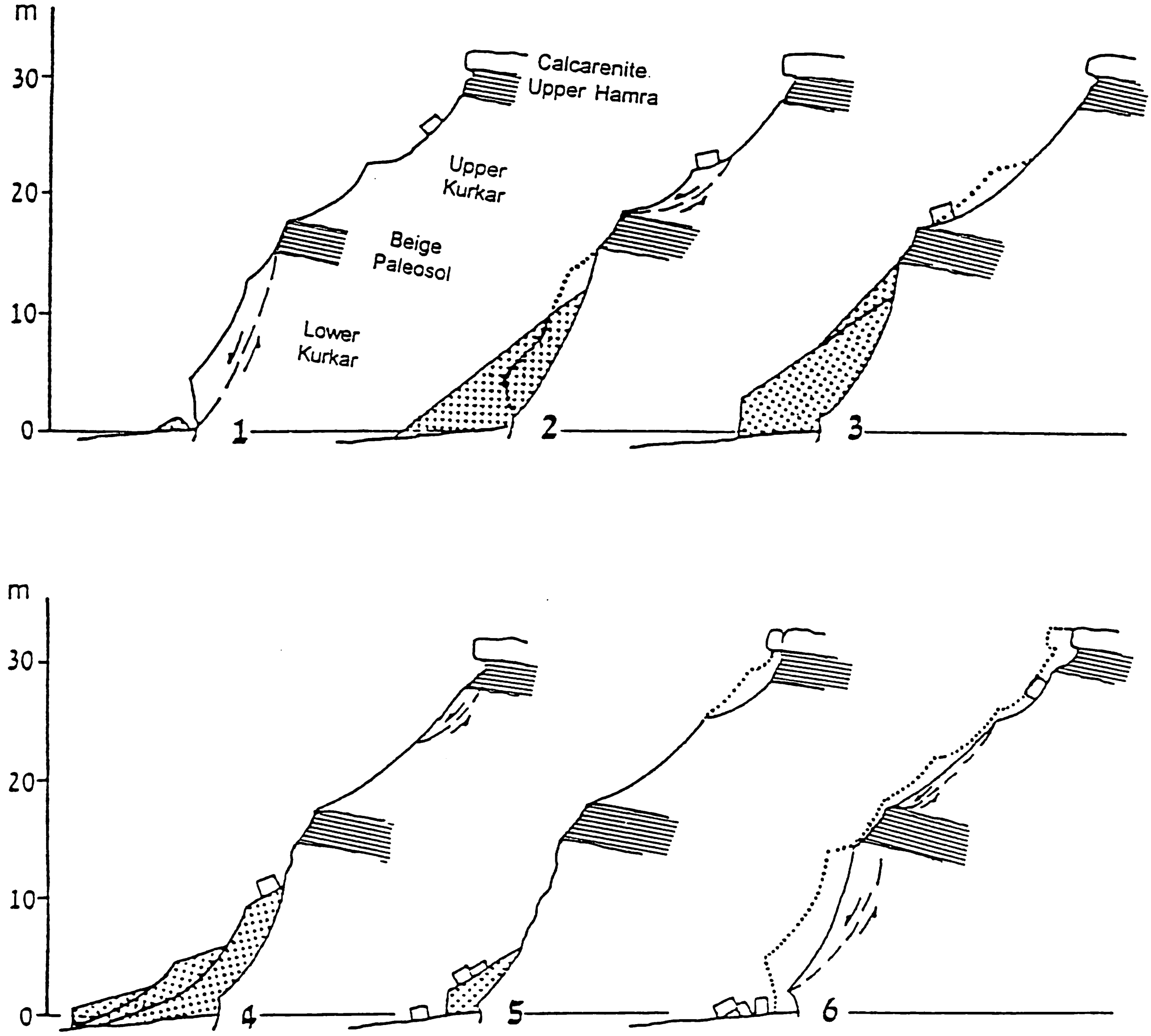

Fig. 34. Risk cycle: 1 - A; 2 - Risk C; 3,4,5 - Risk B; 6 - Risk A. Dashed line - potential failure plane; dotted line - part of the cliff that slumped; hatched area - talus apron).

2. Distribution of slump risks along the Sharon Escarpment

Representative segments of cliffed beach totalling 32,710 m were surveyed by oblique aerial photography and ground-based measurements. Altogether, 372 risk sections were determined. (It should and could be emphasized that the data represent a random moment in the behavior of a dynamic morphologic system. Repeat data acquired at later and earlier dates should determine how representative the sample is). 74% of the risk sections are shorter than 100 m. Some 46% are shorter than 50 m, and only about 14% are longer than 150 m, the longest reaching 950 m.

