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Coastal processes affecting the clayey sediments of the exposed mudflats on the receding western Dead Sea shore

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Abstract

The present study documents coastal processes of movement and subsidence that affect the clayey sediments of the exposed mudflats ('mudflat sediments') on the receding western shore of the deep Dead Sea ('western Dead Sea shore') and the formation of subsidence features – subsidence strips and clustered sinkholes. Properties of the clayey sediments that promote movement and subsidence and the development of the subsidence features in the exposed mudflats are the unconsolidated fine-particle texture composed of clay and carbonate minerals, their being dry near the surface and wet at the subsurface, the soaking with saline water and brine, and the abundance of smectitic clays saturated with sodium and magnesium. Field observations indicate that narrow subsidence strips with/without clustered sinkholes were developed by movement and subsidence in mudflat sediments via lateral spreading. Wide subsidence strips with clustered sinkholes were developed by increased subsidence in mudflat sediments due to progress of dissolution within a subsurface rock-salt unit. The emergence of sinkholes occurs by subsidence of mudflat sediments into subsurface cavities resulting from dissolution within a subsidence rock-salt unit. The coastal processes on the receding Dead Sea shore and the formation of the subsidence features are part of the adjustment of the Dead Sea periphery to the lowering of the base-level. A contribution of slow mass-movement seaward to the coastal processes on the receding Dead Sea shore is indicated.

Keywords: Alluvial fan; Clustered sinkholes; Lateral spreading; Mudflat sediment; Narrow bay; Sea retreat; Sediment-creep; Subsidence strip.

The current study is based on field-observations of coastal processes of movement and subsidence that affect the mudflat sediments on the receding western Dead Sea shore and the development of subsidence features – subsidence strips and clustered sinkholes – in the exposed mudflats. The present study continues a preliminary study of the properties of clayey sediments of the exposed mudflats, based on laboratory analyses (Shoval, 2023).

The fast drop of the Dead Sea level in recent decades is an interesting case of the impact of sea-level retreat on coastal processes. The coastal environment is sensitive to changes in sea level and their impact on coastal processes, in particular on coastal landslides (Budetta *et al.*, 2008; Vardy *et al.,* 2012; Devoto *et al.*, 2013; Leshchinsky *et al.*, 2017; Chacón *et al.*, 2019; Soldati *et al.*, 2019). Climate-related sea-level changes have recently received attention due to global warming and the impact of climate change on coastal landslides (Jakob & Lambert, 2009; Doi *et al.*, 2020; Alberti *et al.,* 2022). Effects of human activity on coastal landslide and subsidence have also been recorded (Notti *et al.*, 2015; Candela & Koster, 2022).

The retreat at the western Dead Sea shore has exposed littoral sediments and mudflats on the shore (Arkin & Gilat, 2000), caused land subsidence (Baer *et al.*, 2002, 2024; Abelson *et al.*, 2003, 2006, 2018; Nof *et al.*, 2013, 2019; Yechieli *et al.*, 2016; Shviro *et al.*, 2017) and emergence of clustered sinkholes (Abelson *et al.*, 2017a; Yechieli *et al.*, 2006; Frumkin *et al.*, 2011; Ezersky *et al.*, 2017; Abelson, 2021). Coastal processes and formation of sinkholes have also been reported from the eastern Dead Sea shore (Taqieddin *et al.,* 2000; Closson, 2005; Closson *et al.*, 2005; Closson & Abou-Karaki, 2009a, 2009b; Al-Halbouni *et al.*, 2017, 2019; Watson *et al.*, 2019).

Most previous work on the subsidence features at the western Dead Sea shore was focused on the emergence of sinkholes (most recently by Ezersky & Frumkin, 2020, 2021; Abelson, 2021). The present study expands on coastal processes of movement and subsidence that affect the clayey sediments of the exposed mudflats on the receding western Dead Sea shore and on the development of subsidence strips – narrow subsidence strips with/without clustered sinkholes and wide subsidence strips with clustered sinkholes – in the exposed mudflats. Properties of the mudflat sediments that promote movement and subsidence and the development of the subsidence features are considered.

The current study also examines the extension of subsidence features in exposed mudflats. The arrangement of the clustered sinkholes on the western Dead Sea shore (Abelson *et al.*, 2017a) is attributed to subsidence of the sediments along lineaments (Ezersky & Frumkin, 2013), tracking the existing tectonic faults of the Dead Sea Rift along the Dead Sea shore (Abelson *et al.*, 2003, 2006; Yechieli *et al.*, 2003, 2006, 2016). However, recently doubts have risen about the connection between the formation of clustered sinkholes and fault lines. These doubts are based on the understanding that the sinkholes sites on the Dead Sea shore often appear at the boundary of the subsurface rock-salt layer (Ezersky & Frumkin, 2013; Abelson *et al.*, 2017a). Although a large number of faults have crossed the Dead Sea shore (Garfunkel, 1981), sinkholes are usually developed in a single narrow strip 50–100 m wide, roughly parallel to the Dead Sea shore (Ezersky *et al.*, 2017). Also, the fault escarpments and cracks in the Dead Sea coastal area resemble to appearance surface expressions of landslides (Baer *et al.,* 2002). The occurrence of landslides due to lake level lowering has been reported from the eastern Dead Sea shore by Closson *et al.* (2010); and the development of sinkholes along tension cracks by Closson & Abou-Karaki (2009a). In the present study, a contribution of slow mass-movement seaward to the coastal processes on the receding Dead Sea shore is indicated.

The clays of the Dead Sea were analysed by Nathan *et al.* (1990, 1992, 1994) and the clay minerals of the Sedom Formation by Shoval & Zlatkin (2009). Geotechnical characteristics of sediments on the western Dead Sea shore have been reported by Ezersky & Livne (2013) and on the eastern Dead Sea shore by Taqieddin *et al.* (2000), Khlaifat *et al.* (2010) and Salameh *et al.* (2019). Geotechnical studies of evaporitic-lacustrine sediments in the saline environment of the Dead Sea have been informed by Frydman *et al.* (2008, 2014). A viscoelastic modeling of sinkhole precursory subsidence along the Dead Sea shore has been proposed by Atzori *et al.* (2015) and Baer *et al.* (2018).

METHODOLOGY

Based on field-observations, the present study investigates coastal processes of movement and subsidence that affect the mudflat sediments on the receding western Dead Sea shore, and documents the development of subsidence features – subsidence strips and clustered sinkholes – in the exposed mudflats. The laboratory analyses of the clayey sediments of the exposed mudflats were performed in a preliminary study (Shoval, 2023) and are summarized in the 'Results' section below. Official data published by the Geological Survey of Israel were also utilized.

