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# Quaternary rise of the Sedom diapir, Dead Sea basin

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# ABSTRACT

Mount Sedom is the surface expression of a salt diapir that has emerged since the Pleistocene in the southwestern part of the Dead Sea basin. Milestones in the uplift history of the Sedom salt diapir since its inception were deduced from angular and erosional unconformities, thickness variations, caprock formation, chemistry and isotope composition of lacustrine aragonite, cave morphology, precise leveling, and satellite geodesy. Thickness variations of the overburden observed in transverse seismic lines suggest that significant growth of the Sedom diapir may have initiated only after this thickness exceeded ~2400 m in the Late Pliocene. The formation of the caprock signifies the arrival of the Sedom diapir from depth to the dissolution level between 300,000–100,000 yr B.P. During this period and later, angular and erosional unconformities in the upper part of the overburden near Mount Sedom are attributed to the piercing diapir. Rapid solution of rock salt from parts of Mount Sedom inundated by Lake Lisan after ca. 40,000 yr B.P. is inferred from Na/Ca ratios in aragonite and their relation to  $\delta^{13}$ C. On the mountain itself, the older parts (70,000–43,000 yr B.P.) of the lacustrine Lisan Formation are missing. The top of the preserved sediments is covered by alluvial sediments that must have been deposited when the elevation of Mount Sedom was not higher than 265 m below sea level (mbsl) at ca. 14,000 yr B.P. The present elevation of these sediments at 190 mbsl indicates an average uplift rate of ~5 mm/yr over the past 14,000 yr. Similar uplift rates of 6-9 mm/yr are inferred for

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the Holocene from displacement of the "salt mirror" and hanging passages of caves. The present uplift rate, calculated from precise leveling and interferometric synthetic aperture radar (InSAR), is similar to the average Holocene rate. Based on the gathered data, we reconstruct the topographic rise of Sedom diapir and its relation to lake level variations during the late Pleistocene and Holocene.

Keywords: salt diapirs, salt tectonics, InSAR, Dead Sea basin.

# **INTRODUCTION**

Mount Sedom is a north-south-trending ridge ~10 km long and 2 km wide, located in the southwestern part of the Dead Sea basin (Fig. 1). The mountain is the surface expression of a salt diapir that has emerged since the Pleistocene (Zak, 1967).

Of a series of salt bodies that exist in the Dead Sea rift (Fig. 1A), the Sedom diapir is the only one exposed. It has penetrated the overlying sediments, reaching an elevation of ~200 m below sea level (mbsl). Mount Sedom, which comprises the diapir and a veneer of Late Quaternary sediments (including an up to 40-m-thick caprock), reaches an elevation of 160 mbsl, rising ~90 m and 250 m above the Ami'az Plain and the Dead Sea, respectively (Figs. 1B and 2A).

In previous studies, the discussion of the emergence and topographic rise of Mount Sedom was mainly limited to its later phase (Picard, 1950; Vroman, 1951; Zak, 1967; Gerson, 1972; Zak and Freund, 1980; Frumkin, 1992, 1994, 1996a, 1996b; Weinberger et al., 1997; Marco et al., 2002; Pe'eri et al., 2004). This phase occurred after the final fall in the level of Lake Lisan (Bartov et al., 2002, 2003; Bookman et al., this volume), following the deposition of the youngest beds of the Lisan Formation, dated ca. 14,000 yr B.P. (Kaufman, 1971; Druckman et al., 1987; Haase-Schramm et al., 2004). In recent years, new information has been gathered concerning the Dead Sea tectonic framework, the history of its Quaternary lakes and fluvio-lacustrine sediments, and the recent rate of uplift of the Sedom diapir. Hence, we assemble here the published and unpublished information and present a more complete history of the rise of the Sedom diapir since its inception.

# **GEOLOGIC SETTING**

#### **The Tectonic Framework**

The Dead Sea basin is a continental depression located within the rift valley that accompanies the Dead Sea fault, also termed the Dead Sea transform. It is widely agreed that the basin is a rhomb-shaped pull-apart graben that was formed due to left-lateral displacement along the segmented Dead Sea fault (Quennell, 1958; Freund et al., 1970; Garfunkel, 1981; ten Brink and Ben-Avraham, 1989; Garfunkel and Ben-Avraham, 1996; Garfunkel, 1997; Ben-Avraham, 1997). The basin is bounded on the east and west by a series of step faults. The total throw of pre-basin rocks in its center is estimated from gravity and seismic data to be in the range of 8.5–10 km (Zak, 1967; ten Brink et al., 1993; Ben-Avraham, 1997; Al-Zoubi and ten Brink, 2001).