The types of risk are more or less equitably distributed among the three categories (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 season of surveying, which was toward the end of the uncommonly stormy 1992 season, when frequent wave swash had recently transmuted many Risk B and C situations to Risk A. This by itself is no proof that risk transitions are always season-clustered. When comparing cumulative lengths, one finds that Risk C occurs along 40% of the surveyed beach length, Risk B (the most transient situation) along 27%, and Risk A along 33%. 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. It is not at all clear how the risk distribution or their overturn rate would be affected by different conditions (less or more storms; stronger or weaker rock; faster or slower retreat) would affect the risk distribution.

A definite range of lengths seems to characterize all the risk categories alike, and is determined by the random interplay of random wave swashings with rock of random strength distribution.

When lumping length values of the three risk categories together (Fig. 35), it appears that the pattern is most strongly influenced by the distribution of Risk C - the safer cliff is the more dominant.

The trend, however, is cyclic, and is reversed each time when Risk A inherits Risk C. The risk situation are uniformly distributed along the cliff, confirming that cliff retreat is uniform even over short time intervals.

CONCLUSIONS AND RECOMMENDATIONS

1. The entire Sharon Escarpment, like a waterline, a glacier or a mountain peak, should be taken for granted. 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.

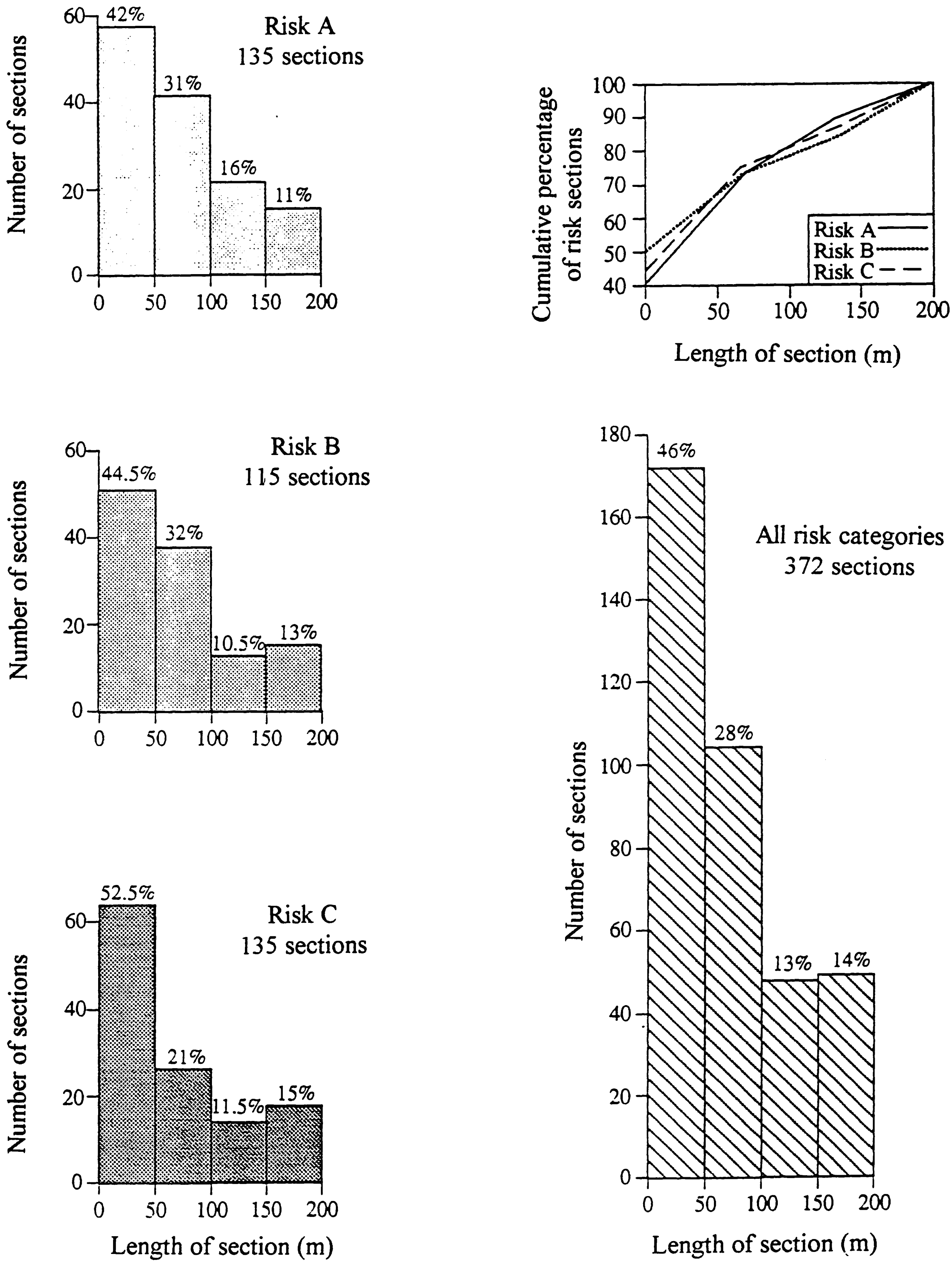

Fig. 35. Distribution of risk according to length of risk sections.