The studied area on the western Dead Sea shore

The Dead Sea is located in the Dead Sea Basin, which is part of the Dead Sea Rift (Fig. 1a; modified from Hall & Calvo, 2005). This sea is a hypersaline terminal desert lake that terminates the drainage system of the Jordan River (Fig. 1a). The Dead Sea level is the lowest exposed place on Earth's continents, currently about 440 m Below Mean Sea or ocean Level (BMSL). The lake fills the deep northern Dead Sea basin 'Deep Dead Sea' (Fig. 1b; base on NASA image by Simmon, 2012) with the deepest underwater point being ~ 730 m BMSL; and the shallow southern part 'Shallow Dead Sea' (Fig. 1b), separated by the Lisan Peninsula, is occupied by evaporation ponds (Neev & Hall, 1979). The studied sites are located on the western shore of the deep Dead Sea (Fig. 1c).

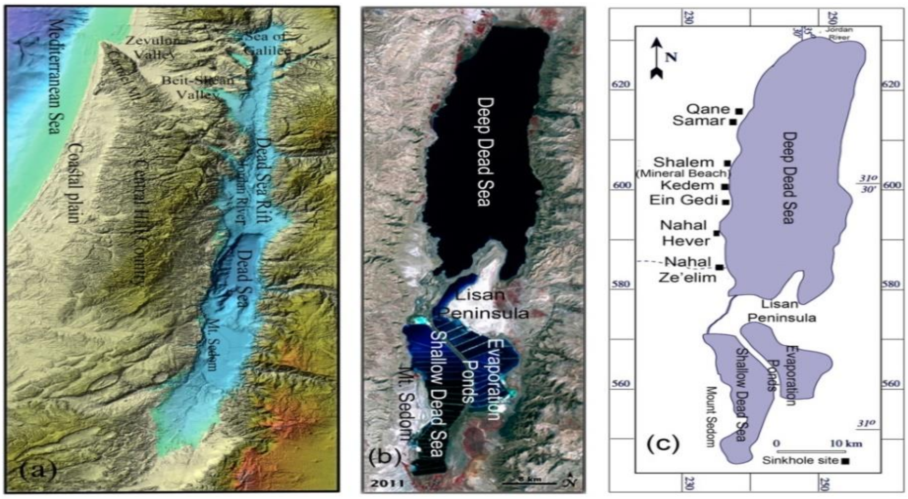

Figure 1. Maps of the Dead Sea region: (a) A location map of the Dead Sea (modified from the digital shaded relief map of the region by Hall & Calvo, 2005, the Geological Survey of Israel: https://www.gov.il/he/pages/israel-and-regions-aerial-photo-map).

(b) A satellite map of the Dead Sea Valley (base on NASA image by Simmon, 2012, using Landsat data from the USGS: https://visibleearth.nasa.gov/images/77592/the-dead-sea).

(c) A map of the studied sites on the western Dead Sea shore; coordinates on the map are of the new Israel Mercator grid in km.

Sites morphology and location maps

The fieldwork was carried out at the Samar, Shalem, Kedem, Ein Gedi, and Hever sites on the western Dead Sea shore (Fig. 1c). The studied sites are located along a 50 km long and 1 km wide strip along the shore. Photographs of the sites morphology and location maps are shown in Fig. 2. The location maps in Fig. 2 were modified from official maps of the Geological Survey of Israel provided on the website "Dead Sea sinkholes and subsidence monitoring".

Figure 2 Photographs of the sites morphology and location maps of: (a) Samar site (b) Shalem site (c) Kedem site (d) Ein-Gedi site and (e) Hever site. The location maps were modified from official maps of the Geological Survey of Israel provided on the website: "Dead Sea sinkholes and subsidence monitoring": https://egozi.gsi.gov.il/WebApps/hazards/sinkholes_subsidence/. Coordinates are given on the location maps. The photographs of the sites morphology were taken in the field by the author.

RESULTS

Field-observations at the studied sites

The field-observations document coastal processes of movement and subsidence and the formation of subsidence features at the studied sites on the receding western Dead Sea shore.

Features of receding on the western Dead Sea shore

The progressive retreat of the Dead Sea is evident by the exposure of mudflats (Fig. 3a), the formation of beach stapes and lines of coastal regression (Fig. 3b-c). The coastal receding is marked by the disintegration of an old pier from the current beach (Fig. 3d).

Figure 3. Features of receding on the western Dead Sea shore: (a) Exposure of mudflats. (b) Beach stapes in an exposed mudflat (Kedem site). (c) Lines of coastal regression in an exposed mudflat (Kedem site). (d) Disintegration of an old pier from the current beach (Ein Gedi site).

Main geomorphic features at the studied sites

The main geomorphic features at the studied sites are exposed mudflats and alluvial fans (Fig. 4). The exposed mudflats with subsidence features are generally located at the lower Dead Sea shore closer to the coastline (Fig. 4a). The mudflats contain laminated clayey sediments (Fig. 4b). The alluvial fans are generally located on the higher Dead Sea shore (Fig. 4c). Gravel deposits of the alluvial fans overlie the mudflat sediments (Fig. 4d).

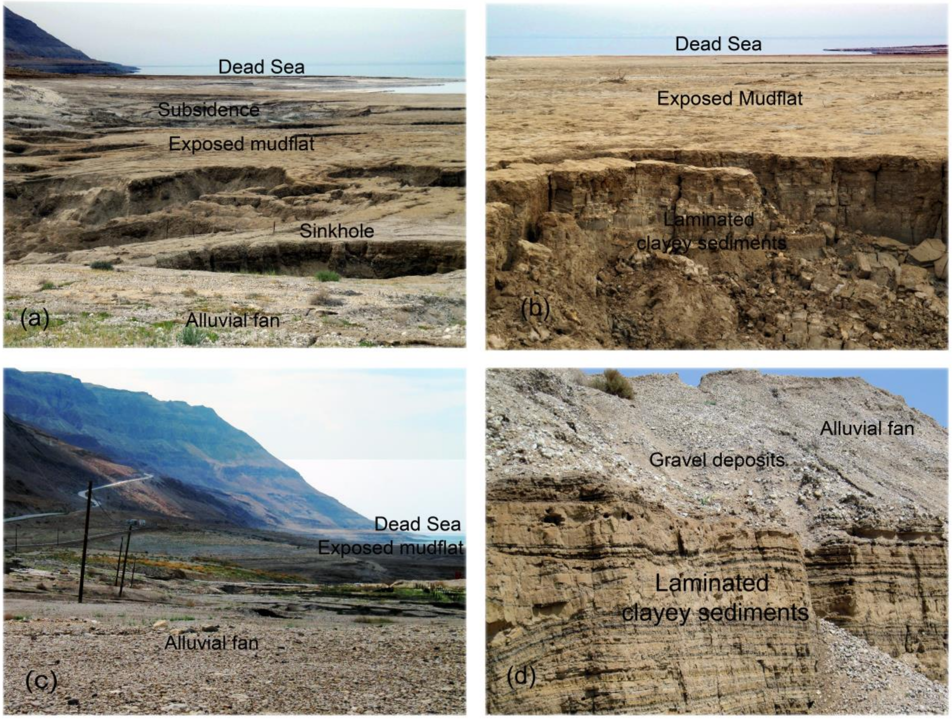

Figure 4. The main geomorphic features at the studied sites: (a) Exposed mudflats with subsidence features (Shalem site). (b) Mudflat sediments contain laminated clayey sediments (Shalem site). (c) Alluvial fans on the higher Dead Sea shore (Shalem site). (d) Gravel deposits of the alluvial fan overlie the mudflat sediments (Hevar site).

