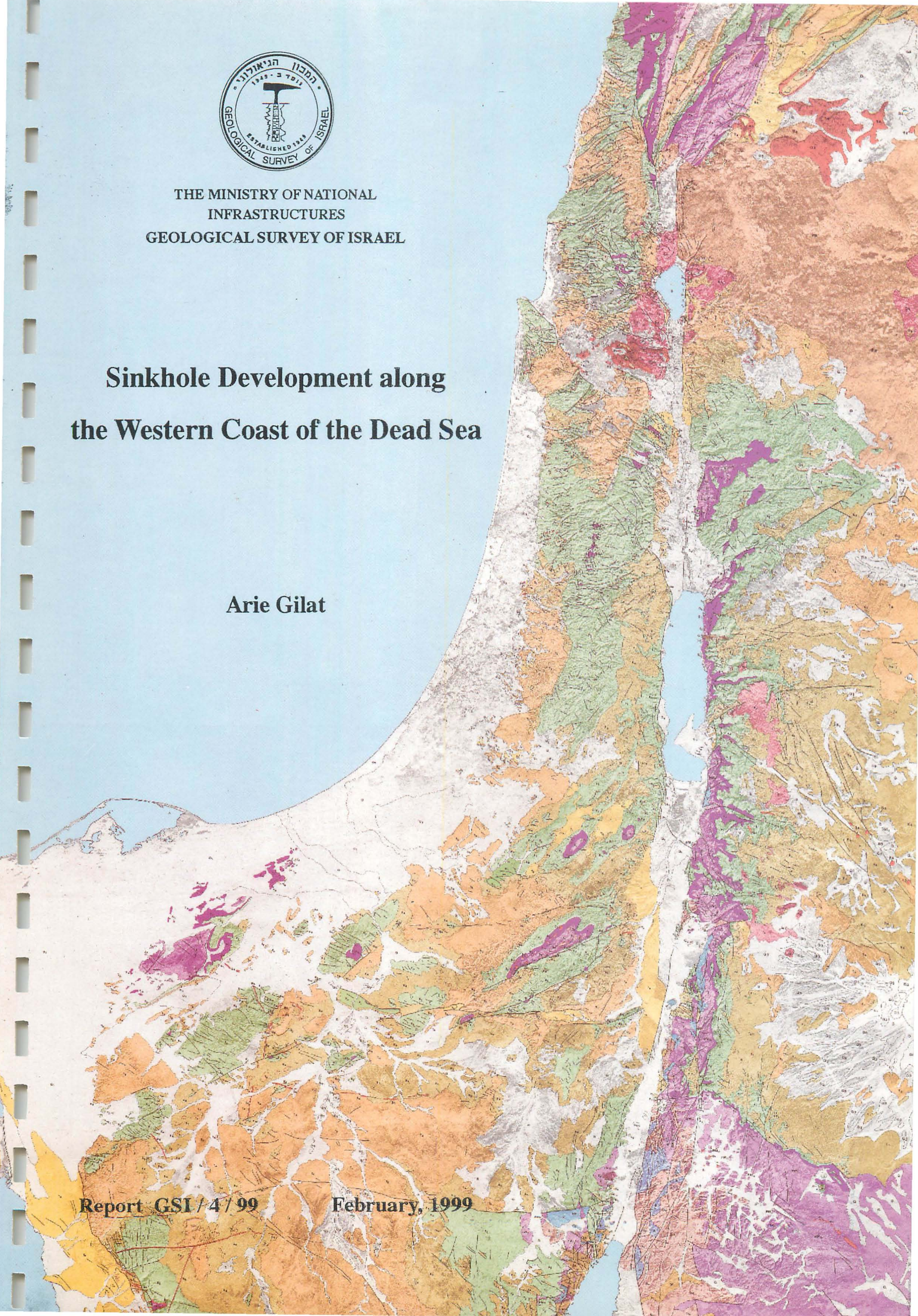

THE MINISTRY OF NATIONAL
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Sinkhole Development along the Western Coast of the Dead Sea

Arie Gilat

Report GSI / 4 / 99 February, 1999

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Contents

Abstract

Sinkhole distribution along accessible segments on the western shore of the Dead Sea (DS) was studied during July-October 1998, and 9 sinkhole sites were recorded (Fig. 1). The sinkholes appear in different sedimentary settings, namely, young and old alluvial fans, comprised of sand-gravel with some clay lenses, and mud flats of the lowermost marine terraces. The mud flats are comprised of multi-colored unconsolidated clays typically composed of illite/smectite and kaolinite with minor palygorskite. This clay contains 60-70% water, which is a brine. The sinks appear at a distances of 0 to 500 m from the Dead Sea, in groups of 3 to 20 and more. Most of them have a circular form, and are from 0.5 to 70 m in diameter and from 0.5 to 12 m deep. Sometimes they merge, forming elongated depressions; many contain puddles of murky water of different color and varying salinity (Table 1). The sink development process can be very slow or very fast: in one recorded case more than 100 m^3 of alluvium disappeared in a single sinkhole during one month. Sinksholes developed on areas not covered by vegetation, are observable on 1:18,500 aerial photographs.

The information collected herein indicates that an apparent escalation in activity of sinkhole forming processes took place during the last two years (Table 1), accompanied by escalation of surface-water erosion and mass-wasting all around the Dead Sea area. As sinkholes occur along the entire length of the Dead Sea shore, a common process must be sought. The rapid lowering of the DS water level, about 20 m during the last 20 years, may be responsible for this process.

The author suggests the following model: sinkhole development is associated with subsurface flow along gravel layers and along vertical and horizontal fractures in the brine-saturated marine clay. As a consequence, salts are dissolved and insoluble fines are washed out in suspension, leaving a hollow. The hollow expands upwards by collapse and fluidization of the clay, which occurs as groundwater reduces its effective strength (by dilution of the interstitial water and destruction of the ionic clay bonds). At the surface level mud-holes expand as walls collapse by slumping and by mud-flow. In places where the subsurface hollow is overlain by alluvium the hollow grows upwards (piping) due to continuous roof collapse until it reaches the surface, as

Fig. 1. Location map showing sinkhole sites along the western shore of the Dead Sea:1-Attraction Beach; 2-Samar springs; 3-Mineral Beach; 4-En-Gedi Holiday Village; 5-En-Gedi Hame Jesha springs; 6-N. Hever north; 7-N. Hever south; 8-Newe Zohar; 9-N. Hemar (from the Satellite Map of Israel, 1993, Historical Productions Ltd., C.N.E.S.).

Sinkhole site	Coordinates	Lithology/water presence	Number of sinks/ year of appearance	Width (m)	Width/ depth ratio	Distance from the October 1998 shoreline	Figure N°N°
Attraction Beach	1982/1307	Marine clay overlain by alluvial fan. Water puddles present in all sinks	3/1992 or later	0.7-8.0	1.5-2.0	3 m-70 m	3-4
Samar springs	1885/1120	Marine clay. Water puddles present in all sinks	~20/1996 or later	3.0-20.0	1.5-5.0	20 m-200 m	5-6
Mineral Beach	1876/1061	Marine clay, in places intercalated with, or overlain by alluvium. Water present	~25/1995 or later	0.7-30.0	1.5-6.0	100 m-300 m	5, 7
En-Gedi Holiday Village	1877/0959	Alluvial fan, sand-gravel – pebbles with clay lenses. No water visible	~10/1994 and later	1.0-10.0 (1 sink – 40.0)	0.0.2-1.0 (1 sink –10.0)	100 m-300 m	8-11
En-Gedi Hame-Jesha springs	1873/0939	Marine clay. Water present in all sinks	>30?most in 1996-98	0.5-70.0	1.0-12.0	100 m-300m	8, 12
N. Hever, northern	1866/1872	Alluvial fan with clay lenses/ layers. Water present in half of the sinks	>20/?most in 1996-98	0.5-20.0	0.2-2.0	0.0 m-300 m	8, 13, 14
N. Hever, southern	1872/0893	Alluvial fan. No water visible	3/?	2.5-3.5	1.0-3.0	~500 m	8, 15
Newe Zohar	1851/0625	Alluvial fan often underlain by clay layers. Water always present	~10/1991- present	3.0-5.0	0.6-5.0	~100 m	16, 17A
N. Hemar	1863/0614	Alluvial fan. No water visible	1(merged)/1995?	3.0-15.0	3.0	~200 m	16, 17B

Table 1. Main parameters of sinkholes developing along the western Dead Sea coast.

described by Arkin (1993). The development of the sinks is effected by underground mass mobilization; mass transport is accomplished by alluvial and artesian waters with different salt contents. Thus the areas in which sinkholes appear are limited to the places where there are local underground streams and springs, or where water-wasting occurs as a result of human activity. The susceptibility of the new coast and of the nearby alluvial fans to accelerated underground mass mobilization has to be taken into consideration when planning its future use.

Introduction

Troublesome sinkholes started to appear in alluvial fans and in unconsolidated sediments along the Dead Sea coast (Fig. 1). The development of sinkholes in the Dead Sea area was first noted in 1990, when a small group of sinkholes, 2 to 15 m in diameter and up to 7 m deep, repeatedly showed up in the alluvial sediments around and in the middle of the main asphalt road 2 km north of the Mt. Sedom (Fig. 1). A bridge was constructed over the dangerous site (and later a new road segment was built on the solid carbonate rock terrain to the west).

First descriptions and appraisal of the processes involved were made by Arkin (1993), Arkin and Michaeli (1995) and Shtivelman et al., (1994) for the Newe Zohar and En-Gedi areas. In 1997-1998 some geophysical surveys were conducted in search for related subsurface features.

The first sinkhole in the En-Gedi area opened at the Deqalim site in 1991-1992; it is about 20 m in diameter, 3-5 m deep, surrounded by circular open fractures. The second sinkhole opened in 1994-1995 in the holiday village caravan site. During the last two years (notably, during the last months), more than ten new sinkholes up to 10 m deep have opened there. Two people fell into a 9 m deep gap that opened suddenly (the last case, on 4.1.98), and trees disappeared into them. Some of the sinks were manually filled with alluvium which was later "swallowed" by the developing depressions. One of the sinkholes in the site was filled repeatedly (up to twenty times, 2-3 trucks every time, according to local information). Asphalt covering of secondary roads at the site shows fracturing, and tension and compression features in the same locality.

In the last few years another set of sinkholes interspaced with springs and seepages, which include waste water outputs, developed 0.5 km south of the holiday village, on the receding sea-coast area opposite Kibbutz En-Gedi. Additional groups of sinkholes have been also recorded 1 km to the north (Samar springs) and 3 km south of N. Darga (Mineral Beach site). In the Mineral Beach area 10-15 new sinkholes, some of them 6-7 m deep, developed during the last few months.

In the lowermost part of the N. Hever alluvial fan a group of impressive sinkholes developed during October 1998 (E. Raz, pers. comm.). At least two sinkholes have been filled by contractors in the hotel-construction area of En-Boqeq; sinkhole development has been reported also in the Dead Sea Works (DSW) area, south of Mt. Sedom, and on the eastern coast of the Dead Sea, in Jordan. All these observations indicate an increase in the rate of sinkhole development.

A complex geological and geophysical study of the Dead Sea sinkholes was initiated in 1998. This report describes a first systematic survey of the features observable at the surface. The data herein were collected during field trips conducted in the context of the first phase of this project.

Local Quaternary geology and physical setting

The main structural feature in the area is the western border of the Dead Sea (DS) Rift, where several large normal step-like faults form cliffs 400-500 m high. West of the Dead Sea, in the Judean Desert, the total thickness of a mostly carbonate ,Phanerozoic sedimentary cover reaches 3-4 km. The area studied is located between the DS and the western cliffs. This area is mainly composed of unconsolidated continental sediments of Quaternary age. The sediments are near-cliff deluvial debris and gravel, sand and clay, deposited in alluvial fans, with some intercalations of lacustrine Lisan Lake (brackish water precursor of the DS of a much larger size) sediments (clay, gypsum and aragonite). Further from the cliff and closer to the sea sediments are of a finer grain size (Fig. 2).