2. Since the rate of cliff retreat, even though high on geological and even historical time scales, is slow with regard 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 at different times and rim localities, 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 is recommended. A sloping concrete or a non-kurkar revetment should be built to a height of 3-5 m (a higher wall involves danger from free-falling objects), founded or grouted down to solid kurkar, and aproned to half its height by heavy, non-erodible, environment-friendly rubble at no more than 45° angles. Grading is ineffective due to the magnified erosion hazard. Buttressing is not recommended (even if 100% effective) where its construction and maintenance4 costs are is higher than the economic value of the 50 m long-range 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. Both shoulders must have leak-proof drainage facilities. 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 western trough 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 slow to disintegrate under natural conditions, and mechanically inert; (b) the deposit is not more cohesive than naturally occurring kurkar, and contains no single components that are more massive than average blocks of sheared calcarenite; and (c) the deposit contains no light materials that will eventually become a huge accumulation of 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 (rough-terrain vehicles, dune buggies, cross-country motor bicycles, field bikes *etc.*) between the water divide at the top of the cliff (either the natural ridge line or the rim itself, including the 10 m safety strip east of it) 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. As yet, the understanding is not complete and the measurements must still be systematically repeated, if modeling is to be based on a firm database. This long way is nevertheless the shortest toward a harmonious environmental policy.

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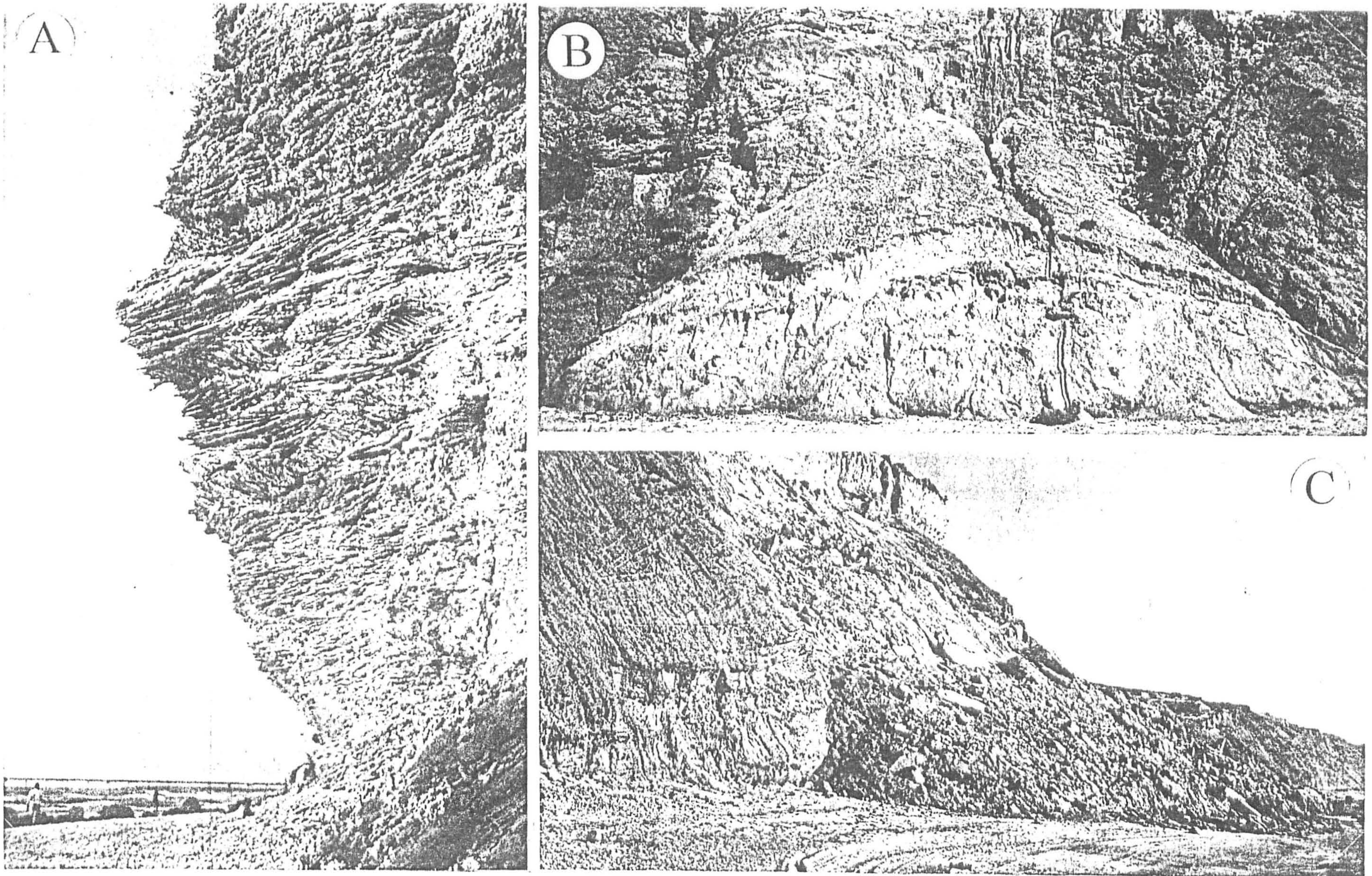