Subsidence features in exposed mudflats

The subsidence features in exposed mudflats on the western Dead Sea shore include narrow subsidence strips with/without clustered sinkholes (Fig. 5), and wide subsidence strips with clustered sinkholes (Fig. 6). At specific sites, subsidence features extend in the exposed mudflats up to 1 km long and up to 200 m wide (Yechieli *et al.*, 2006, 2016).

Movement and subsidence of mudflat sediments are visible in the narrow subsidence strips (Fig. 5a-b). Collapse of mudflat sediments occurs in clustered sinkholes in narrow subsidence strips (Fig. 5c-d).

Increased subsidence of mudflat sediments is visible in wide subsidence strips with clustered sinkholes (Fig. 6). Subsidence strips and clustered sinkholes extend in exposed mudflats aligned roughly parallel to shoreline (Figs. 5-6), and are gradually broadening over time.

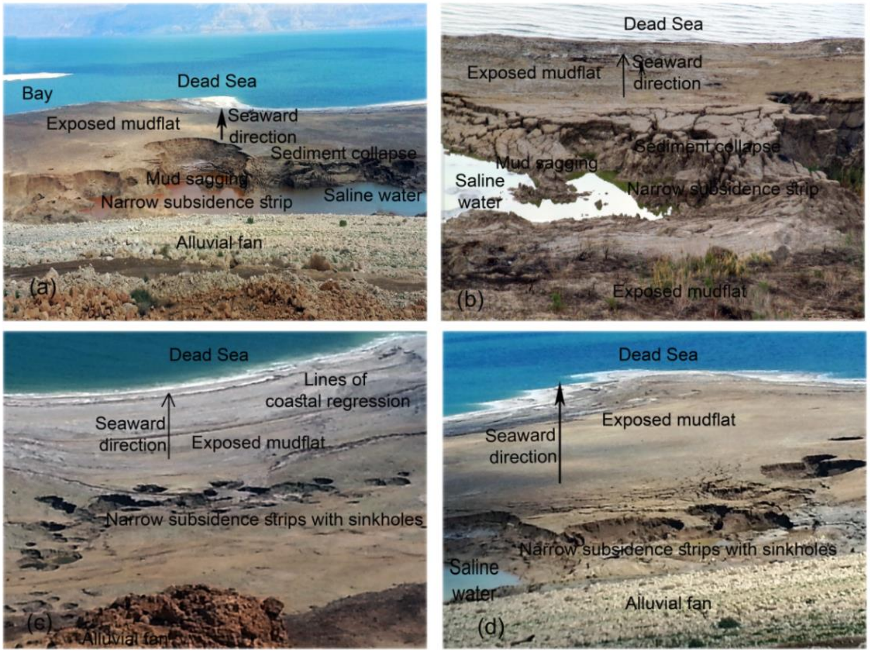

Figure 5. Narrow subsidence strips in exposed mudflats: (a-b) Movement and subsidence of mudflat sediments in narrow subsidence strips (Samar site). (c-d) Collapse of mudflat sediments in clustered sinkholes in narrow subsidence strips (Kedem site).

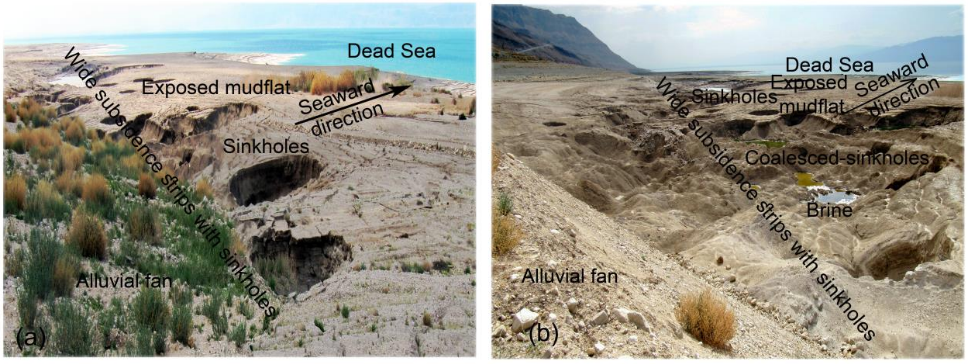

Figure 6. Wide subsidence strips with clustered sinkholes in exposed mudflats: (a-b) Increased subsidence of mudflat sediments in wide subsidence strips with clustered sinkholes (Shalem site).

Sinkholes in exposed mudflats

Clustered sinkholes occur in narrow subsidence strips (Fig. 5c-d) and in wide subsidence strips (Fig. 6). Collapse of mudflat sediments is visible in the sinkholes (Fig. 7a-b). The sinkholes are widening in exposed mudflats from funnel-shaped sinkholes, collapse-sinkholes, wide collapse-sinkholes to coalesce-sinkholes (Fig. 7). The diameter of individual sinkholes ranges from 2-15 m and up to a depth of 7 m (Arkin & Gilat, 2000).

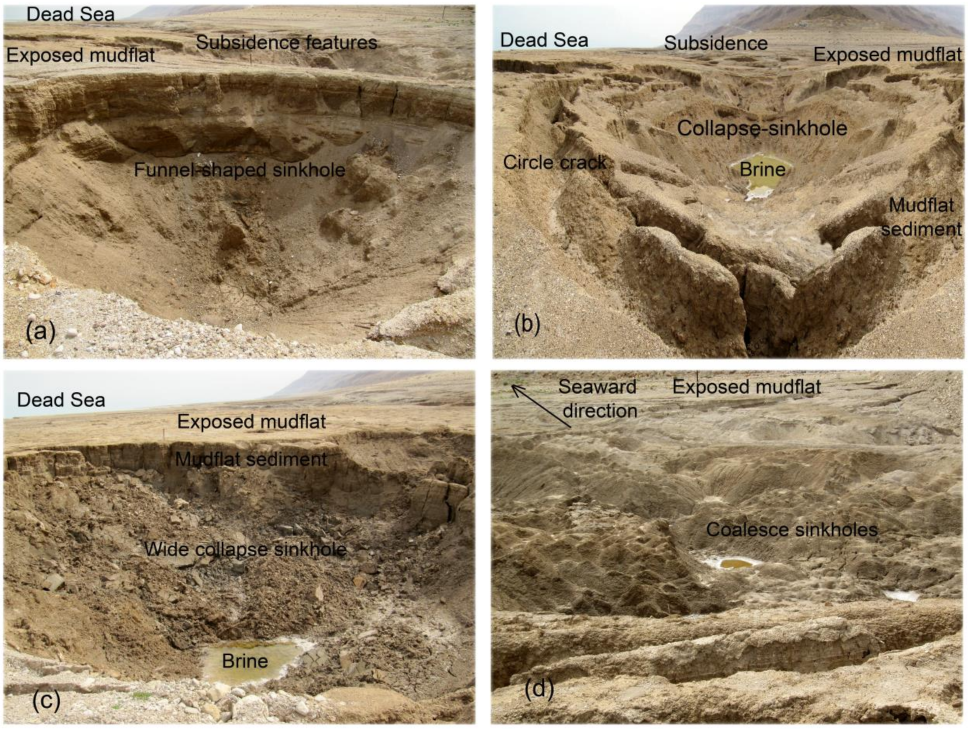

Figure 7. Widening of sinkholes: (a) A funnel-shaped sinkhole, (b) A collapse-sinkhole, (c) A wide collapse-sinkhole, and (d) coalesce-sinkholes (Shalem site).