#### **Evaporites in the Dead Sea Rift**

Neogene massive evaporite beds and several types of evaporite bodies have been found in the Dead Sea rift, between Lake Kinneret and the Dead Sea (Fig. 1). In the north, evaporites are exposed in the Gesher gypsum quarries (Schulman, 1962; Segev and Wachs, 1978) and were penetrated in the Zemah drillhole south of Lake Kinneret (Marcus and Slager, 1985). In the Bet She'an valley, they are known from drillholes (Shaliv, 1991) and were surmised from geophysical data (Braun and Flexer, 1991; Gardosh and Bruner, 1998; Flexer et al., 2000). At Zahrat El-Qurein in the Jordan Valley (Fig. 1), rock salt was interpreted as a diapir based on geomorphological evidence (Zak and Bentor, 1972; Belitzki and Mimran, 1996). At Jericho basin, several diapiric salt bodies and salt-related structures were interpreted based on newly acquired high-resolution reflection data (Shamir et al., 2005). In the Dead Sea basin, several surface and subsurface evaporites are found. The Lisan Peninsula (El-Lisan, Fig. 1) is underlain by a massive diapir penetrated by wells (Picard, 1950; Bentor and Vroman, 1960; Bender, 1974; Hassouneh, 1997; Bartov, 1999; Bartov et al., this volume). Seismic profiles show diapirs that rose to shallow depths near the bottom of the Dead Sea, as well as other, deeply buried evaporitic bodies (Neev and Hall, 1979; Gardosh et al., 1997; Al-Zoubi and ten Brink, 2001). Finally, evaporite sequences have also been penetrated by several drillholes near the Sedom diapir, in the southern Dead Sea (e.g., Sedom Deep-1, Amiaz-1; Kashai and Croker, 1987; Gardosh et al., 1997). The geographic extent of all these evaporite bodies delineates a narrow, elongated gulf within the tectonically subsiding Dead Sea rift, into which sea water penetrated through the Yizre'el and Bet She'an valleys during the late Miocene to Pliocene (Avnimelech, 1937; Zak, 1967; Zak and Bentor, 1972; Shaliv, 1991). Hence, this segment of the Dead Sea fault, between Bet She'an and Sedom, may be paved at depth by more evaporites, overlain by a thick overburden comprising mainly sedimentary fill of fluvio-lacustrine origin.

The evaporites in the subsurface of the Dead Sea basin are of three types: layered salt, salt swells, and large piercing diapirs. Layered salt is conformable to the bedding of the overburden, whereas salt swells and diapirs generally represent different stages of salt flow (Jackson and Talbot, 1986). Subhorizontal salt layers were penetrated by several drillholes in the southern Dead Sea basin (e.g., Amiaz-1; Amiaz East-1, and Sedom Deep-1; Fig. 3). These layers typically contain thick shale units that are also observed in the exposed evaporitic sequence at Mount Sedom. In seismic profiles, the layered salt and shale often appear as a series of highand low-amplitude reflections that are not readily differentiated from the fluvio-lacustrine deposits of the basin fill (Fig. 4). In these profiles, the salt swells and diapirs are easily recognized by the tilted and raised beds of the overburden surrounding them and are often characterized by a disordered or reflection-free appearance associated with internal deformation (Fig. 4).

Seismic data further indicates that many, if not all, salt bodies in the Dead Sea basin are located above or near deep-seated faults (Neev and Hall, 1979; ten Brink and Ben-Avraham, 1989, Gardosh et al., 1997). The piercing Sedom diapir is found above the north-south–striking Sedom fault, a major tectonic line that was penetrated by the Sedom Deep-1 well, ~1 km south of the diapir (Figs. 3 and 4, western flank). The north-south elongated shape of the Sedom diapir suggests that salt migration and piercing took place along the trace of the Sedom fault. The relationship of the Lisan diapir to deep-seated faults is less clear. Seismic data indicates that the Lisan diapir may be rising along a transverse fault that extends from the Sedom fault to the northeast (Figs. 2 and 3).

Listric growth faults are identified in seismic data near salt swells and diapirs throughout the Dead Sea basin (see Figures 5.4-5.8 in Gardosh et al., 1997). Such growth faults were formed on top of or near salt swells due to flow of the underlying salt layers. Contemporaneous salt migration and sediment deposition resulted in increased thickness of the overburden on the hanging wall of the faults. The Amazyahu fault is a prominent listric fault, exposed south of the Sedom Diapir (Fig. 3); ten Brink and Ben-Avraham (1989) suggested that it was initiated as a slide over the salt layers during the early to middle Pleistocene. The activity on the fault continued throughout the Pleistocene and is contemporaneous with the flow of salt into several swells. Seismic data indicate that in the subsurface, the Amazyahu fault curves northward toward the southern edge of Mount Sedom and the salt layer beneath the fault connects to the salt body of the diapir. Hence, the activity on the Amazyahu fault is the result of salt withdrawal into the rising Sedom diapir (Gardosh et al., 1997).