Fig. 33. A. Risk A - Pre-slump situation: steep, exposed cliff notched at its base.
B. Risk B - Pre-slump situation in talus: wave-cut, vertically stepped apron toe.
C. Risk C - No-risk situation: talus apron protects the cliff's base.

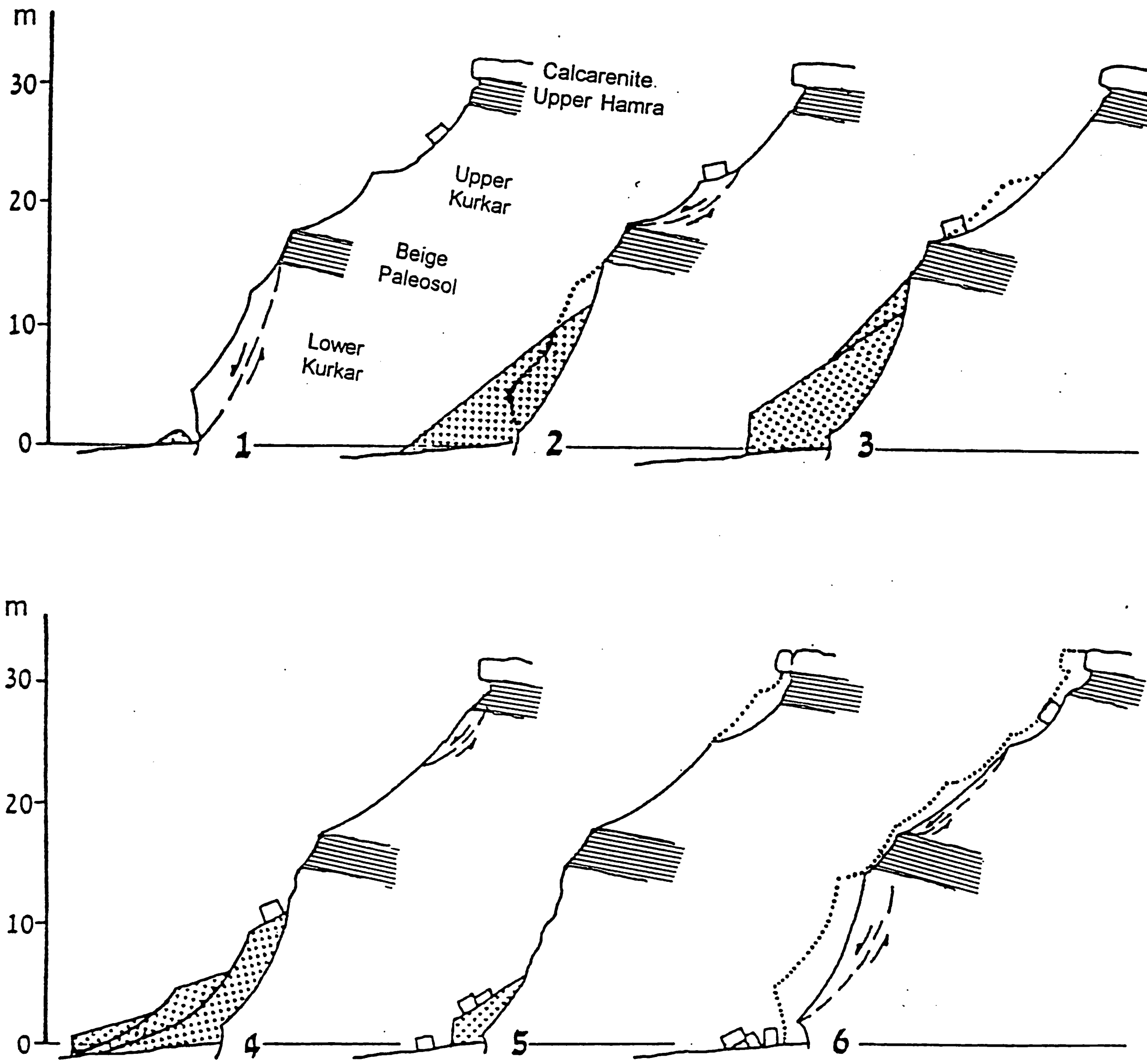

Fig. 34. Risk cycle: 1 - A; 2 - Risk C; 3,4,5 - Risk B; 6 - Risk A. Dashed line - potential failure plane; dotted line - part of the cliff that slumped; hatched area - talus apron).