Cracking features in alluvial fans

Cracking and formation of open cracks (Fig. 8a-b) and tension gaps (Fig. 8c-d) affect the alluvial fans on the higher Dead Sea shore (Fig. 8). The cracking features are aligned roughly parallel to shoreline and gradually widen with time (Fig. 8a-c). Gravel sinkholes also occur in alluvial fans (Arkin & Gilat, 2000; Ezersky & Livne, 2013). Gravel sinkholes with open cracks and collapse of gravel deposits in gravel sinkholes are observed (Fig. 9).

Figure 8. Cracking features crossing alluvial fans on the higher Dead Sea shore: (a) Open cracks in an alluvial fan (Shalem site). (b) Broadening of open cracks (Shalem site). (c) Tension gap in an alluvial fan (Hever site). (d) Profile of a tension gap (Hever site).

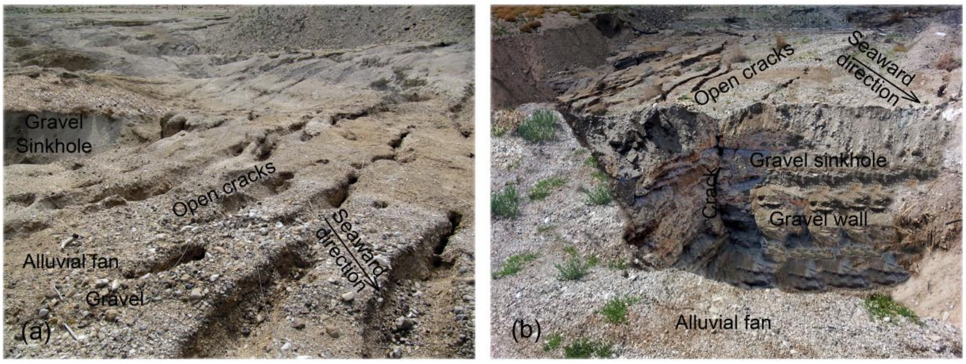

Figure 9. Gravel sinkholes in alluvial fans: (a) A gravel sinkhole with open cracks (Shalem site). (b) Collapse of gravel deposits in a gravel sinkhole (Shalem site).

Composition of the mudflat sediments at the studied sites

Properties of the clayey sediments that promote movement and subsidence of the mudflat sediments and the development of the subsidence features are the unconsolidated fine-particle texture, the bulk and clay mineralogical compositions, the water content and the salinity. Fine-particle sizes of 2-5 μm were reported for the decalcified clay fraction of mudflat sediments in a preliminary study (Fig 10 in Shoval, 2023). The fine detritus material and the suspended sediments of the Ze’elim Fm. (mudflat sediments) have grain-size peaks at 5-10 μm and at 2-4 μm, respectively (Haliva-Cohen *et al.,* 2012).

Mineralogical composition and the clay mineral composition

Laboratory analyses of the mudflat sediments were performed in a preliminary study (Shoval, 2023). Fig. 10 summarizes the bulk mineralogical composition and the clay mineral composition of mudflat sediments at studied sites. The histograms in Fig. 10 show average results for specimens of the same type at individual sites. In Fig. 10a the mineralogical composition is calculated with the amounts of the total clay mineral contents. The bulk mineralogical composition consists of clay minerals and carbonate minerals (calcite, aragonite and dolomite) with some quartz and feldspar (Fig. 10a). The main clay minerals present are R0 mixed layer illite–smectite (I/S) and kaolinite with minor discrete illite and palygorskite (Fig. 10b).

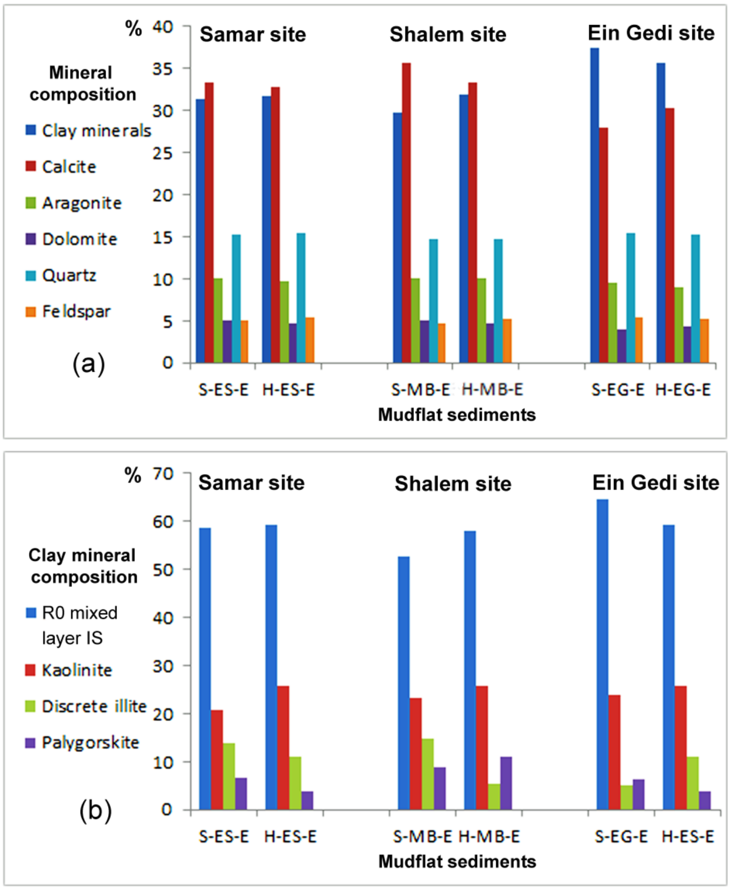

Figure 10. Mineralogical composition of the mudflat sediments at the studied sites (based on data from Shoval, 2023): (a) Bulk mineralogical composition, (b) Clay mineral composition.