The Dead Sea is a highly saline lake developed in an arid zone, the terminal lake for drainage systems of Jordan, the Negev, western Judea, Samaria and the Galilee Mountains, the Golan heights and southern Lebanon. Its present (1998) water level is

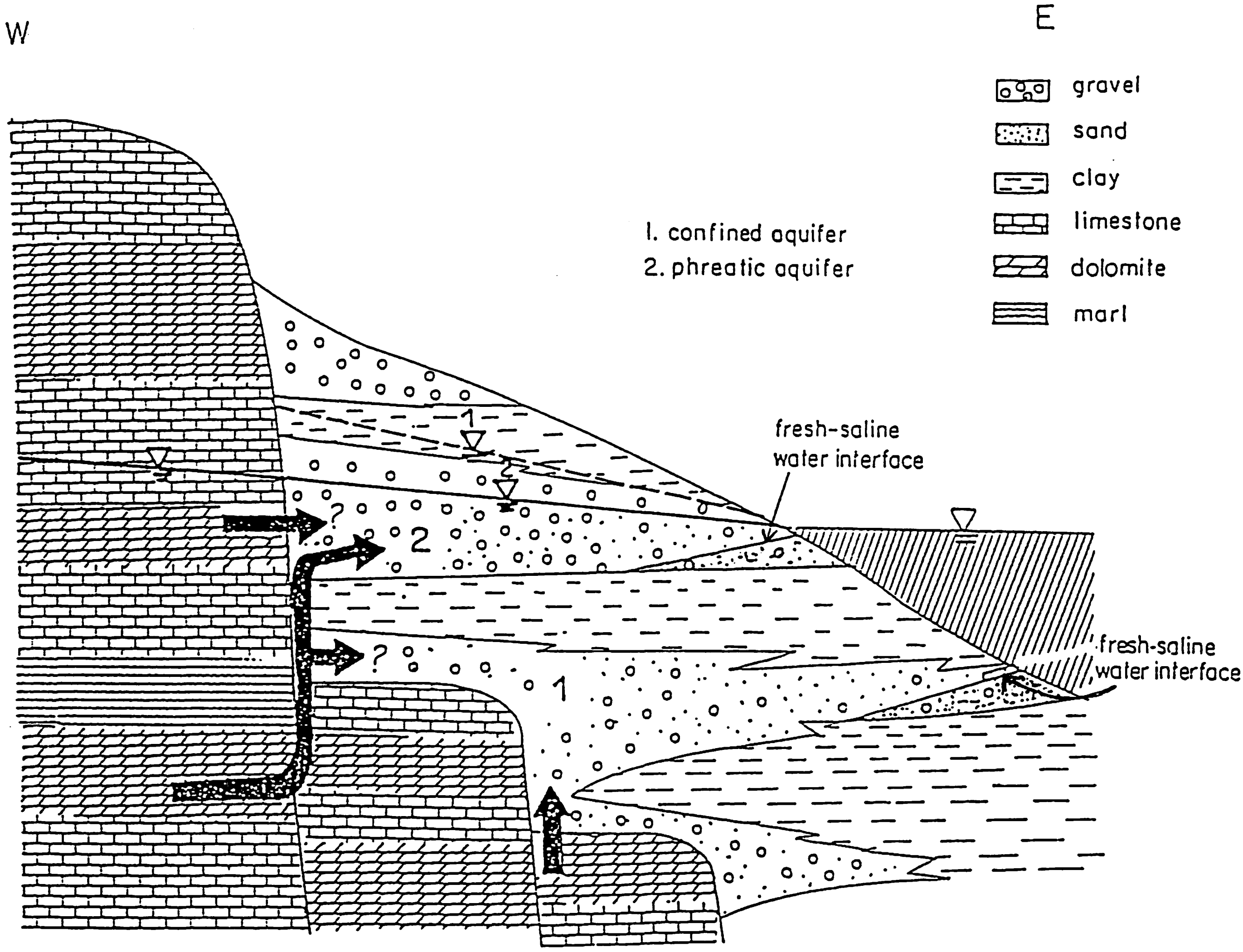


Fig. 2. Schematic cross-section showing the relations between the different aquifers and the DS. Note that the western part is built of limestone, dolomite and some marl belonging to the Judea Group aquifer, while the area between the cliff and the DS is built of gravel and clay belonging to the Quaternary aquifer; further from the cliff and closer to the sea sediments are of a finer grain size (from Yechieli, 1993).

about 413 m below mean sea level. The level dropped from around -392.5 m during the first quarter of this century to -403.5 m between 1929 and 1979 (Klein, 1985), exposing the shallow southern basin. Later it receded further due mainly to anthropogenic activity, exposing tens of square kilometers of its former bottom, mostly composed of clayey sediments. In a comprehensive study concerning effects of water level changes in the Dead Sea on the surrounding rocks, Yechieli (1993) came to the following conclusions: (1) a water balance of the whole DS area indicates that a large amount of groundwater reaches the DS (about $680*10^6$ m^3); (2) the response of the groundwater level to changes in the DS Level (DSL) is rapid (usually in the order of days); (3) the fast recession of the DS over the past 30 years caused rapid drainage of residual brines into the DS, flowing mainly in a salt layer, which was proven to be very conductive in this system; (4) the two most important processes in the newly exposed coast are evaporation and flushing by groundwater. Flushing reduces the effectiveness of the ionic bonds between the clay platelets and thereby reduces the overall strength and cohesiveness of the clay, turning it into quick clays (Monroe and Wicander, 1992; see also Arkin, 1980). Consequently, when the quick clays are disturbed by a sudden shock or shaking (earthquake), they essentially turn to a liquid and flow (ibid).

The comprehensive study of the DS clay mineralogy made by Nathan et al., (1992) concluded that the DS clay fraction is typically composed of illite/smectite and kaolinite in similar amounts with minor illite and palygorskite. The lowermost newly formed coastal section is often composed of very thin alternating layers of dark clay and white aragonite with some gypsum (resembling the typical sediment of the Lisan Formation).

Field description of the sinkhole sites

The field descriptionsof the sinkhole sites on the western coast of the DS is from the north to the south. The basic data are summarized in Table 1.

Attraction Beach site

The northernmost sinkholes are found 500 m north of the Attraction Beach vacation area, 5 km west of the Jordan River delta, 50 m northwest of the sea shore, near coord. 1982/1307 (Figs. 1,3).

The largest among three sinkholes (~8 m in diameter and ~4 m deep) developed in a dark-green detritic clay overlain by cross-bedded alluvial fan sand-gravel sediments; the overall visible thickness of the clay beds is more then 10 m (Fig. 4A). The sinkhole is cut by two small seasonal flows and at its bottom a spring appears forming a small stream of brownish and murky water. The spring's water flows out from the clay, and shoveling about 0.5 m deep into the spring did not indicate any change in lithology. This sinkhole is developing on the sea terrace ~5 m above the present (09.1998) DSL and is probably less than 5 years old. Two additional sinkholes, 0.7 m and 1.0 m in diameter, and 0.5 m and 0.7 m deep, respectively, are developing in marine clay, near the beach, about 70 m south of the large one. A small stream disappears in the clay sequence 1-2 m above each of them and reappears as a small spring at each of the sinks' bottom; both springs exhibit muddy water (Fig. 4B).

Samar springs site

A group of about 20 sinkholes was recorded at the Samar springs (near coord. 1885/1120, Fig. 5) on the newly formed clay sea terrace, about 6 m above the present DSL (Fig. 6A). Most of the sinkholes are rounded, 3 to 20 m in diameter, with a standing water depth at 2.0-0.1 m (Figs. 6B and 6C), with different water levels even in the sinkholes developing only 3-4 m apart (Fig. 6C). One of these has an elongated form about 15 m wide and 100 m long, surrounded by 0.3-0.5 m deep concentric fractures (cracks) separating slumping blocks (Fig. 6D). In some of the sinkholes a salt crust formed (Fig. 6C), possibly related to the water salinity. A small stream flows from the largest E-W oriented sinkhole pool into the sea (Figs. 6A and 6D).

One additional round, water-filled sinkhole, about 10 m in diameter, is situated close to the DS shore and is clearly seen from the main asphalt road, 1 km south of the Samar group of sinkholes. According to Y. Arkin (pers. comm., 1998), sinkholes were not developed in the Samar springs area in the middle of 1997.

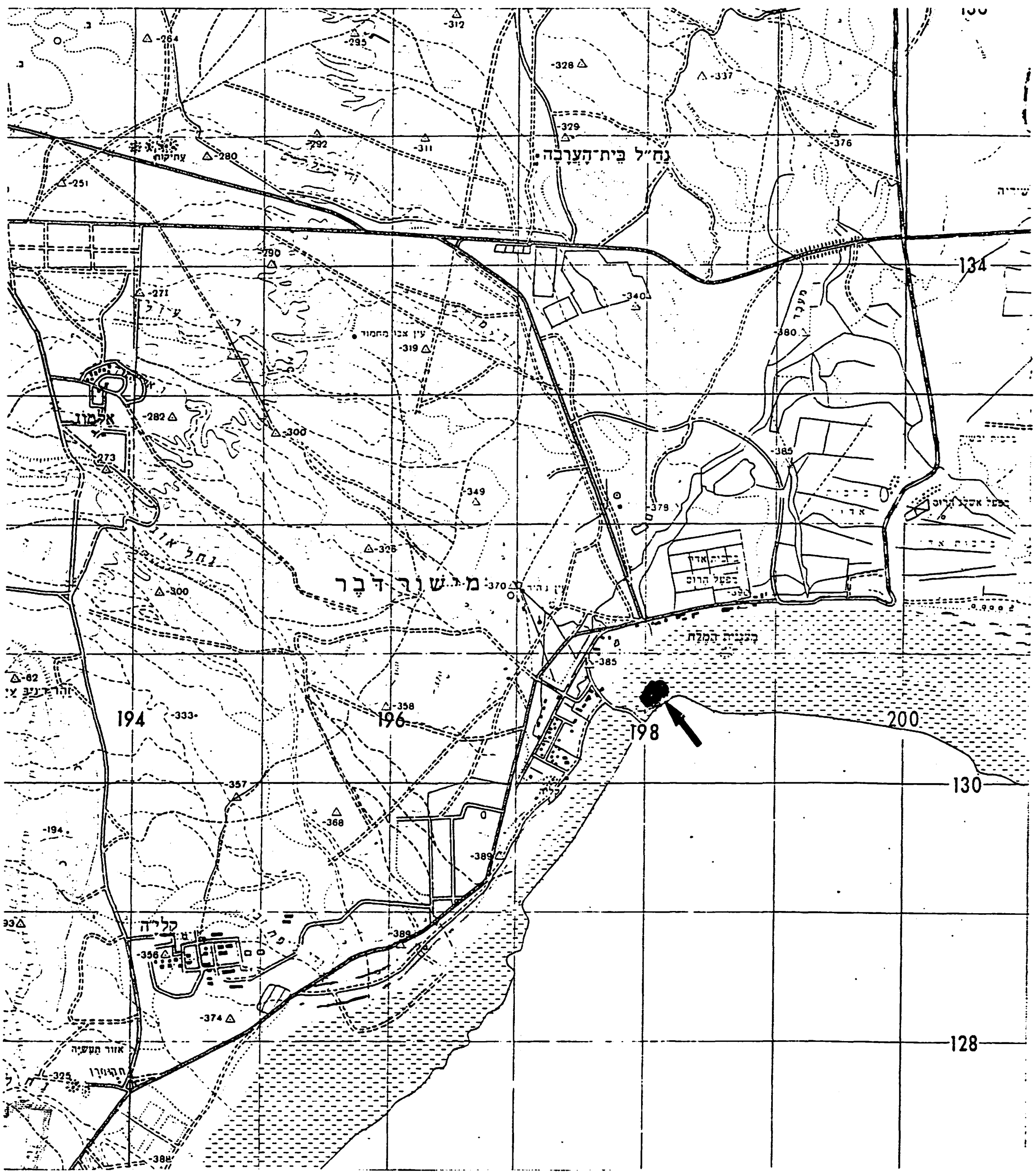


Fig. 3. Location map of the Attraction Beach sinkholes site near coord. 1982/1307.

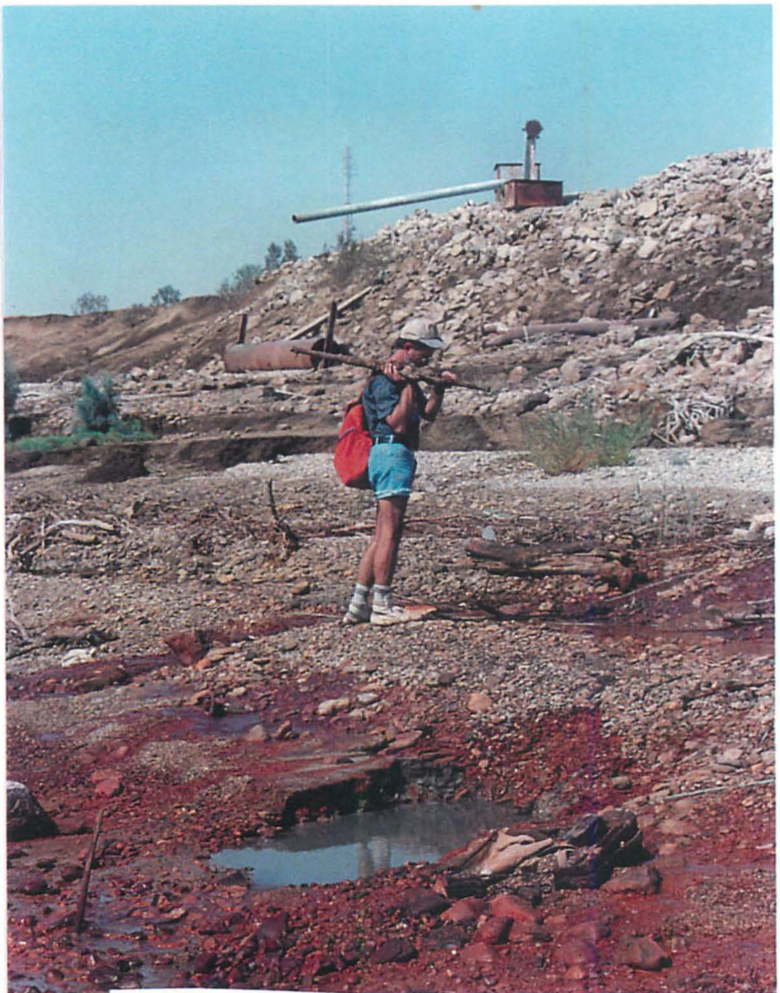


Fig. 4. Sinkholes on the Attraction Beach site. A-the largest sinkhole within the thick (altogether more than 10 m) clay, overlain on the sea terrace by a 1-2 m thick alluvial fan. The sinkhole is open seawards. Note a small spring in the sinks bottom, which gives rise to the brownish water stream in the foreground. B-one of the smaller sinks near the shore; note a small disappearing stream to the right of the human figure. A spring appears 2 m below the disappearing stream, from the bottom of the 0.7 m deep sinkhole, the muddy water of which flows into the sea carrying suspended clay particles. Photographed on 27.08.1998.