# Stratigraphy

#### **Sedom Formation**

A series of 1500–2000-m-thick evaporites, known as the Sedom Formation (Zak, 1967), builds most of Mount Sedom. West of Mount Sedom, the Ami'az-1 drillhole penetrated 1300 m of evaporites, and the Sedom Deep-1 drillhole penetrated 900 m of evaporites southeast of Mount Sedom (Kashai and Croker, 1987; Gardosh et al., 1997). The Sedom Formation is usually considered to be of Pliocene age based on stratigraphic (Zak, 1967) and palynological (Horowitz, 1987) evidence. The formation, consisting of sequences of evaporite units alternating with thinner clastic units, is divided into five members (Zak, 1967). The evaporite units are composed of well-bedded rock salt



Figure 1 (on this and following page).



Figure 1. (A) Location map showing the salt bodies (small solid circles) along the Dead Sea rift, based on data from Zak (1967), Marcus and Slager (1985), and Belitzki and Mimran (1996). Arrows indicate the ingression path of the Mediterranean Sea during the Neogene. Solid rectangles mark the location of chemically studied Lisan sections. (B) Shaded relief image of Mount Sedom and its vicinity. The western border fault (partly dotted) forms an escarpment and separates outcrops of Cretaceous rocks to the west of Ami'az Plain from the Quaternary fill of the Dead Sea basin. Solid square marks the location of wellexposed unconformities in the Hamarmar and Lisan formations. The location of geologic cross section A-A' (Fig. 5) is marked by a solid line. Dashed lines represent radial clastic dikes.

layers, some anhydrite and dolomite, as well as thin siltstone layers dispersed within the sequence. The other units are composed of well-bedded dolomite, mudstone, and clay with layers of sandstone, gypsum, and anhydrite.

# Amora, Hamarmar, and Lisan Formations

Based on seismic data (Fig. 3; Al-Zoubi and ten Brink, 2001), the maximum thickness of sediments that overly the Sedom

Formation in the southern part of the Dead Sea basin is ~5500 m. This overburden is ~1700 m thick west of Mount Sedom (e.g., Ami'az-1; Kashai and Croker, 1987) and 3700 m thick southeast of Mount Sedom (e.g., Sedom Deep-1; Gardosh et al., 1997).

The Amora Formation, a 400-m-thick sequence of marl, chalk (authigenic aragonite), rock salt, sandstone, and conglomerate that overlies the Sedom Formation, is exposed on the eastern flank of Mount Sedom (Zak, 1967). The uppermost Amora

#### Quaternary rise of the Sedom diapir



Figure 2. (A) View from the northwest showing Mount Sedom rising ~250 m above the Dead Sea. (B) View from the southeast of a salt quarry area. A "salt mirror" separates vertical beds of rock salt from the overlying residual caprock. The salt mirror and the overlying caprock are displaced along bedding planes. Person at the bottom of the photo for scale.



Formation may be correlative to the Hamarmar (Langozky, 1961) and is overlain by the Lisan Formation.

The Hamarmar Formation, also referred to as the Samra Formation (Waldmann, 2002), is more than 60 m thick and comprises several sequences, each consisting of conglomerate and sandstone at the base and laminated sediments of aragonite, clay, siltstone, and marl in the middle and top. The base of the exposed section of the Hamarmar Formation near Mount Sedom is older than 350,000 yr, and the age of its top is ca. 100,000 yr B.P. (Kaufman, 1971; Kaufman et al., 1992; Waldmann, 2002).

The Lisan Formation consists of authigenic aragonite and gypsum layers alternating with silty and sandy layers, with a typical thickness of ~40 m (Begin et al., 1974). The Sedom area is within the "aragonite facies" of the Lisan Formation (Begin et al., 1980; Machlus et al., 2000). The age of the Lisan Formation, as established through U-Th series, is ca. 70,000–14,000 yr B.P. (Kaufman, 1971, Schramm et al., 2000; Haase-Schramm et al., 2004).

The Amora, Hamarmar, and Lisan formations are not well defined in the subsurface. Based on gamma ray log characteristics and lithology of the overburden in the Ami'az East-1 and Sedom Deep-1 drillholes, Gardosh et al. (1997) proposed a somewhat different, threefold stratigraphic subdivision. The lower part of the overburden is dominated by massive beds of quartzose sand, known as the ~1000-m-thick Melekh Sedom Sands (Horowitz, 1987; Weinberger, 1993). The middle part is composed of quartzose sand, marls, shales, and some conglomerates. The upper part is dominated by gray marl and contains a minor amount of anhydrite, halite, sand, and conglomerate. The three units display an overall upward-fining trend, reflect-

ing a gradual change from fluvio-lacustrine and possibly eolian depositional environments to lacustrine, occasionally brackish to hypersaline environments.