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Salinity of the mudflat sediments

The salinity of the mudflat sediments is identified by the presence of saline water and brine and precipitated gypsum and halite (Frydman *et al.,* 2008). Local saline water is associated with subsidence features in exposed mudflats (Fig. 5a-b). Brine accumulates within sinkholes (Fig. 7b-c). Saline groundwater has been reported in shallow aquifers along the Dead Sea shore (Yechieli, 2000; Ezersky & Frumkin, 2017). Fig. 11 summarizes the concentrations of dissolved cations (mg/l) in saline water and in sinkhole brines from studied sites (data from Shoval, 2023). Na and Mg are the main cations of the brines (Fig. 11). The variations in the compositions of sinkhole brines are due to local precipitation of salts at the bottom of sinkholes – halite, gypsum, and possibly carnallite and bischofite (Zilberman-Kron, 2008).

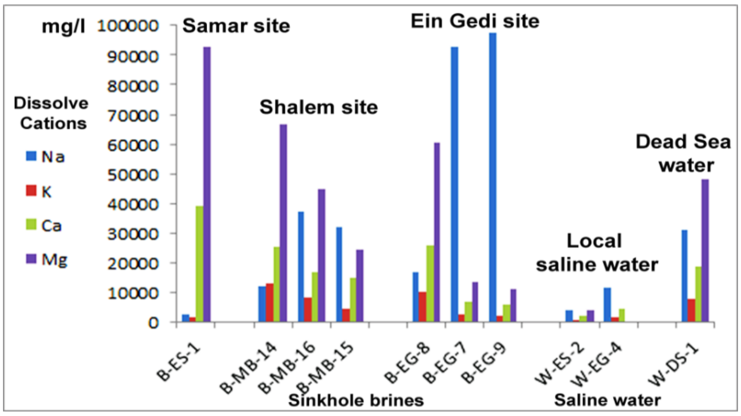

Figure 11. Concentrations of dissolved cations (mg/l) in saline water and in sinkhole brines from studied sites (based on data from Shoval, 2023). (B=brine; W=saline water; ES=Samar site; MB=Shalem site; EG=Ein-Gedi site; DS=Dead Sea).

DISCUSSION

The impact of the Dead Sea retreat on coastal processes

The coastal processes on the receding Dead Sea shore and the subsidence features are part of the adjustment of the Dead Sea periphery to the lowering of the base-level. In recent decades the Dead Sea has experienced a fast drop of the water-level (Lipchin *et al.*, 2004; Ghazleh et al., 2011; Vey *et al.*, 2021), rapid retreat (Bookman *et al.*, 2004) and lowering of the base-level (Watson *et al.*, 2019). Fig. 12 displays a diagram of the drop in the Dead Sea water-level over the years 1978-2025 (official data from the Israeli Hydrological Service). Over the past 47 years, the water-level of the Dead Sea has dropped by about 40 m and on 02/27/2025 it stood at 439.78 m BMSL. The average rate of decline in these years was about 85 cm per year. Fig. 3 shows features of receding on the western Dead Sea shore.

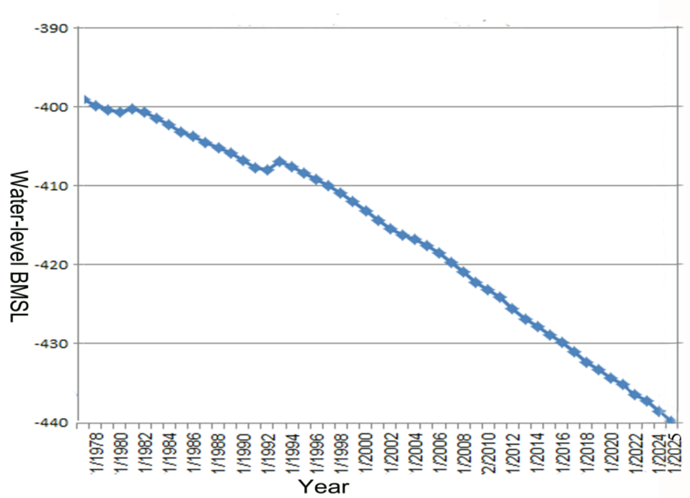

Figure 12. Diagram of the fast drop in the Dead Sea water-level in the years 1978-2025 (official data from the Israeli Hydrological Service: https://data.gov.il/dataset/https-www-data-gov-il-dataset-683/resource/823479b4-4771-43d8-9189-6a2a1dcaaf10).

The retreat at the western Dead Sea shore exposed littoral sediments (Fig. 3a), mudflats (Fig. 4a-b), and contributed to development of subsidence strips (Figs. 5-6), and the emergence of sinkholes (Fig. 7). The sinkholes first appeared in the 1980s when the Dead Sea level was about 400 m BMSL and their numbers has increased over the years as the water level has dropped (Ezersky *et al.*, 2017; Abelson *et al.*, 2018). Since their first appearance over 6,000 of sinkholes have been documented on the western Dead Sea shore (Yechieli *et al.*, 2016; Abelson *et al.*, 2017b) and their formation continues today. In the western Dead Sea, the newly-formed clustered sinkholes migrate seawards (Fig. 13a, modified from Abelson *et al.*, 2017a). Fig. 13b shows the bathymetric morphology of the coastal margin, and subsea mass transport on the subsea slope (modified from Sade *et al.*, 2014).

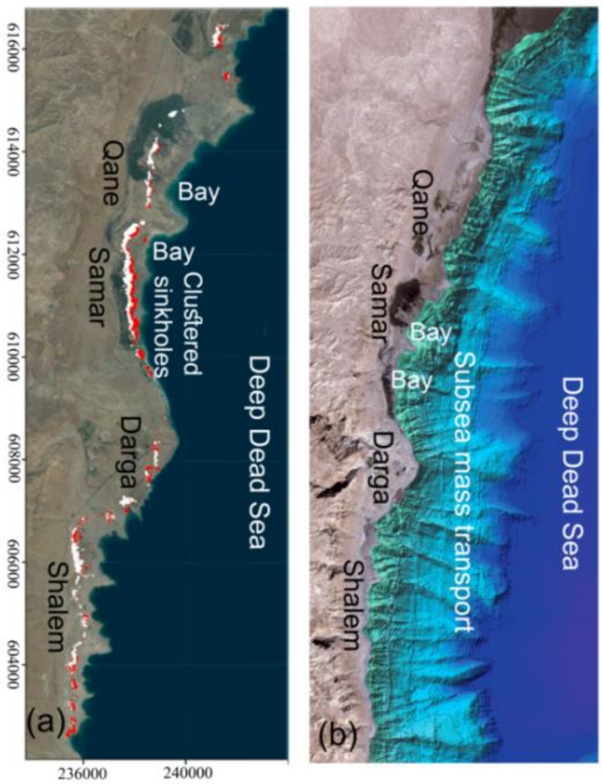

Figure 13. (a) A satellite photograph map of the western Dead Sea, illustrating the roughly shoreline-parallel extending of subsidence features, and the seaward migration of newly-formed clustered sinkholes (red symbols) relative to older sinkholes (white symbols) (modified from the Satellite Photograph Map of the Dead Sea region by Abelson *et al.*, 2017a; the Geological Survey of Israel: https://www.gov.il/BlobFolder/reports/abelson-et-al-report-2017/he/report_2017_GSI-24-2017.pdf).