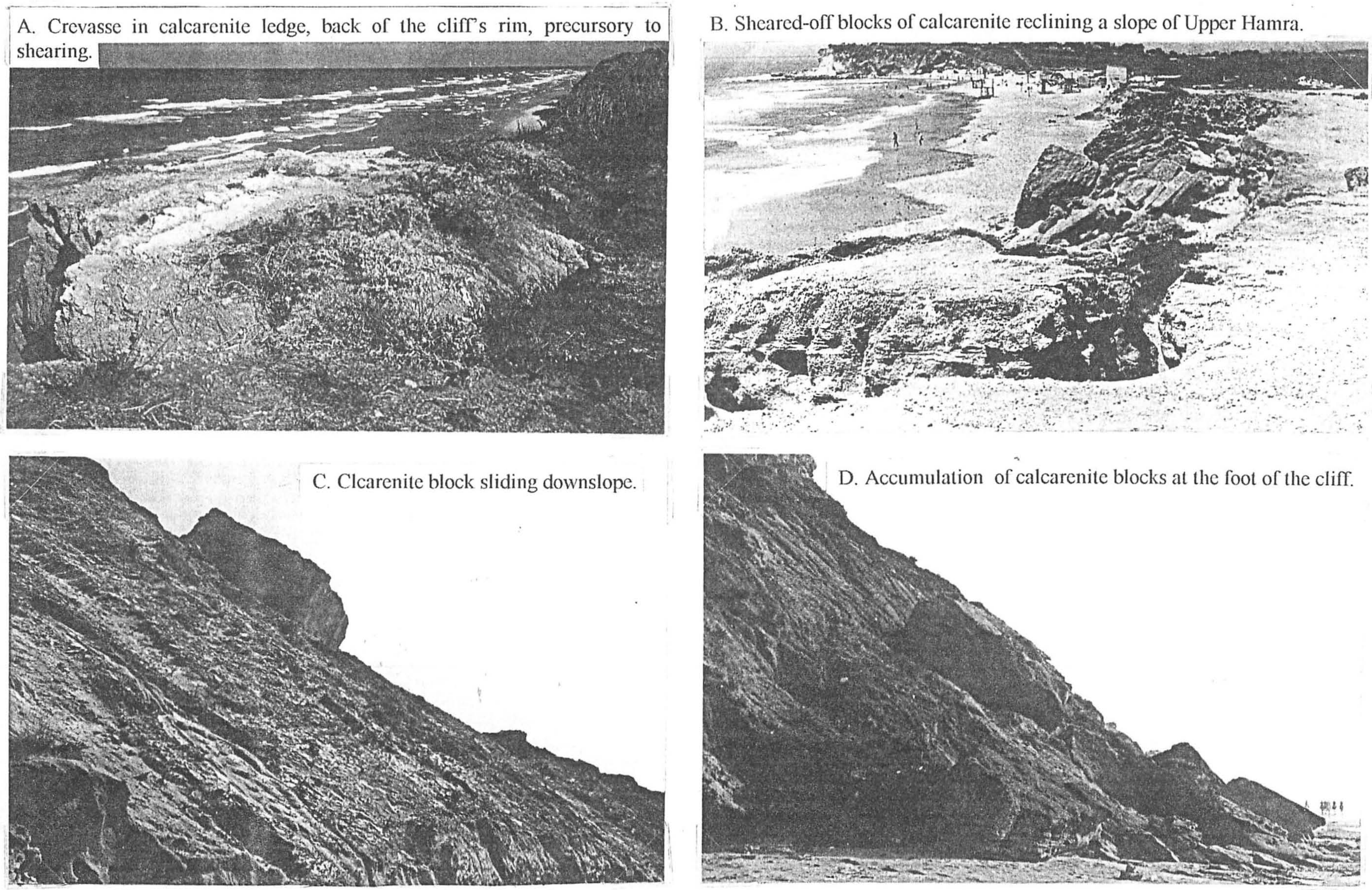

Fig. 10. Process of Calcarenite block detachment and downslope sliding.