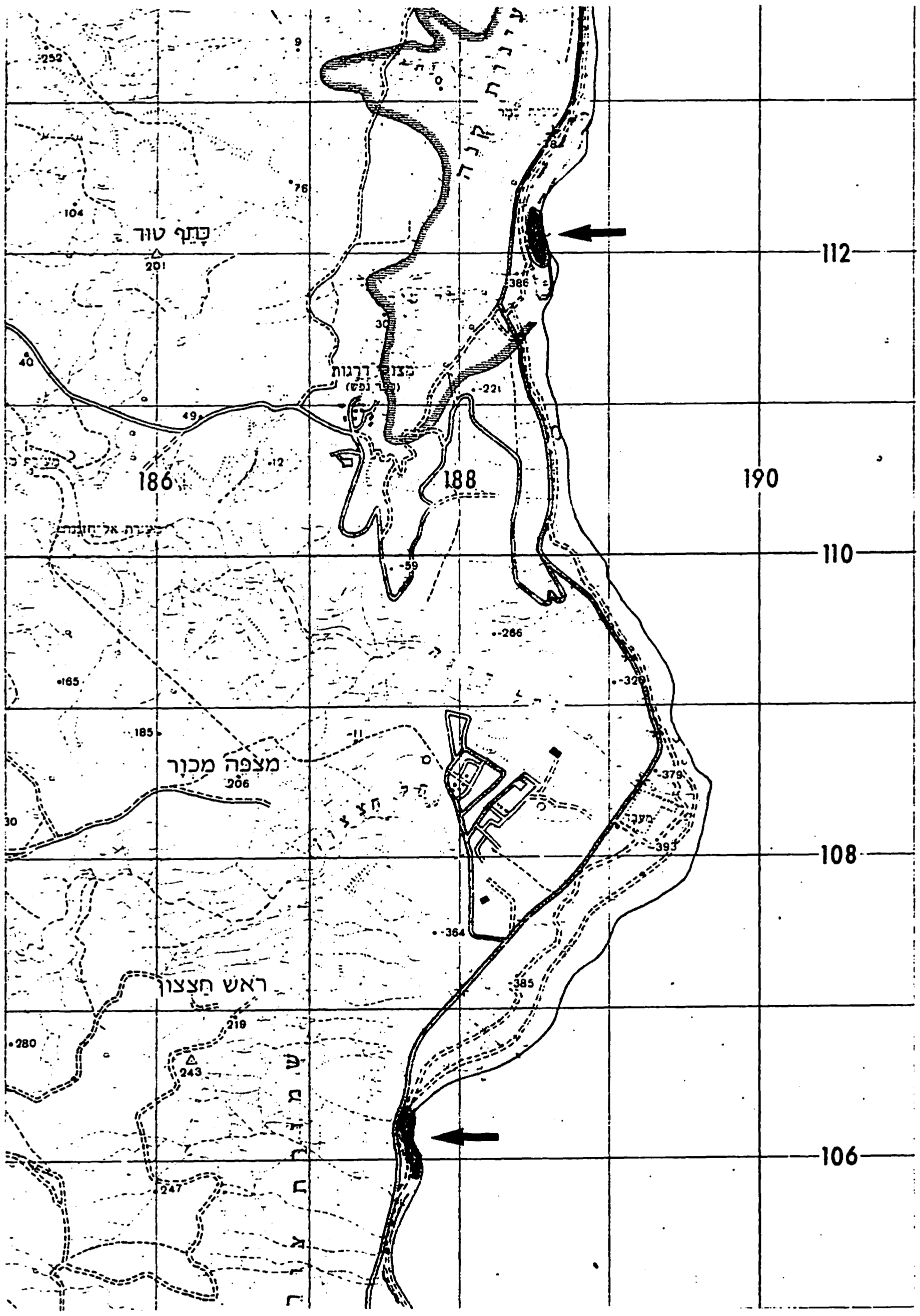


Fig. 5. Location map of the Samar springs (cord. 1885/1122) and of the Mineral Beach (coord. 1876/1061) sinkholes sites.

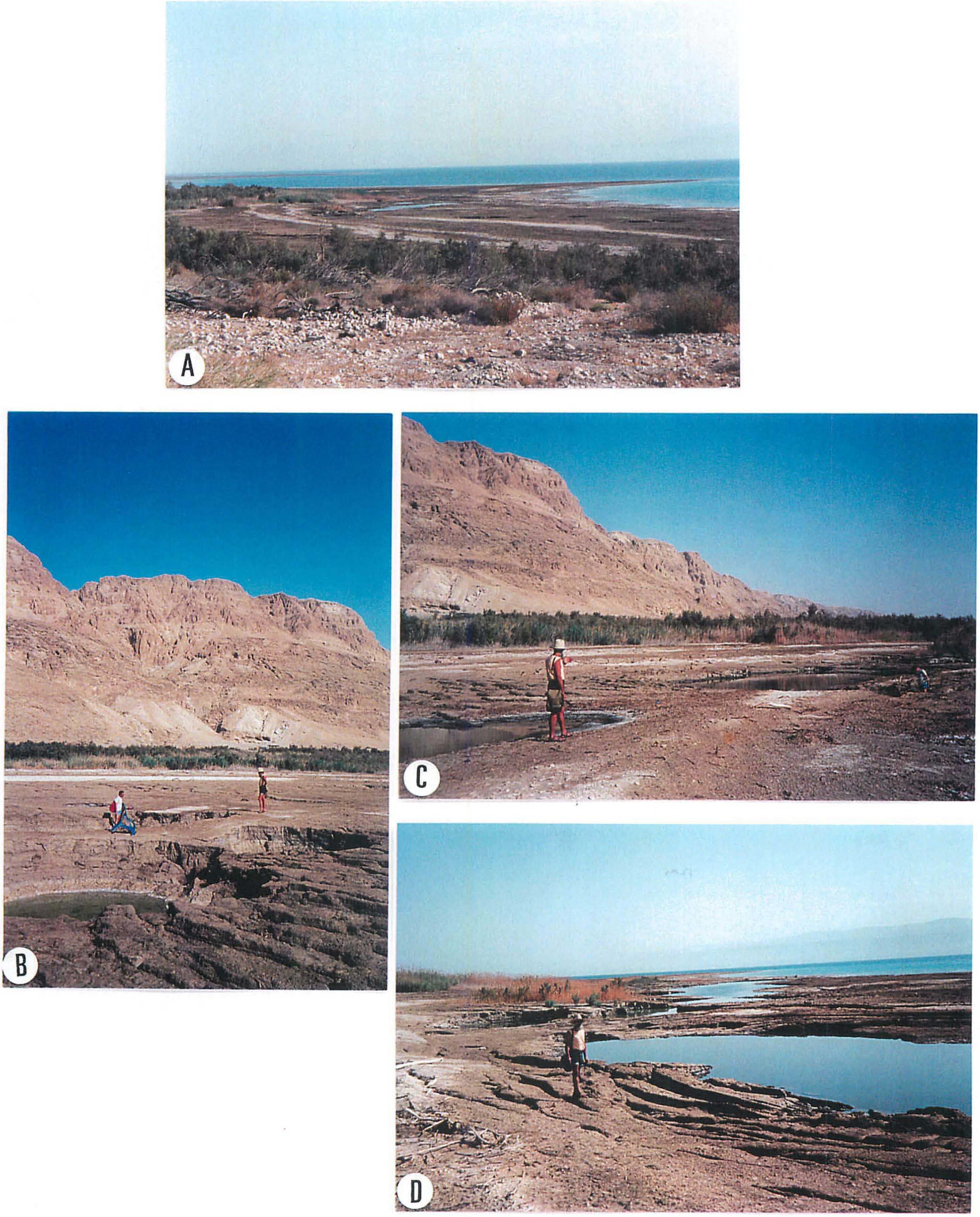


Fig. 6. A group of sinkholes in the Samar springs site: A-general view from the south-east; note the sinks on the recent clay-build marine terraces; B-rounded sinkholes 3-6 m in diameter; note the slumping of clay blocks; C-elongated sinkholes, foots of the human figures stand adjacent to water levels, thus marking their differences in closely spaced sinkhole pools; D-up to 100 m long sinkholes formed by merges of adjacent sinks, note the 0.3-0.5 m deep concentric fractures separating slumping clay blocks. Photographed on October 14-15, 1998.

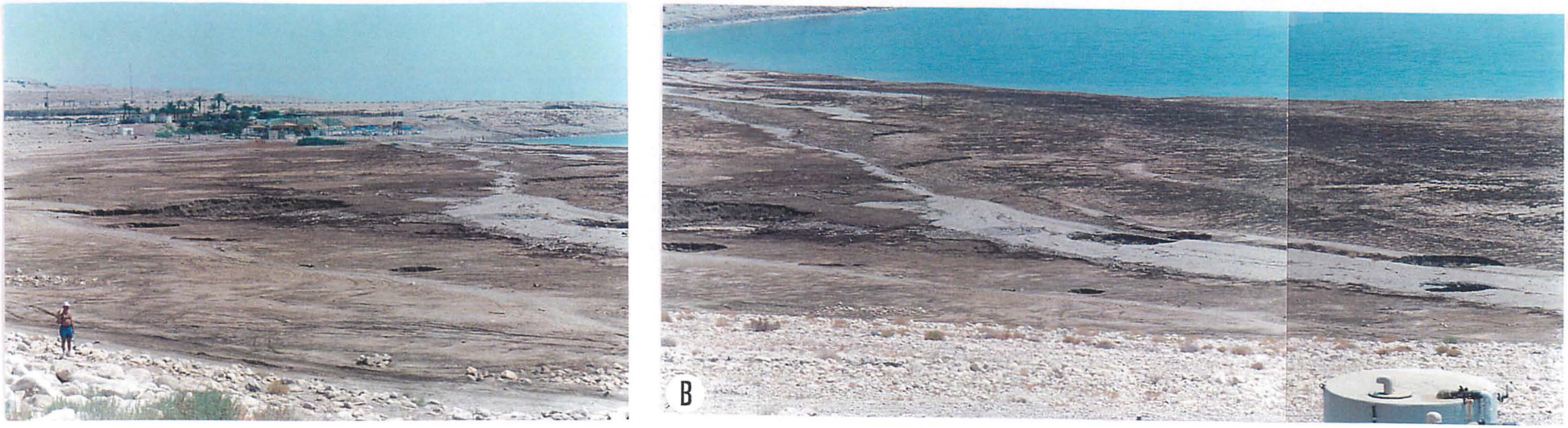
Mineral Beach site

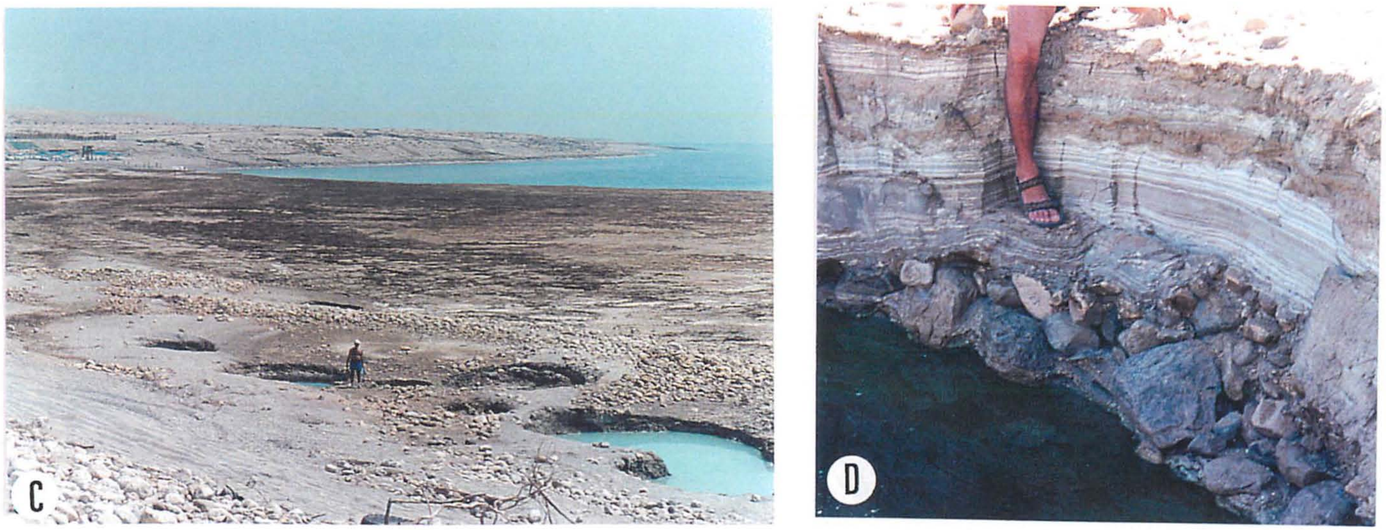
The group of sinkholes at the Mineral Beach site is located some 3 km south of N. Darga, on the surface of the 5-7 year-old DS terrace, south of and adjacent to the alluvial fan of N. Hazazon, centered near coord. 1876/1061 (Fig. 5). In 1995-1997 3-5 sinkholes were known in this site, just north of the hot-water (42^{0}C) springs, rich in hydrogen sulfide. At present (end 1998) there are more than 20 rounded or irregularly shaped sinkholes. Some of the recently formed sinks are less than 1 m in diameter and less than 0.5 m deep, some of them are mature, up to 30 m in diameter and up to 5 m deep, and some of them have merged (Figs. 7A, 7B, 7C). Most of the sinks are surrounded by concentric fractures. The water level, even in holes which are close to one another, differ by up to 0.5 m. The water color in the different holes varies: it can be murky blue, yellow, brown, red or white (with the smell of hydrogen sulfide, Fig. 7C). The water salinity differs too (based on presence or absence of a salt crust, and according to the results of analyses of water samples from 7 different sinks of the site, where Cl-content varied from 157 to 379 mg/l); measurement of water temperature yielded 28^{0}C, 30^{0}C, 41^{0}C and 42^{0}C: all these differences show that several types of water, alluvial and artesian, occur in the sinkholes.