(b) The Multibeam bathymetric map of the western Dead Sea, illustrating the bathymetric morphology of the coastal margin, and subsea mass transport on the subsea slope (modified from bathymetric map of the Dead Sea by Sade *et al.*, 2014; the Geological Survey of Israel: https://www.gov.il/BlobFolder/generalpage/dead-sea-relief-map/he/img_BLA_Shaded-batimetry_map-Dead-Sea-Poster-Front-300dpi.pdf).

Properties of clays that promote movement and subsidence

The abundance of clay minerals contributes to movement, subsidence, displacement, landsliding and sliding of sediments and soils (Bhandary *et al.*, 2005; Brooks, 2013; Di Maio *et al.*, 2015). The presence of smectitic clay layers in clayey sediments facilitates movement and subsidence (Al-Homoud *et al*., 1996). The ability of smectite layers to adsorb water and swell (Yariv & Cross, 2012) provides the muddy and lubricant properties of the clayey sediments under wet conditions, thus initiating sliding processes. Movement and subsidence are promoted by soaking with saline water and brine (Mariotti *et al.*, 2016, 2019). Saturation of smectitic clay with sodium leads to clay dispersion (Pearson & Bauder, 2006) and enhances the muddy and lubricant properties of the clayey sediments.

The subsidence of the clayey sediments during development of the subsidence features in the exposed mudflats (Figs. 5-6) involves sediment collapse of dry mudflat sediments near the surface and mud sagging of wet mudflat sediments at the subsurface. The near-surface collapse of the dry mudflat sediments (Fig. 4a-b) is favoured by their unconsolidated fine-particle texture composed of clay and carbonate minerals (Fig. 10a), and by the lack of significant cohesion (Ezersky & Livne, 2013). The subsurface mud sagging of wet mudflat sediments (Fig. 5a-b) is promoted by the soaking with saline water and brine, and by their muddy and lubricant properties under wet conditions, due to the abundance of swelling smectitic clay (Fig. 10b) saturated with Na and Mg (Fig. 11).

The development of narrow subsidence strips

Field observations indicate that the development of narrow subsidence strips with/without clustered sinkholes (Fig. 5) occurs by movement and subsidence in mudflat sediments via lateral spreading

(Fig. 14). Lateral spreading in clayey sediments and soils is described by Buma & Van Asch (1996) and Pasuto *et al.* (2022). The lateral spreading locally interrupts continuity of mudflat sediments, causes subsidence of the clayey sediments and formation of the narrow subsidence strips (Fig. 14a). Fig. 14b illustrates the movement and subsidence in the formation of a narrow subsidence strips, which involves collapse of dry mudflat sediments near the surface and mud sagging of wet mudflat sediments at the subsurface.

A roughly shoreline-parallel extending of narrow subsidence strips in exposed mudflats (Fig. 5) and their gradual broadening over time suggests contribution of slow mass-movement seaward.

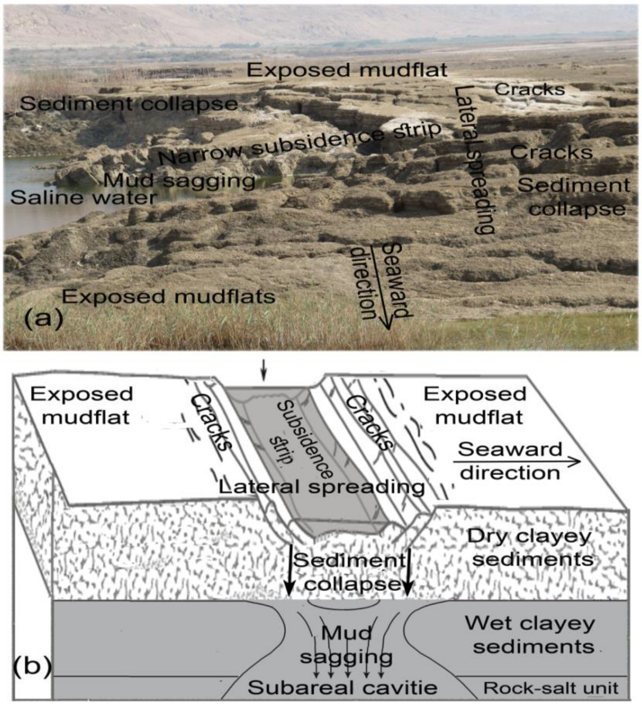

Figure 14. The formation of a narrow subsidence strip: (a) Movement and subsidence in mudflat sediments via lateral spreading (Samar site). (b) An illustration of the subsidence in the formation of a narrow subsidence strip, which involves sediment collapse and mud sagging.

The development of wide subsidence strips

Wide subsidence strips with clustered sinkholes (Fig. 6) were developed by increased subsidence in mudflat sediments due to progressive dissolution within a subsurface rock-salt unit. Land subsidence with sinkholes on the Dead Sea shore due to salt dissolution within a subsurface rock-salt unit was reported by Baer *et al.* (2002), Abelson *et al.* (2003, 2006), Nof *et al.* (2013, 2019), Filin *et al.* (2014) and Yechieli *et al.* (2016). Salt-karst systems on the western shore were reported by Avni *et al.* (2016) and Baer *et al.* (2024) and on the eastern shore by Watson *et al.* (2019).

It seems that an earlier formation of narrow subsidence strips in exposed mudflats (Fig. 5) promotes broadening into wide subsidence strips with clustered sinkholes (Fig. 6) as the former served as a preferential subsurface pathway for groundwater that enhanced the dissolution and salt karstification within the subsurface rock-salt unit.

A roughly shoreline-parallel extending of wide subsidence strips in exposed mudflats (Fig. 6) and their gradual broadening over time suggests contribution of slow mass-movement seaward.

The emergence of clustered sinkholes in exposed mudflats

The emergence of sinkholes occurs by subsidence of mudflat sediments into subsurface cavities, which result from dissolution within a subsidence rock-salt unit (Shalev *et al.*, 2006; Frumkin *et al.*, 2011; Ezersky & Frumkin, 2020, 2021; Abelson, 2021). Fig. 15 shows the emergence of a sinkhole containing bottom brine in exposed mudflats by subsidence of mudflat sediments. Fig. 15b illustrates the subsidence into a subsurface dissolution cavity in emergence of the sinkholes, which involves collapse of dry mudflat sediments near the surface and mud sagging of wet mudflat sediments at the subsurface. Geophysical methods confirm the existence of clay layer saturated with brine at the base of the sinkholes; and dense mud was found within the dissolution cavity at the subsurface salt-rock unit by drilling of boreholes (Ezersky *et al.*, 2009).

Increased subsidence in the formation of the sinkholes in exposed mudflats due to dissolution within the cavities in the subsurface rock-salt unit caused progressive widening from funnel-shaped sinkholes, collapse-sinkholes, wide collapse-sinkholes to coalesce-sinkholes (Fig. 7).