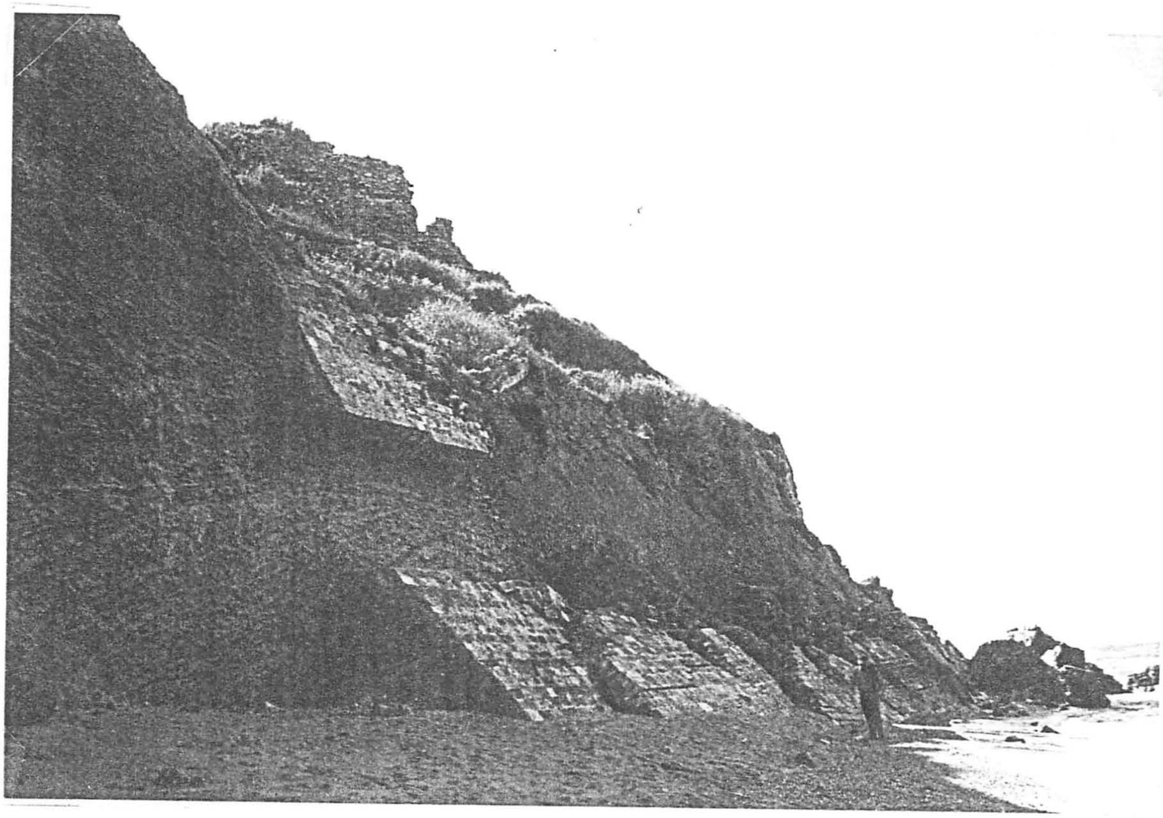

Fig. 11. Slabs of masonry from the defensive moat of the 13th century castle of Arsuf which slumped in 1994.