In the northern part of the Mineral Beach site, a typical section consists of plastic detritic clay (Figs. 7A, 7B), but in its southern part intercalations of clay with alluvial fan clastics can be clearly seen (Figs. 7D, 7E). A ~3 m drop in the elevation of the sulfurous artesian springs during last 5 years was witnessed by local people and is marked by a dried spring-bath 3 m above the currently flowing spring.

En-Gedi holiday village

The En-Gedi holiday village is situated just east of the main asphalt road, on the sea shore, located on the N. Arugot young alluvial fan (Arkin and Michaeli, 1995, fig. 4) at an altitude of -390 to -395 m, near coord. 1877/0959 (Fig. 8), about 20 m above the DSL. The nearby sea-bottom slopes steeply eastward (100 m depth/1 km surface). Composition of the alluvial fan sequence is probably similar to that shown on Fig. 9A. The sinkholes appear here in an area affected by human activity. The first sinkhole started to develop about 8 years ago in the date plantation to the west of the main





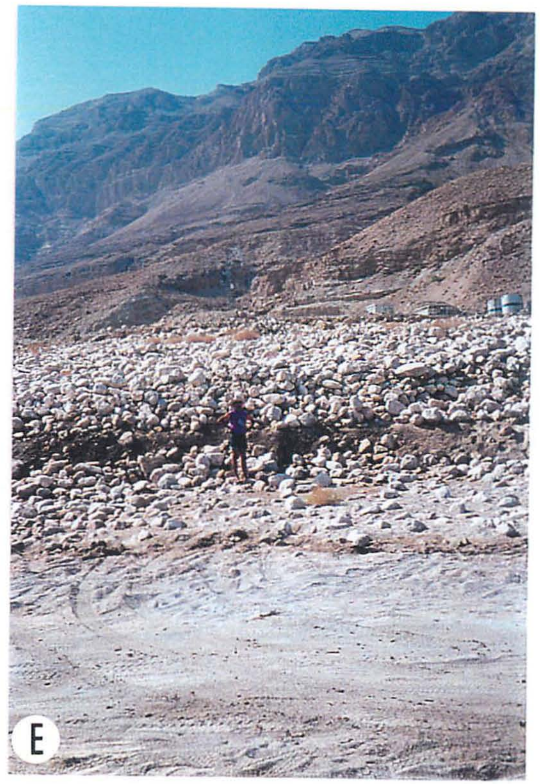


Fig. 7. Groups of sinkholes in the Mineral Beach site: A-general view on sinkholes of 1 to 20 m in diameter, developed in the marine clay, northern part of the site; B-central part of the site, note the sinks developed in the beach established four years ago (1994, white, in the center), with the double line of car-tracks left before these sinks were formed; C-a group of southernmost sinks; note the different kinds of water appearing in them, including a milky one in the biggest sink; D-small sinkhole with a murky water puddle, its walls composed of older alluvium and younger clay of the marine terrace; E-the human figure accentuates a marine clay layer overlain by recent alluvium above the sinkholes. 7A, 7B and 7C photographed on 22.07.1998; 7D and 7E on 10.11.1998.

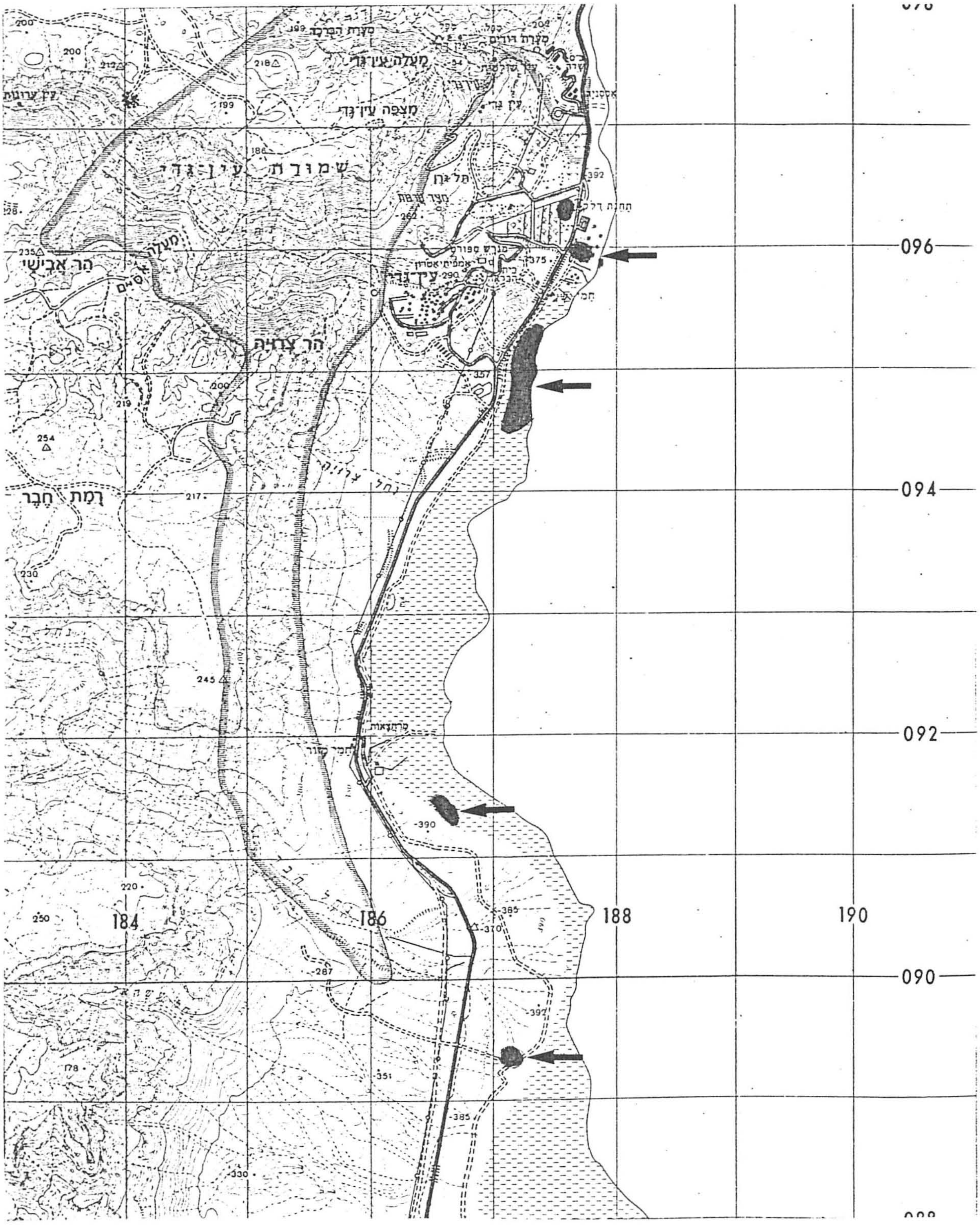


Fig. 8. Location map of the sinkhole sites in the En-Gedi and N. Hever areas: date plantation (coord. 1876/0963), Holiday village (coord. 1877/0959), Hame Jesha (near coord. 1873/0959), N. Hever, northern site (near coord. 1876/0913), N. Hever, southern site (coord. 1872/0893).