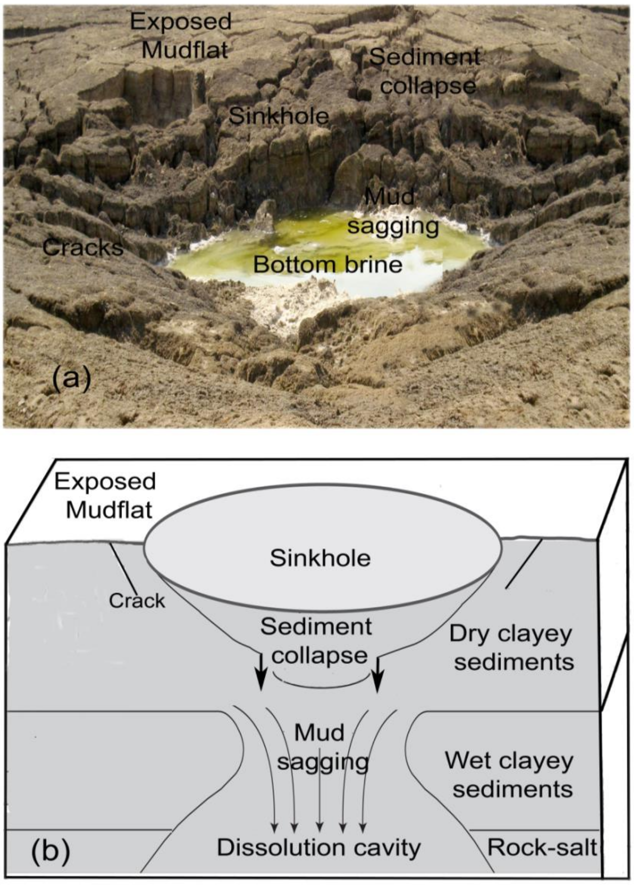

Figure 15. The emergence of a sinkhole containing bottom brine in exposed mudflats: (a) Subsidence of mudflat sediments in the sinkhole (Shalem site). (b) An illustration of the subsidence into a subsurface dissolution cavity in emergence of the sinkhole, which involves sediment collapse and mud sagging. (b, is modified from Shoval, 2023).

Coastal processes affecting gravel deposits in alluvial fans

In the alluvial fans on the higher Dead Sea shore, the retreat at the western Dead Sea shore formed cracking features – open cracks (Fig. 8a-b) and tension gaps (Fig. 8c-d). Fig. 16 shows indications of movement of gravel deposits in alluvial fans via sediment-creep seaward, through slow mass-movement. Indications of sediment-creep in the alluvial fans are the presence of tilt poles downslope, bent tree, tilt building, tilt fence and deformation on road asphalt along with cracking features (Fig. 16a-c) (Sharpe, 1938; Parizek & Woodruff, 1957). Fig. 16d illustrates the indications of sediment-creep in the alluvial fans.

In the alluvial fans, the roughly shoreline-parallel extension of the cracking features – open cracks and tension gaps – (Fig. 8a-c) and their gradual broadening over time confirm the contribution of slow mass-movement seaward. The location of the alluvial fans on the higher Dead Sea shore (Fig. 4c) appears to be significantly above the subsurface rock-salt layer, where this layer occurs. Thus, the movement of gravel deposits in the alluvial fans is less affected by subsurface dissolution.

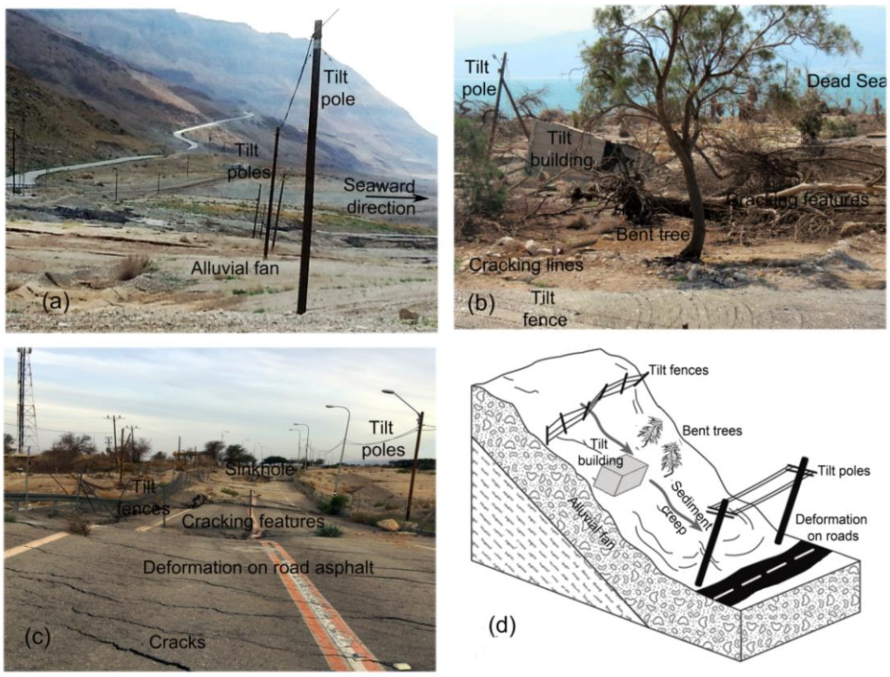

Figure 16. Indications of sediment-creep in the alluvial fans: (a) Tilt poles downslope in the alluvial fan (Shalem site). (b) Bent tree, tilt building, tilt pole and tilt fence along with cracking features (Ein Gedi site). (c) Tilt poles, tilt fences and deformation on road asphalt along with cracking features (Ein Gedi site). (d) An illustration of the indications of sediment-creep in the alluvial fans.

Processes affecting mudflat sediments on the coastal margin

Processes of coastal degradation alongside the coastline (Fig. 17a-c) and development of narrow coastal bays (Fig. 17d) affect the mudflat sediments on the coastal margin. The scarred slopes of the Dead Sea provide evidence of intensive subsea landsliding (Lensky *et al.*, 2014). The bathymetric morphology of the coastal margin (Fig. 13b) indicates subsea mass transport on the subsea slope (Lensky *et al.*, 2014). Mass transport deposits as seismites in the Dead Sea depocenter have been reported by Lu *et al*. (2017).