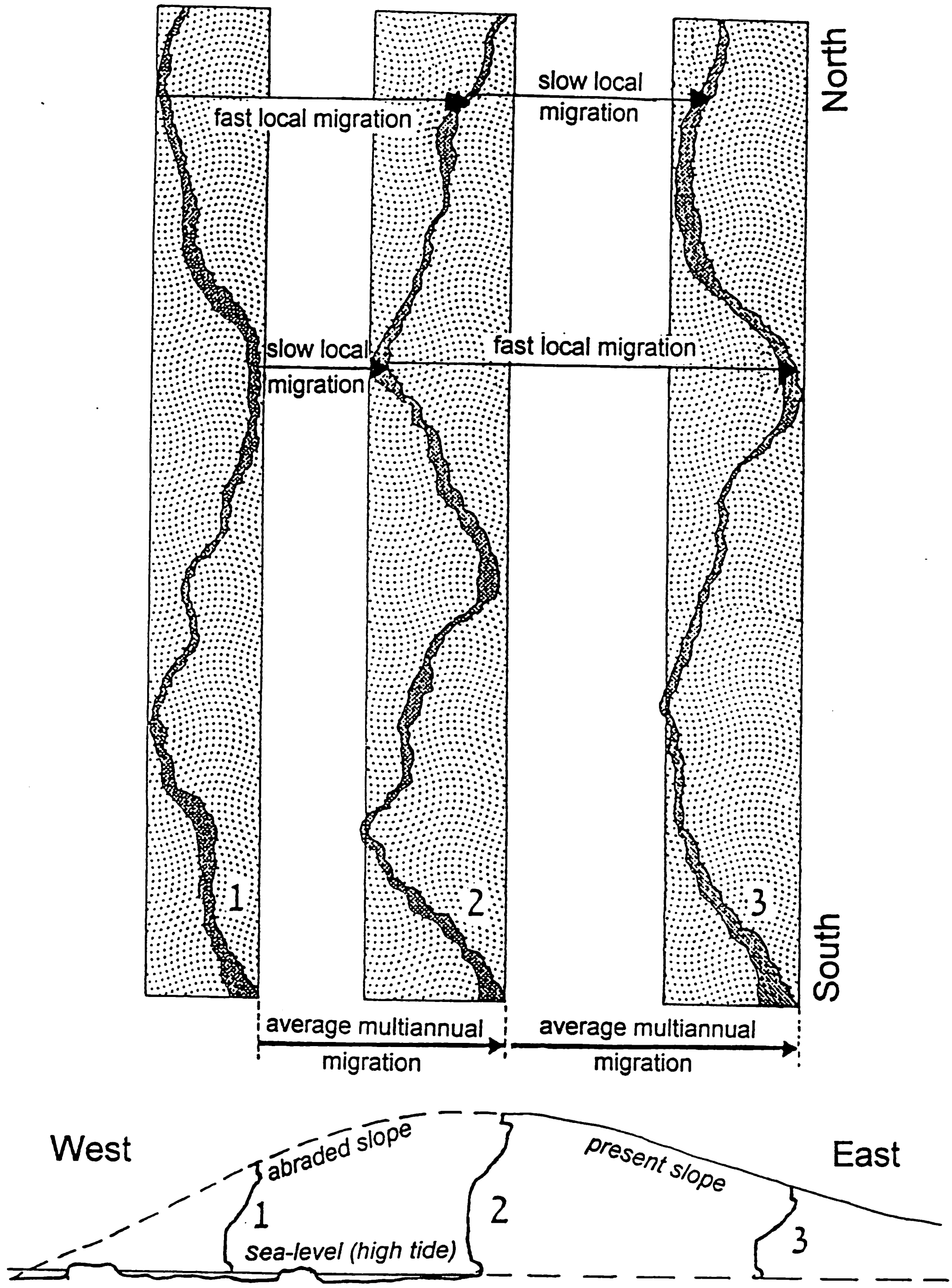

Fig. 12. Stages of the process of cliff retreat.

Cross Section: (1) Past - submerged and abraded kurkar reefs - remnants of the western part of the ridge; (2) Present - the Sharon Escarpment approximately coincides with the ridge line; (3) Future - ridge abrasion will reach the western trough.