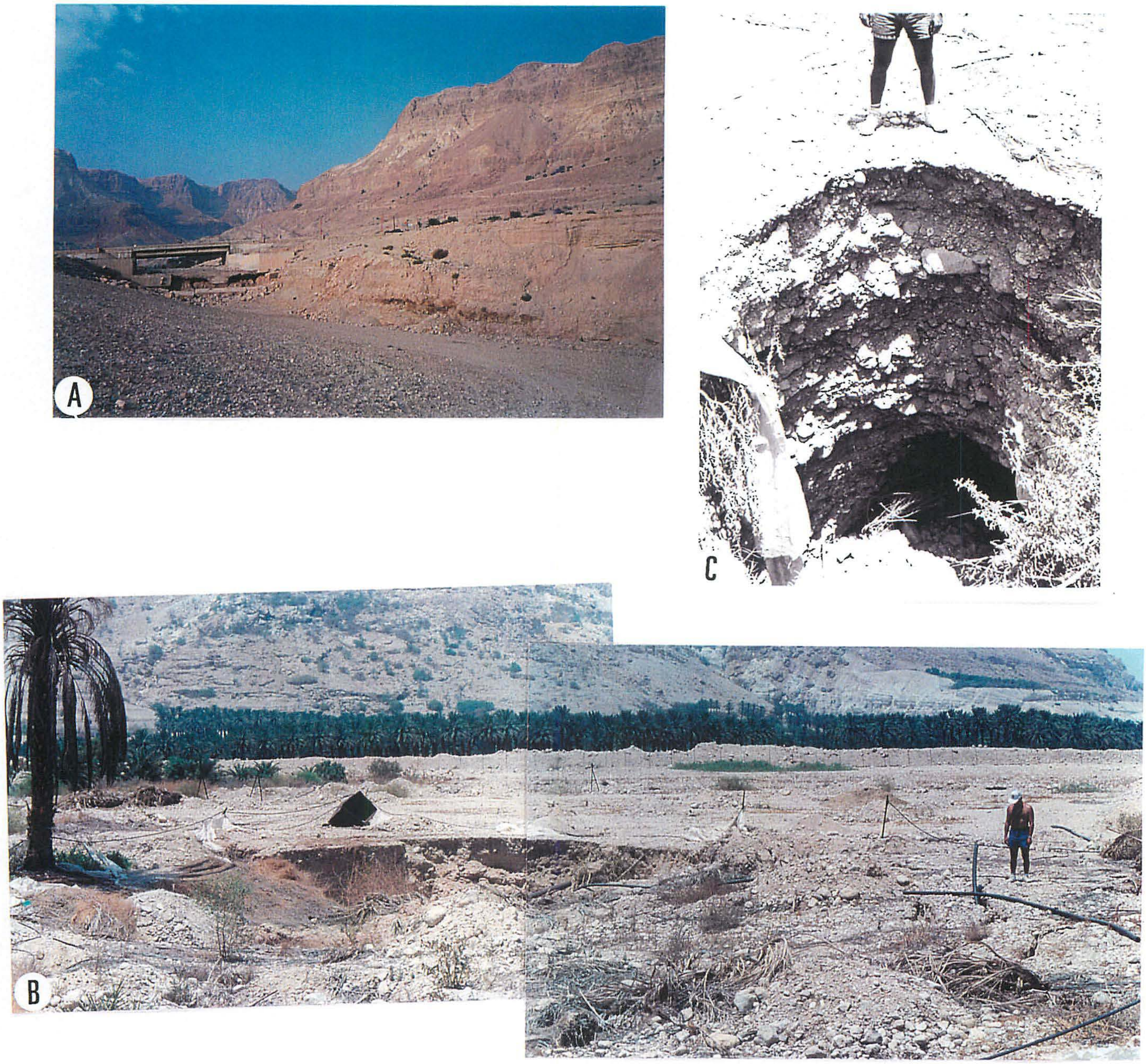


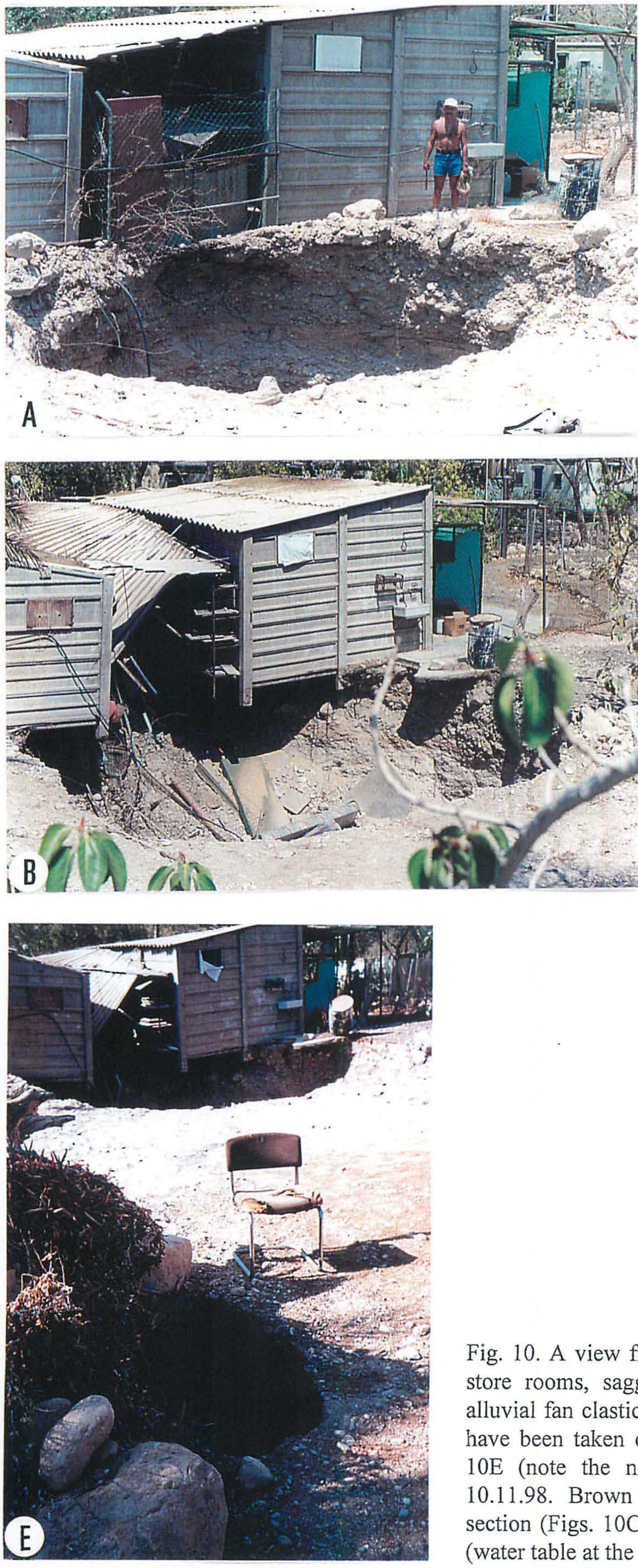
Fig. 9. En-Gedi Holiday village vicinity: A-a view from the east on the N. Arugot channel about 400 m north of the holiday village sinkholes, exposing a typical alluvial fan cross-section. Note the chocolate clay layers close to the bottom of the alluvial sequence (center). 10.11.1998; B-a view from the south on the largest, about 8-year-old (1990) sinkhole of the En-Gedi date plantation. Note the 0.3-0.5 m deep concentric fractures (on the right) surrounding it on 22.07.1998; C-a narrow but very deep sink (9 m at the time of its collapse in 1996) in the alluvial fan, 15 m south of the larger sinkhole shown on Fig. 9B. (22.07.1998).

road. It is about 40 m in diameter and 2-3 m deep, surrounded by open concentric cracks 0.3-0.5 m deep (Fig. 9B). Another sinkhole, 10 m away, is about 2 m in diameter and 9 m deep, and collapsed in 1997 (Fig. 9C).

Sinkholes in the holiday village are concentrated along a narrow (50-70 m wide) zone about 100 m long, trending southeast. The first sinkhole appeared in 1994; in 1966 four additional holes opened between the caravans and internal local asphalt roads (Figs. 10, 11A, 11B, 11E). The development of the largest one between 22.07.1998 and 19.08.1998 can be seen on photographs 10A - 10D, which document sink growth from 8 to 10 m in diameter, while appearing to retain the same depth of about 6 m in the center, with vertical walls 4 m high. Assuming a cylinder 5 m deep, a simple calculation shows that its volume was enlarged during one month from about 250 to 390 m^3. The youngest sink appeared close to November 10, 1998; through its small opening (Fig. 10E) a bell-shaped underground cavern is observable, about 4 m deep and about 5 m in diameter near its base level. Figs. 10C and 10D exhibit the upper few meters of the heterogeneous alluvial sequence containing brownish gravel layers. These could have served as local subsurface channels for the alluvial waters at the time when the water table was several meters higher than the present level. Creeping asphalt nearby indicates further underground mass movement (Figs. 11C, 11D). Sinkholes have been repeatedly filled with 2-3 trucks of alluvial material each time, but the fill has been slowly sagging and disappearing (Fig. 11E).

En-Gedi Hame Jesha springs site

The site is situated on the low DS, few-years-old, marine terraces (~1985) composed of more than 7 m of clay, east of the main asphalt road, 0. 5 km south of the En-Gedi holiday village and just east of Kibbutz En-Gedi (center near coord. 1873/0939, Fig. 8). This is the largest and most impressive group of mud-holes (more then 30 sinks). The sinkholes develop along and adjacent to the sea shore, on a 100 m wide and about 500 m long strip. As in the Mineral Beach site, the group consists of both small and large holes (0.5 to 70 m in diameter and from 0.5 to 5 m deep), with different levels, colors, salinity and types of water (Figs. 12A-12G), including sewage water which seeps from the kibbutz oxidation pond, situated about 200 m to the west. Large-scale cracking (concentric and straight, similar to desiccation cracking), slumping and



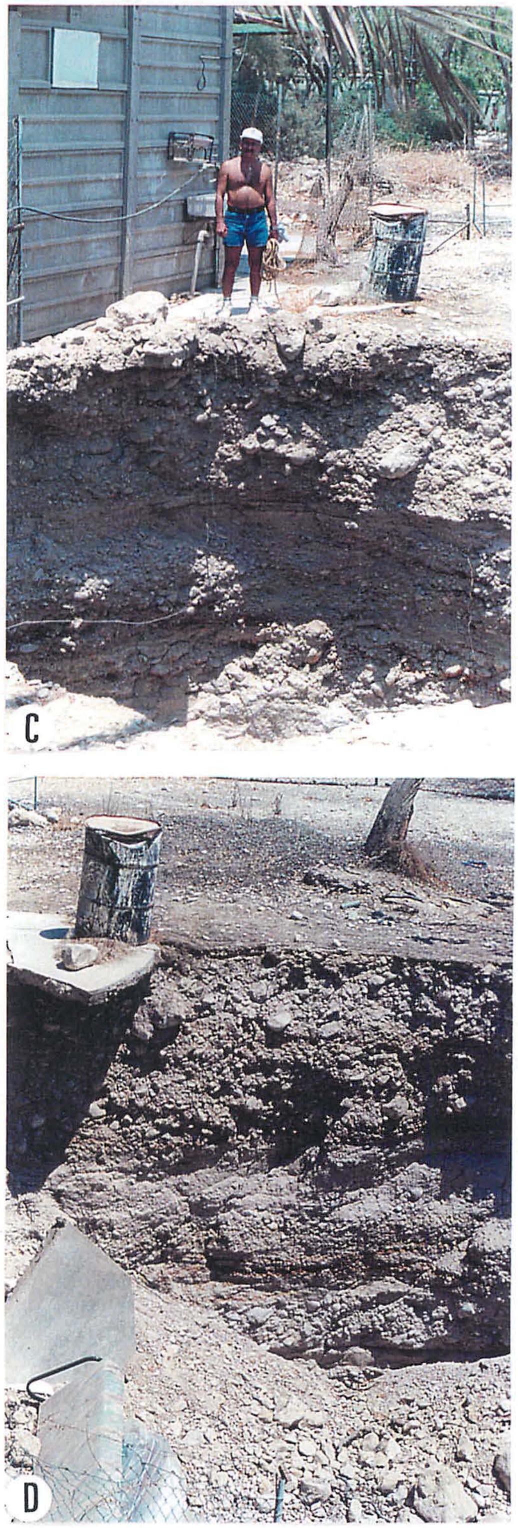


Fig. 10. A view from the east on the En Gedi Holiday Village store rooms, sagging with the sinkhole development in the alluvial fan clastics underneath. The photographs 10A and 10C have been taken on 22.07.98, 10B and 10D on 19.08.98, and 10E (note the newly opened sink on the foreground) on 10.11.98. Brown iron-oxide mineralizations in the exposed section (Figs. 10C and 10D) mark water-flows of the near past (water table at the elevation ~ -395 m).

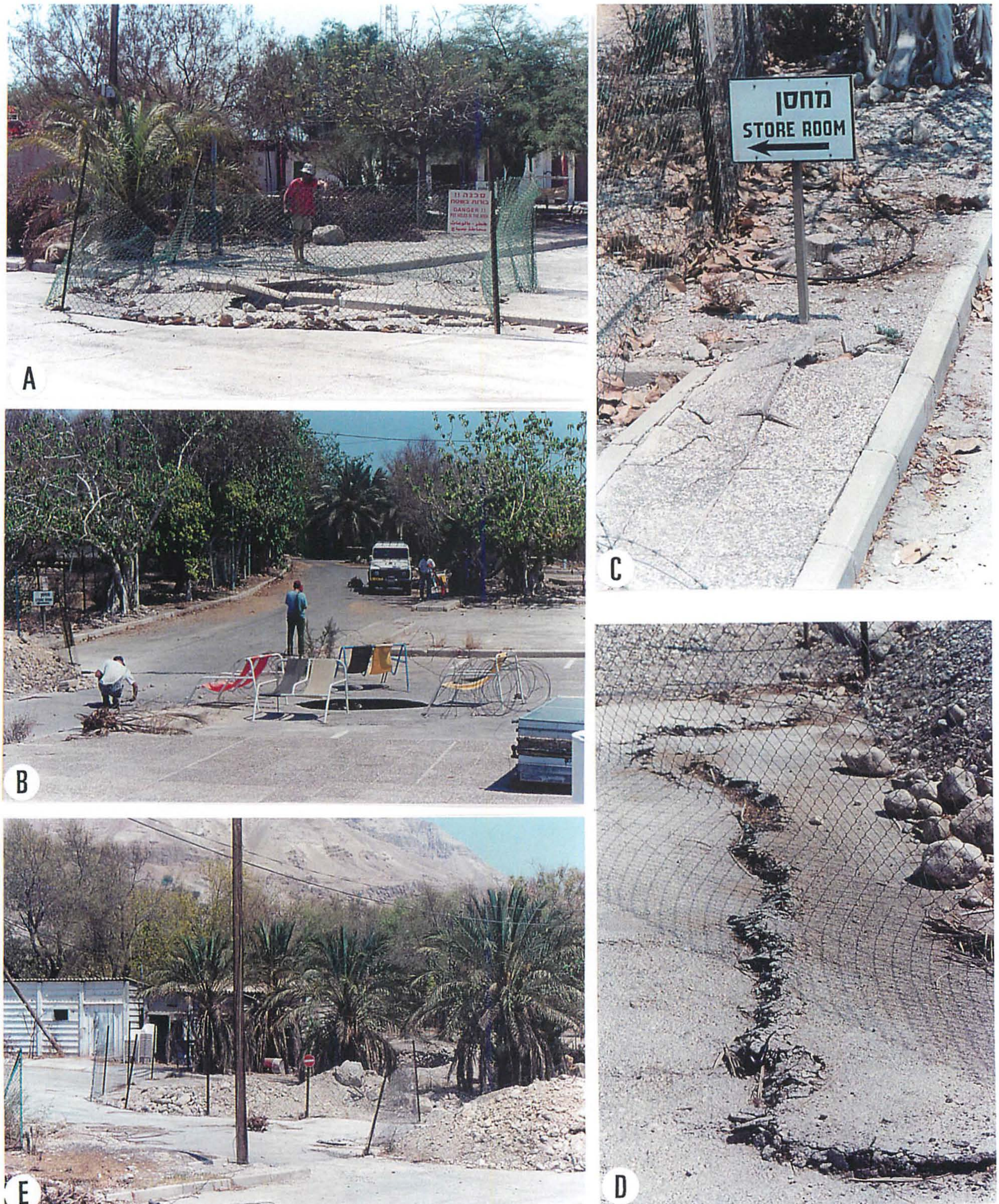


Fig. 11. View on sinkholes developed in the southern part of the EN Gedi Holiday Village: A- small opening in the surface pavement to a 9 m deep gap; B-a 5 m deep sink in the middle of the parking place; C-swelling pavement in the sinkholes vicinity; D-slipping asphalt marked by small "ridges"; E-fenced sinkholes near the store room, filled by alluvial material, with the larger open sink (Fig. 10) on the background.
Photographs taken on 19.08.1998.

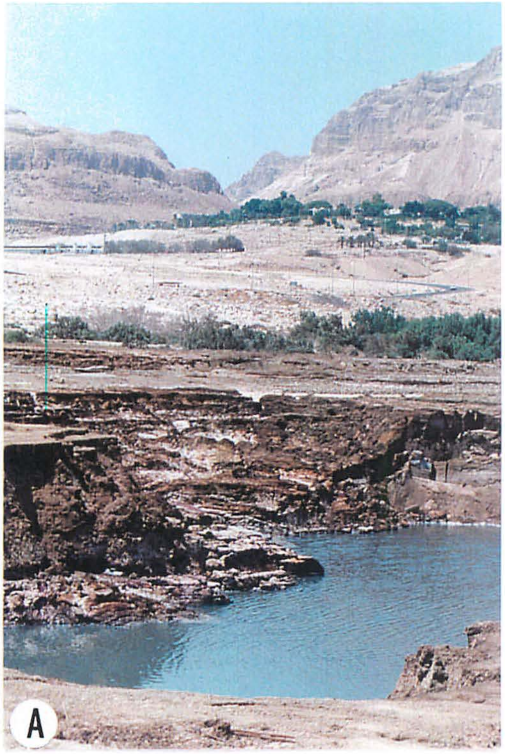


Fig. 12. Mud-holes development in the En-Gedi Hame Jesha springs site. Different size, forms, different liquids and similar slumping process: A-slumping clay walls of merged sinkholes, Kibbutz En Gedi in the background; B-rounded sinkholes with a pool of iron-rich brine; C-sinkholes with sweet water springs; D-one of the large sinks, note subsidence and sagging; E-vertical (on the left) and horizontal (beneath smoking pipe) fractures in the marine clay with recent iron-oxide, halite and gypsum mineralizations (SEM examination), marking water seepages through "impermeable" clay layer and indicating desalination processes; F-largest southernmost sink about 70 m in diameter and only 3-4 m deep; note murky water seepages on its bottom and clay-wasting; G-a group of sinks on the sea-shore near-by, the clay terrace is sagging in the sinks and between them as a result of underground clay wasting. Photographed by M. Arnon on 15. 10 1998.