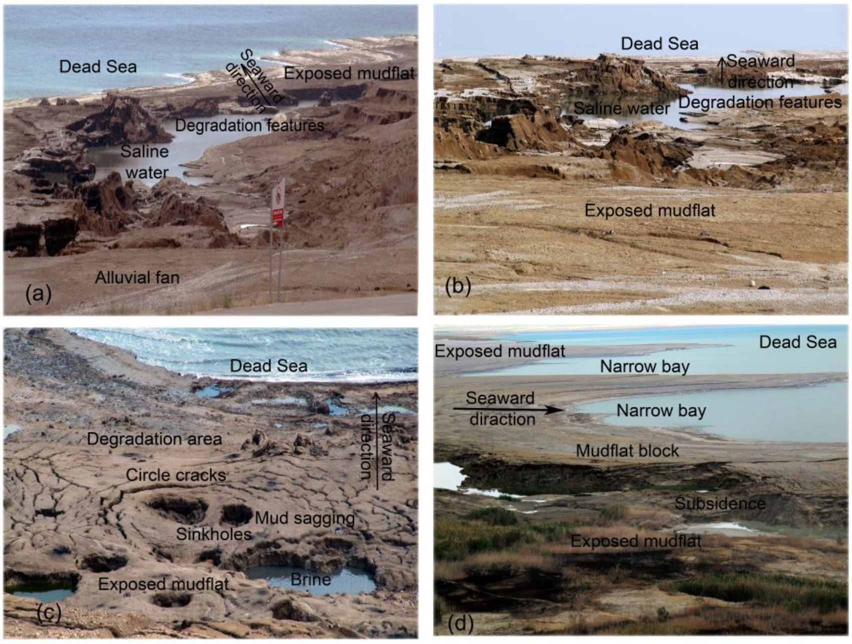

Figure 17. Processes affecting mudflat sediments on the coastal margin: (a-c) Coastal degradation with/without sinkholes alongside the coastline (Ein Gedi site). (d) Development of narrow coastal bays (Samar site).

The narrow coastal bays along the coastline (Fig. 17d) are considered to be scars resulting from slumping of littoral sediments on the subsea slope (Alsop & Weinberger, 2020). These bays are currently visible along the shoreline due to the receding at the western Dead Sea shore. The subsea mass transport on the shelf slope is well documented (Shepard & Dill, 1966; Masson *et al.*, 2006, 2010; Vanneste *et al.*, 2013).

Summary of indications for the contribution of slow mass-movement seaward

Fig. 18 summarizes indications of the contribution of slow mass-movement seaward to the coastal processes on the receding Dead Sea shore. The indications in the exposed mudflats are the roughly shoreline-parallel extension of the subsidence features – subsidence strips and clustered sinkholes – (Fig. 5) and their gradual broadening over time (Fig. 6). The indications in the alluvial fans include seaward sediment-creep (Fig. 16), roughly shoreline-parallel extension of cracking features – open cracks and tension gaps – (Fig. 8a-c) and their gradual broadening over time.

In exposed mudflats, indications of a contribution of slow mass-movement seaward (Fig. 18) may be supported by the occurrence of lateral spreading of clayey sediments in the narrow subsidence strips (Fig. 14) and by the seaward migration of newly-formed clustered sinkholes (Fig. 13a). The coastal degradation alongside the coastline (Fig. 17a-c) and development of narrow coastal bays (Fig. 17d) also involve movement of mudflat sediments towards the subsea slope. Subsea mass transport on the subsea slope is indicated by the bathymetric morphology of the coastal margin (Fig. 13b).

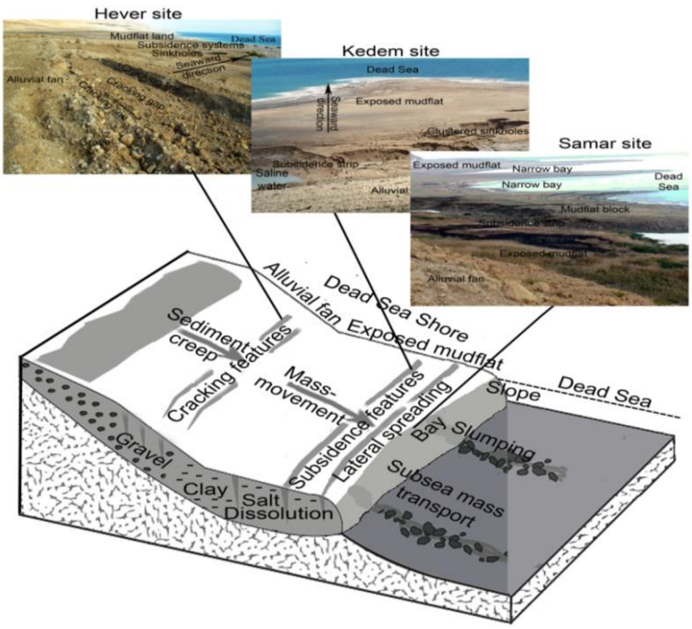

Figure 18. Summary of indications for the contribution of slow mass-movement seaward to the coastal processes on the receding Dead Sea shore. See text for discussion.

Conclusions

(1) The coastal processes on the receding Dead Sea shore and the subsidence features are part of the adjustment of the Dead Sea periphery to the lowering of the base-level. Coastal processes of movement and subsidence of clayey sediments effect the formation of subsidence features – subsidence strips and clustered sinkholes – in exposed mudflats.

(2) The subsidence of the clayey sediments in the development of the subsidence features in the exposed mudflats involves sediment collapse of dry mudflat sediments near the surface and mud sagging of wet mudflat sediments in the subsurface. The near-surface sediment collapse is favoured by their unconsolidated fine-particle texture composed of clay and carbonate minerals, and by the lack of significant cohesion. The subsurface mud sagging is promoted by the soaking with saline water and brine, and by the muddy and lubricant properties under wet conditions due to the abundance of swelling smectitic clay saturated with Na and Mg.

(3) Narrow subsidence strips with/without clustered sinkholes were developed by movement and subsidence in mudflat sediments via lateral spreading. The lateral spreading locally interrupts continuity of mudflat sediments, causes subsidence of the clayey sediments and formation of the narrow subsidence strips.

(4) Wide subsidence strips with clustered sinkholes were developed by increased subsidence in mudflat sediments due to progress of dissolution within a subsurface rock-salt unit. It seems that an earlier formation of narrow subsidence strips in exposed mudflats promotes the broadening into wide subsidence strips with clustered sinkholes as the former served as a preferential subsurface

pathway for groundwater that enhanced the dissolution and salt karstification within the subsurface rock-salt unit.

(5) Increased subsidence in the formation of the sinkholes in exposed mudflats due to the progress of the dissolution within the cavities in the subsurface rock-salt unit is caused progressive widening from funnel-shaped sinkholes, collapse-sinkholes, wide collapse-sinkholes to coalesce-sinkholes.

(6) A contribution of slow mass-movement seaward to the coastal processes on the receding Dead Sea shore is indicated. The indications in the exposed mudflats are the roughly shoreline-parallel extension of the subsidence features and their gradual broadening over time. The indications in the alluvial fans are the features of sediment-creep seaward, the roughly shoreline-parallel extension of cracking features and their gradual broadening over time.

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Data availability. The raw database is available from the contributing author. The data are mainly based on field-observations by the contributing author. All field photographs are of the author and were taken by the author himself in the field. Other Figures are based on Public Domains by NASA, public reports of the Geological Survey of Israel and official maps of the Geological Survey of Israel on the website: "Dead Sea sinkholes and subsidence monitoring".

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