Planar projection: Local retreat of the escarpment (darkly dotted) may be haphazard, but on a multiannual scale, the ribbon delimited by the line that connects the escarpment's headlands and the line that connects its bights (lightly dotted) moves eastward at an even rate.

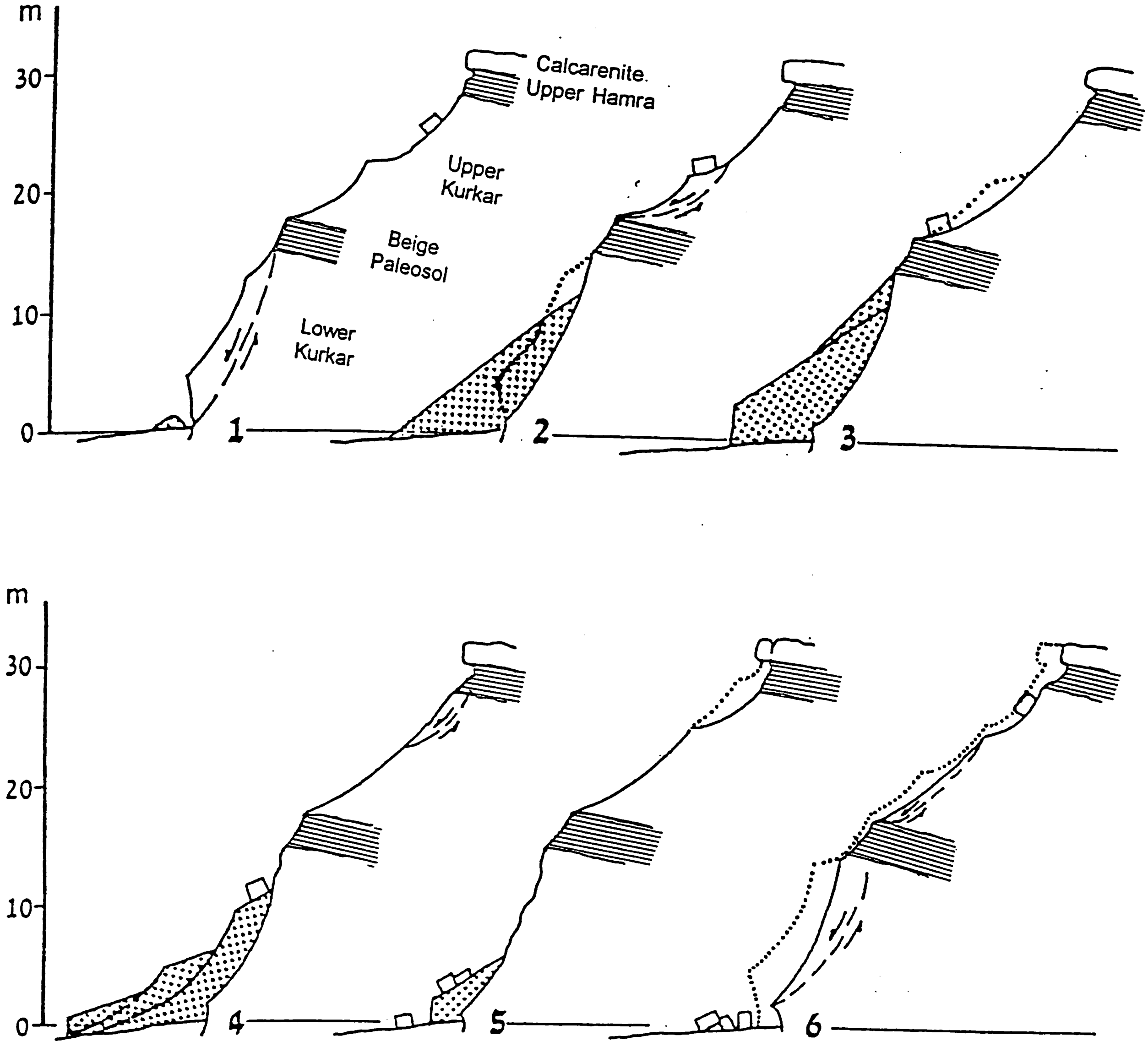

Fig. 34. Risk cycle: 1 - A; 2 - Risk C; 3,4,5 - Risk B; 6 - Risk A. Dashed line - potential failure plane; dotted line - part of the cliff that slumped; hatched area - talus apron).

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