Fig. 12 (cont.)

sagging can be seen along with 1 m and more deep sagging of the clay terrace in the area between sinkholes (Fig. 12G). Examination of the clay sequence shows evidence of groundwater movement through vertical and horizontal fractures in the clay sequence, resulting in surficial (recent) iron-oxide and halite crystallization (Fig. 12E). This was verified by SEM EDS examination of these mineralizations (see SEM analysis).

N. Hever northern site

A group of more than 20 sinkholes up to 12 m deep developed during 1995-1998 in the northernmost part of the N. Hever alluvial fan (Figs. 8), roughly located along three lines perpendicular to the DS shore, each some 200 m long. These sinkholes are very steep and deep on the higher terrace, farther from the shore, and shallower closer to the sea; in about half of them puddles of murky water are visible, their levels marking the water table in the alluvium. The alluvial fan section consists of typical intercalations of 5 to 70 cm thick gravel-sand-clay layers and lenses. Single layers of aragonite, up to 5 cm thick, occur in the upper part of the section (Figs. 13, 14). In the 10-15 m lower level and closer to the sea marine terraces are developed, tens to hundreds of meters wide, composed of wet clay at least a few meters thick (Fig. 14C). It is possible that these clay sediments underlie or intercalate the alluvial fan sequence in places of sinkhole development, in the same way as exhibited at the Mineral Beach site.

In the N. Hever northern site even newly opened sinkholes, with the upper diameter less than 0.5 m on the surface, have a subsurface bell-shaped cavity more than 5 m deep, with a volume of not less than 15 m^3. The 3-5 cm thick aragonite layer is strong enough to prevent the loose near-surface sediments from collapsing, forming a typical bottle-neck (Fig. 13B, 14B). Larger sinkholes are surrounded by up to 0.5 m deep concentric fractures, the separated blocks subsiding and sagging into the hole (Fig. 14C). In the walls of two of them openings into further large underground caverns are clearly visible (Fig. 13C, 13D); one of them, shown on Fig. 13D, collapsed in October 1998, four months after the first examination, bringing down about 10 m^3 of alluvium (Fig. 14A). In the sink's wall brown layers which possibly indicate previous subsurface water conduits, are seen.

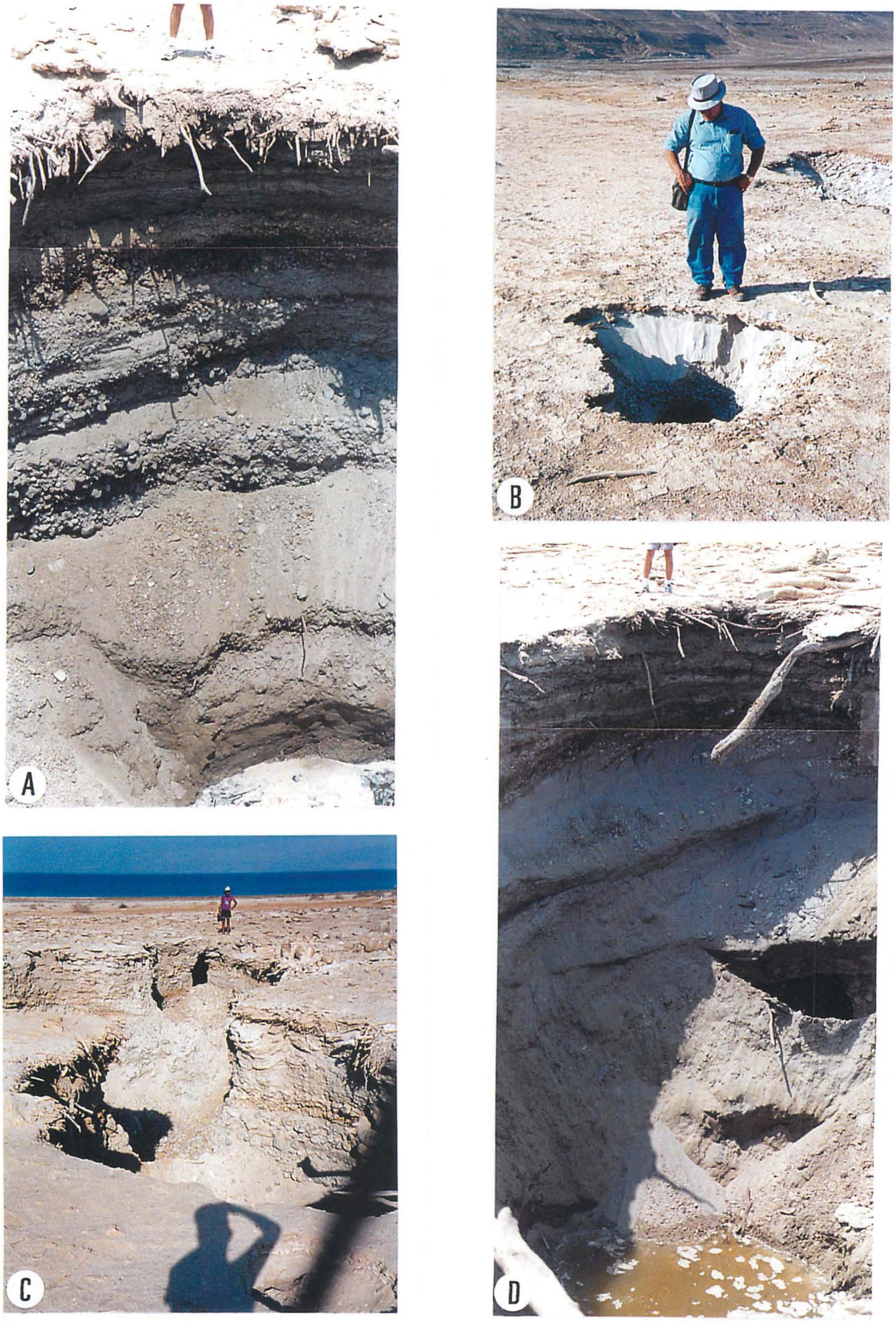


Fig. 13. N. Hever northern sinkholes site: A-typical alluvial sequence with the clay layer near the bottom, exhibited in one of the sinkholes about 7 m deep; note the brown layer, an active aquifer only few years ago, and the present water level; B-a small few-days-old sink, 0.7 m in diameter at its surface level; through the 30 cm diameter hole at its bottom a very large underground cavern can be seen; C-merged sinkholes about 5 m deep; the human figure is standing near the opening of a large seaward oriented cave; D-about a 7 m deep sink; a large adjacent underground cave can be seen through its entrance in the wall of the sinkhole (snapshots of 23.07.98).

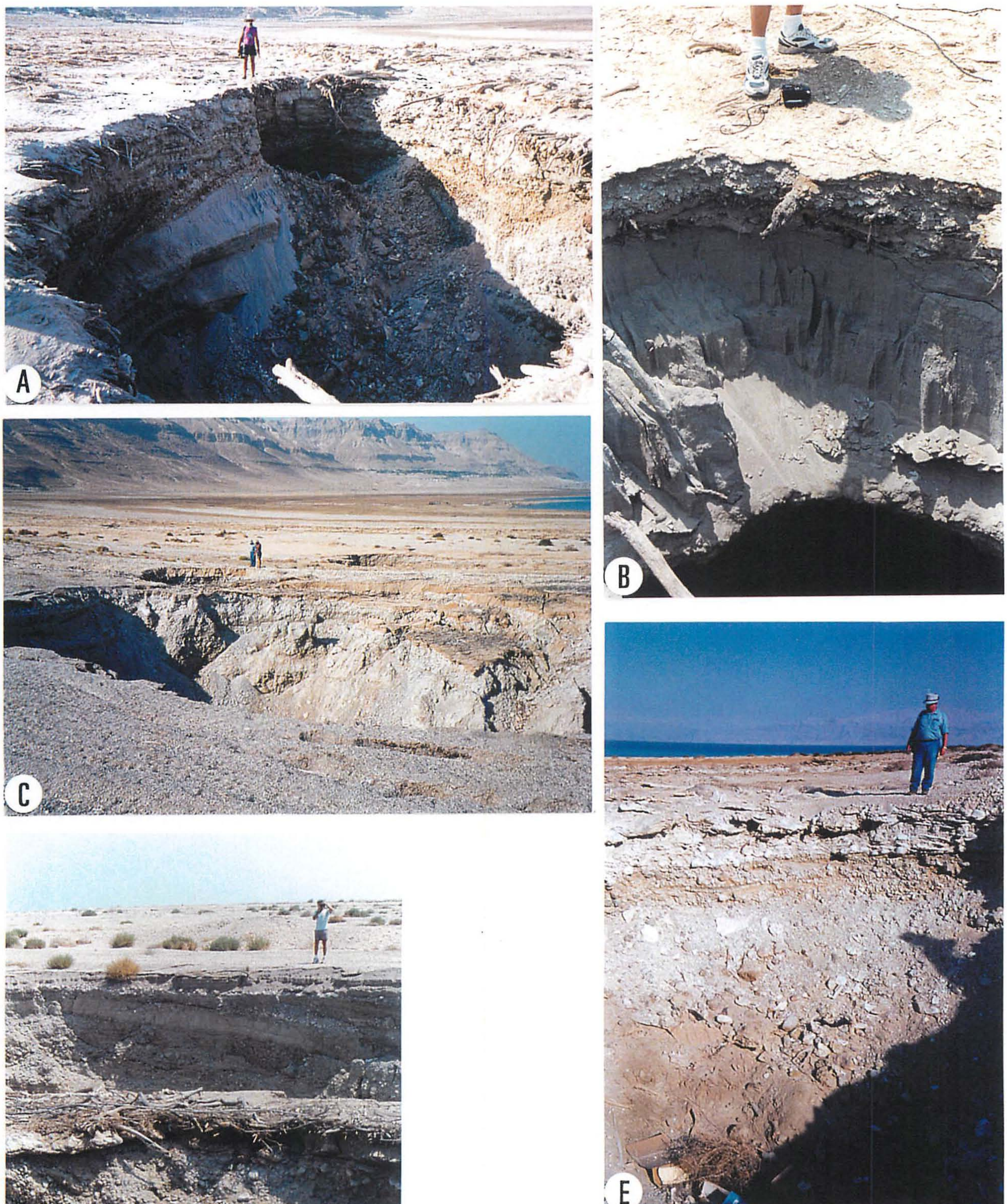


Fig. 14. N. Hever northern sinkhole site: A-freshly collapsed (October 1998) wall through which the cavity was visible three months earlier (Fig. 13D); B-a sinkhole 5 m in diameter, through which a very large underground cavity can be seen; C-large sinkhole slumping of the alluvial fan on the background of the western Dead Sea cliffs and low marine terraces composed of a clay-sequence; D-a large sink more than 15 m deep; E-an inactive sink accumulating wind-driven garbage. Photographs taken: A, C and E on 04.11.1998, B and D on 23.07.1998.

N. Hever southern site

A group of three sinkholes separated 20- 25 m from each other, developed on the southeastern part of the N. Hever alluvial fan 2 km south of the northern N. Hever site, near coord. 1872/0893 (Fig. 8, 15). Two of the holes are 2.5-3.0 m deep, one is less than 1m; their diameters are close to 3 m on the surface. Their visible section consists of sand-gravel intercalating clay-sand layers; iron oxide mineralizations are also visible. One of the sinkholes apparently developed on a young fault-related fracture (Fig. 15A, Raz, pers. comm., 1998). These sinkholes did not change their appearance during the period of observation (July-October 1998).

Newe Zohar sinkholes site

In 1991 a sinkhole appeared in the asphalt of the main road passing along the western side of the DS near the entrance to the Newe Zohar administrative center, at coord. 1851/0625 (Fig. 16). A circular hole of about a 3 m diameter and 5 m depth developed in a gravel section consisting of conglomerate layers 1-2 m thick, of various size components. The hole was filled with gravel several times, only to reappear. A detailed survey of this phenomenon was then requested as a basis for remedial works (Arkin, 1993; Shtivelman et al., 1994).

In the survey reports, geological and geomorphologic mapping of the site showed a line of eight sinkholes along a surface flow line in the frontal area of the Newe Zohar alluvial fan. The holes ranged in diameter from 3 to 5 m, partly filled, with depths up to 5 m. In some sinkholes the floor was wet, and a continuous flow of water was observed at the base of the easternmost sinkhole, on the main road. Three boreholes were drilled around the latter sinkhole to test the gravel section and width of the subsurface flow. In two of the boreholes lenses of silty clay up to 1.5 m thick were found and in each borehole a perched water level was recorded. A trench was dug where the flow line crossed the road, showing it was wider than 3 m. The remedial solution involved constructing a bridge in the form of an "n" across the flow line, with the road passing over it allowing the natural flow to continue; it was assumed that a disturbance of this flow is the main cause of sinkhole development, since new

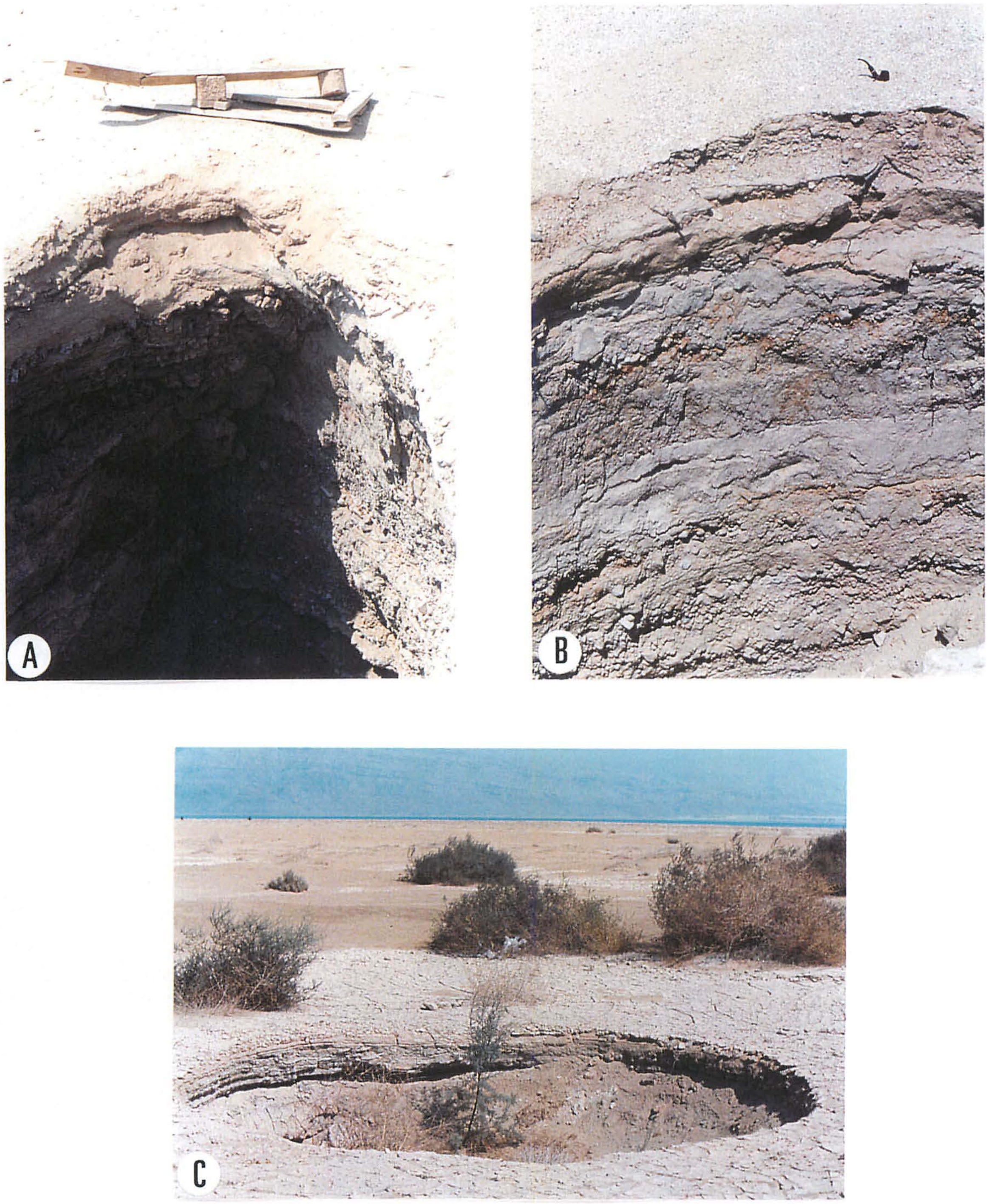


Fig. 15. Three sinks of the N. Hever southern sinkholes site: A-fracture, possibly Recent fault (E. Raz, pers. comm., 1998), visible in the wall of the southernmost sink; B-alluvial fan sequence in the wall of the northern sink; C-sagging, demonstrated in the eastern sink of the group. Photographs taken on 23.07.1998.

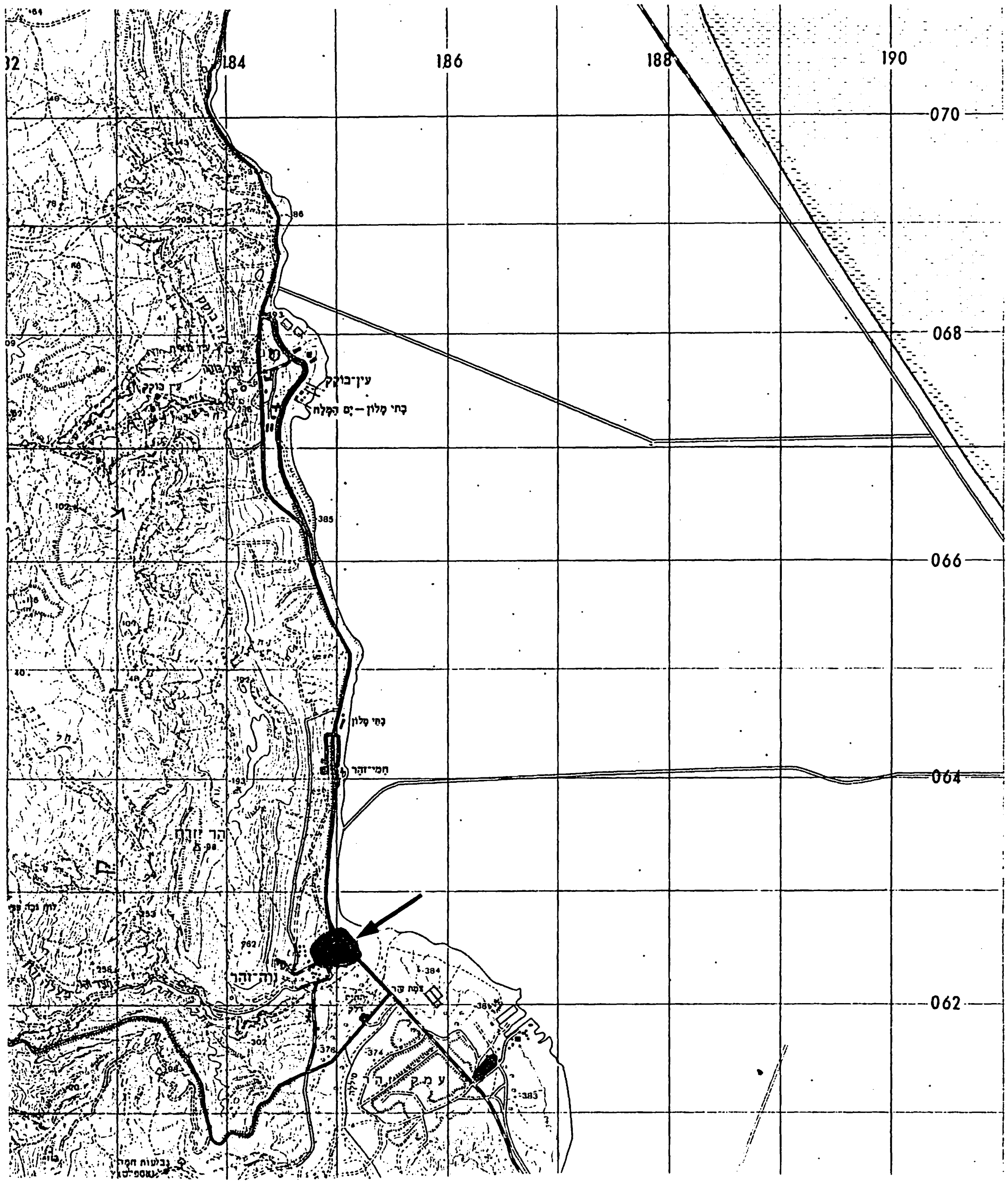


Fig. 16. Location map of the Newe Zohar (coord. 1850/0625) and the N. Hever (coord. 1863/0614) sinkholes sites.

sinkholes have developed along the flow line both upstream and downstream of the road; the largest is shown on Fig. 17A.

N. Hemar site

A very large elongated depression (sink) more than 100 m long, 10-15 m wide and 3-5 m deep, is recorded about 100 m east of (and beneath) the N. Hemar dam (coord. 1863/0614, Fig. 16). It is the result of the mergence and seaward progression of adjacent sinkholes in the mixed alluvial-sea terrace sequence of the gravel-sand-loam, (Fig. 17B). The sinkhole is bordered by a system of slump related fractures, by linear subsidence and formation of piloting sinks; timewise, its appearance parallels the construction in 1995-1996 of the nearby dam.

SEM analysis

SEM analyses were done on seven clay samples with undisturbed structures collected from the mud-holes developing on 3-8 year-old marine terraces (Attraction Beach, Mineral Beach, Samar springs and Hame Jesha); all samples were dried at 95^0C and vacuumed. Analyses show that bischofite ($MgCl_2$ x $6H_2O$) carnallite ($KMgCl_3$ x $6H_2O$), and aragonite with minor halite and sylvite (KCl) are present, the first three often forming some kind of structural network (Figs.18A to 18E). Analyses of the samples taken from the mineralized horizontal fracture in the Hame Jesha site show cubes of halite more than 1 mm in size, aragonite, carnallite, iron-oxides and minor pyrite (Figs. 18F to 18H). All dry samples of clay were very hygroscopic, quickly adsorbing water from the free air in the lab.

Summary and conclusions

The sinkholes described in this study (Table 1) appear in different sedimentary settings, namely alluvial fans and mud flats. The associated sinkholes may be named accordingly: alluvial fan gravel-holes, mud-holes, and a mixed type, where alluvial fans overlie mud layers a few meters thick.

Fig. 17. Southernmost sinkholes of the region: A-one of the oldest, few times refilled and still active sinkhole with the tractor-scraping sites postdating winter 1997 and prior to depression, near the entrance to Newe Zohar administrative center; B-long sinkhole developing sea-wards beneath the N. Hemar dam. Photographs taken on 23.07.1998.

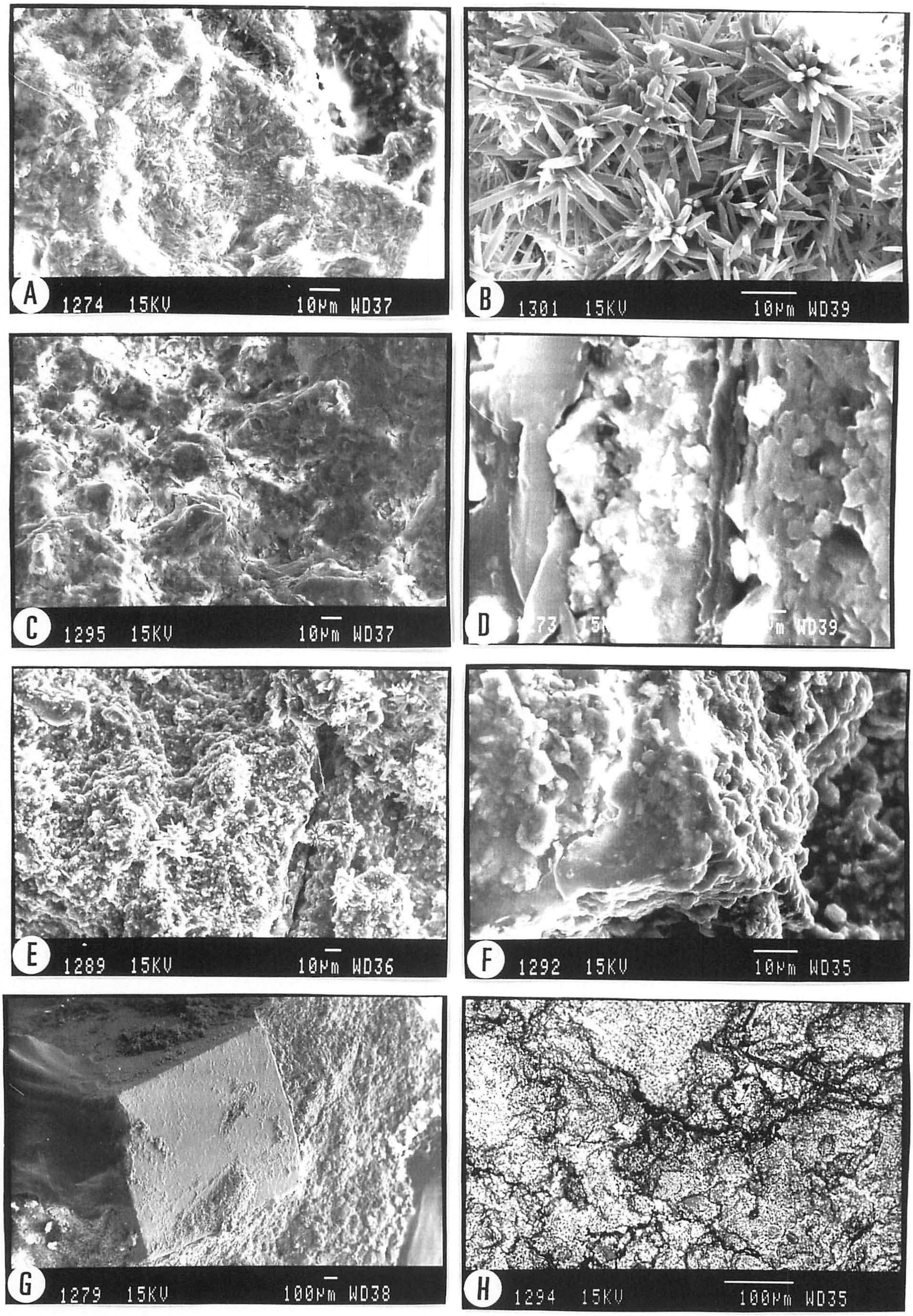


Fig. 18. SEM analyses of minerals found in unconsolidated marine clay from the sinkhole sites of the western Dead Sea coast: A, B - aragonite network, Samar springs site; C, D - mainly carnallite network, Mineral Beach site; E - aragonite (needles) on carnallite network in the clay, Hame Jesha site. Recent mineralization in the 2-3 mm wide horizontal crack in marine clay, Hame Jesha site: F - carnallite; G - aragonite needles on a halite crystal; H - mainly iron-oxide and minor pyrite (backscatter). Photographs taken by M. Dvorachek.

The clay deposits in the intervening bays between alluvial fans consist of gray, brown, dark-green unconsolidated clays typically composed of illite/smectite and kaolinite in similar amounts with minor palygorskite (Nathan et al., 1992). Often very thin laminations of white aragonite, some gypsum and well-developed salt cubes are present. The clay typically contains 60-70% brine, in which total dissolved salts range from 40 g/l to DS water composition of some 320 g/l, depending on the amount of dilution by extraneous water (Arkin and Starinsky, 1981). Observations from the small sinkholes of the Attraction Beach site (Fig. 4B) might indicate that sinks are formed when muddy spring water flowing up through the fractures removes the clay in the form of suspension. In the large seaward open sinkhole at the same site, the same processes seems to be at work, also removing some of the collapsed alluvial fan sediments. The fracturing and cracking (desiccation cracks resulting from the clay drying) in the unconsolidated clay and the muddy or murky underground or surface water, removing the clay in the form of suspension can be seen in every mud-hole site. It is particularly impressive in the Hame Jesha site, where plentiful vertical and horizontal open cracks and fractures with recent mineralizations are observed, which indicate recent flow of mineralizing fluids (Fig. 12E). In this site a more than 1 m sagging and subsidence of large surfaces in and between the sinks were also recorded, which may indicate underground mass mobilization (Figs. 12F and 12G). The author assumes that the large-scale slumping over the surface of the flat bottom of the largest mud-hole (70 m in diameter and 4-5 m deep, Fig. 12F), a surface coinciding with the local water table, indicates a shallow mass transfer of suspended or even fluidized clay directly to the sea in a late stage of the sinkhole development.

In many sites the intercalation of marine clay and alluvial sediments are clearly visible in sinkhole sections (e.g, Figs. 7D, 7E, 13A, 14C), and in canyon cuts of the N. Darga, N. David, N. Arugot and other valleys. Evidently gravel layers beneath clay in some of the mud-holes may serve as an important aquifer by which the fines and sand are carried out to the sea, forming the underground hollows (Figs. 13B, 13C, 13D). A similar role may be played by salt lenses and layers, which were proven by laboratory conductivity measurements and by pumping tests in the DSIF well to be three times more conductive than the gravel layers, the K (cofficient of filtration) being 10^3 and 3^x10^2 m/day respectively (Fig. 19; Yechieli, 1993, pp. 69, 167).

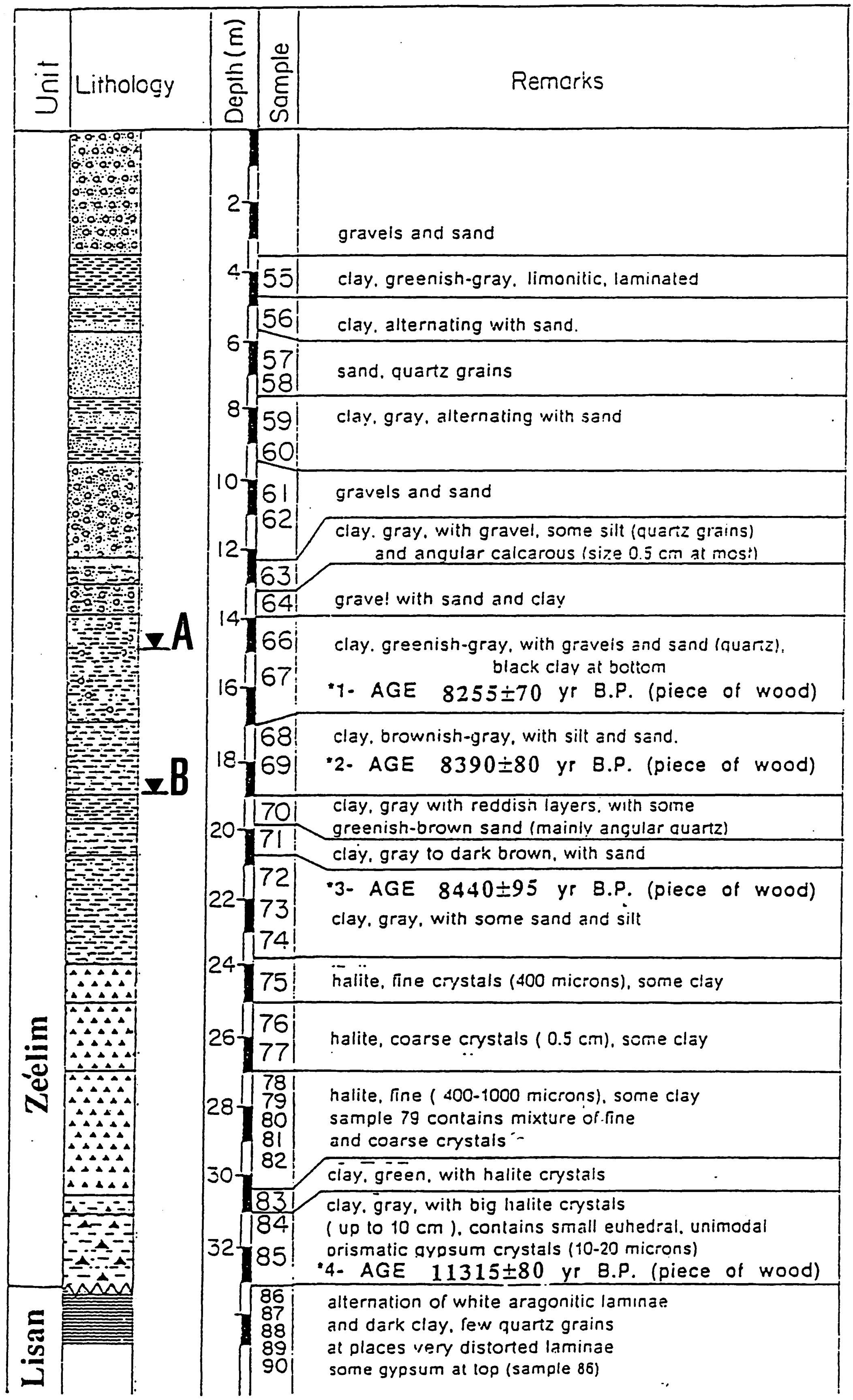


Fig. 19. Stratigraphy and lithology of borehole DSIF (coord. 1880/0822, surface elevation -394 m), including radiocarbon dates (from Yechieli, 1993). A- DS Level in 1989, -409 m; B- DS Level in 1998, -413 m.

Subsurface hollows grow upwards up to the surface, collapse (Fig. 14A) and continue to develop by slumping and merging of sinks. Finally they form a channel with the muddy or murky surface water stream flowing to the Dead Sea (e.g, in the Samar springs site, or the largest sinkhole in the Hame Jesha site.

For sinkholes belonging to the mixed type (where unconsolidated clay is overlain by alluvial fans (e.g, Mineral Beach site, and possibly En-Gedi holiday village), the beginning of the process would have been similar to the mud-hole development, with the later process of piping in alluvial fan sediments leading to surficial collapse (e.g, larger sink of the Attraction Beach). At this stage the preferred process (by author) is that the gravel-holes developed by piping (see Arkin, 1993, and Arkin and Michaeli, 1995). Arkin (1993) and Arkin and Michaeli (1995) relate the sinkhole development to piping caused by change of a laminated underground water flow to a turbulent flow, resulting in washing out of fines and settling down of larger particles, producing a funnel like hollow, which grows upwards to roof collapse.

Sinkhole development along the DS shore is connected to and depends on underground mass mobilization. In such a model the sinkhole sites coincide with underground flow, springs, or with localities where water-wasting is a result of human activity. Based on the SEM observations it is suggested that subsurface (and surface) water removes components of the unconsolidated Dead Sea clay: (a) waters dissolve salt, thus destroying the salt-network which is assumed to be a clay-preserving frame-work, and dilute the brine which is contained in unconsolidated clay, thus breaking ionic bonds of clay platelets, causing subsequent mudflow (Monroe and Wicander, 1992), and washing-out of the clay particles in suspension into the sea; (b) saturated brines remove clay particles in suspension. The underground mass mobilization has to be in direct proportion to the quantity and salinity of underground waters responsible for the flushing and transportation: it could be more than 100 m^3 during one month in a single sinkhole (see the case of the En-Gedi holiday village sink), or practically zero in the case of the N. Hever southern site group of sinkholes, which did not expand during 4 months of observation.

In light of all the information collected herein, an apparent escalation in activity of sinkhole-forming processes took place during the last two years (Table 1); these are accompanied by escalation of surface-water erosion and mass-wasting throughout the

Dead Sea area. In light of the distribution of sinkholes along the entire length of the DS, a common process for the the whole area must be sought. The rapid lowering of the Dead Sea water level, about 20 m during last 20 years to the lowest level in the last 5000 years (Fig. 20), may be responsible for this process. The present rate of decrease in the DS water level is 0.7-1.0 m/year. The retreating sea exposes unconsolidated mud-flats. The susceptibility of the new coast and of the nearby alluvial fans to accelerated underground mass mobilization where underground springs and flows are present has to be taken into consideration in planning future use of the nearshore areas.

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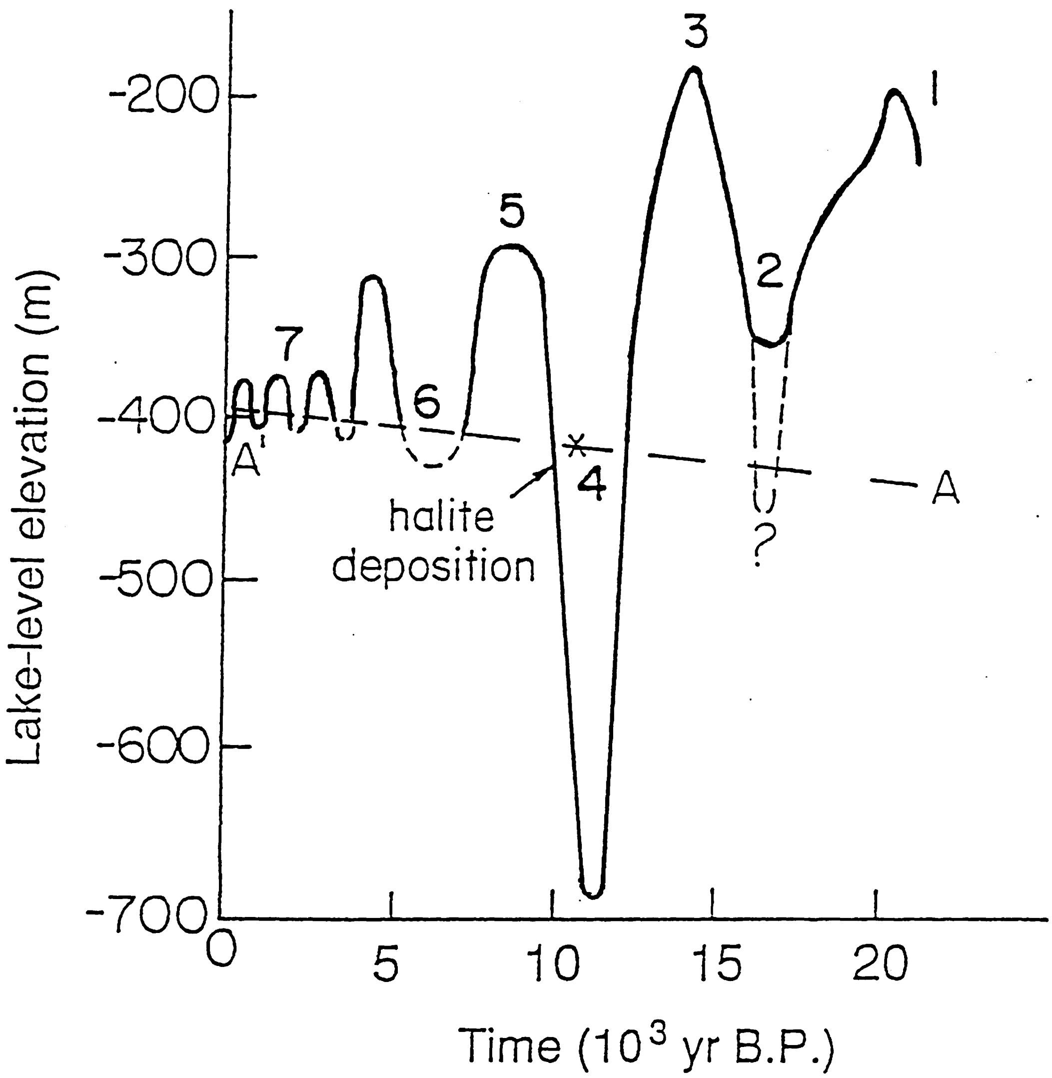

Fig. 20. Lake level elevations of the Dead Sea and its precursor Lisan Lake, since 20000 yr. BP (after Yechieli, 1993).

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