# Caprock and "Salt Mirror"

Parts of the rock salt of the Sedom diapir were dissolved by meteoric groundwater as well as by the lake water to which it was exposed during the late Pleistocene (Vroman, 1951; Zak, 1967). Less soluble components of the Sedom Formation, such as anhydrite and gypsum, as well as marl, dolomite, and clastic material formed a caprock, ~40 m thick, over the entire Sedom diapir (Fig. 2B). The caprock is assumed to represent the insoluble residue (~5% by weight) of a vertical diapiric rock salt column ~600-800 m tall (Zak and Freund, 1980). A flat dissolution surface termed a "salt mirror" (salt table) separates the rock salt beneath from the overlying caprock (Fig. 2B). The salt mirror is thought to have "fossilized" when a new dissolution base developed at a lower level, when that the Dead Sea southern basin desiccated (Zak, 1967). This event occurred between 14,000 and 11,000 yr B.P., when the lake level dropped sharply below 400 mbsl (Neev and Emery, 1967; Yechieli et al., 1993; Frumkin, 1996b). There is no positive evidence for the formation of a new dissolution surface associated with the present lake level.

# Structure of Mount Sedom

Zak (1967) and Zak et al. (1968) suggested that the Sedom diapir structure has the shape of a salt wall rising from a deep

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Figure 3. Map of top of the Sedom salt at the southern Dead Sea basin (after Al-Zoubi and ten Brink, 2001). Contour interval 250 m. The top of the Lisan diapir is covered by 125 m or more of late Pleistocene and Holocene sediments; and top of Sedom diapir is exposed. See Bartov et al. (this volume) for a detailed geologic map of the Lisan Peninsula. Location of the seismic line RV7003 (Fig. 4) and drillholes are shown.

source layer in the east. They assumed that this wall represents the flank of a pseudo-anticlinal structure, the western limb of which remained buried below the Ami'az Plain. A paleomagnetic and structural reconstruction of the Sedom diapir reveals that the evaporite sequence exposed in the southern mountain is composed of two limbs that show an opposite sense of tilting (Weinberger, 1992; Weinberger et al., 1997) (Fig. 5). The western flank of this diapiric antiform is relatively thin (~500 m), and its top faces westward, whereas the eastern limb is thicker (~1500 m), and its top faces eastward. No stratigraphic correlation has been identified between the western and the eastern evaporite sections. A study of the karstic caves in the northern diapir and surface lineaments on top of the caprock showed that the northern part of the mountain also consists of two limbs that dip to different directions, and the contact zone between them is highly deformed (see Frumkin, 1996c, their Fig. 3). These observations led Weinberger (1992), Weinberger et al. (1997), and Frumkin (1996c) to suggest that the deposition and emergence of the evaporitic sequence were from two adjoining but different basins, the deep block and the intermediate Amia'z block, both taking advantage of the existing Sedom fault. Along the eastern flank of Mount Sedom, the piercing salt diapir tilted the Amora Formation ~70° eastward, whereas at the western flank it tilted the adjacent Amora (?) and Lisan formations 25-40° westward.

# MILESTONES IN THE RISE OF THE SEDOM DIAPIR

Milestones in the rise of the Sedom diapir are deduced from various types of evidence. These include angular and erosional unconformities, thickness variations, chemistry and isotope variations of aragonite laminae in the Lisan Formation, clastic dikes, and cave deposits. The current rise of the diapir is determined by precise leveling and by satellite geodesy.

# I: Before 300,000 yr B.P.

At the end of salt deposition, the top of the salt layer constituted a more or less horizontal surface extending throughout the southern Dead Sea basin. Later salt flow resulted from tilting of this surface as well as variations of the thickness of the overlaying basin-fill sediments. The thickness of this overburden at the initial stage of the salt flow is estimated from thickness variations in traverse seismic reflection profiles across the flanks of Mount Sedom. Line RV-7003 (Fig. 4) shows tilting of the sedimentary fill near the eastern flank of the Sedom diapir (see also Kashai and Croker, 1987; Weinberger, 1992; Gardosh et al., 1997; Larsen et al., 2002). It is likely that this tilting is the result of salt migration into the rising diapir and deposition of the overburden within the peripheral rim syncline. The time-thickness ratio of the lower part of the tilted sedimentary fill, between the top of the rock salt and seismic marker M1 (1.8 s two-way traveltime in Fig.4; B6 marker of Larsen et al., 2002), is more or less constant. However, considerable thinning of the section above the M1 marker is observed near the eastern flank of the diaper. In

# Line RV-7003



Figure 4. Time-migrated seismic profile RV7003 showing the western border fault of the rift valley and two structural steps, the intermediate and deep blocks, separated by the Sedom fault. The Sedom salt layer extends east of the western border fault, throughout the intermediate and deep blocks. The Sedom diapir, at the center of the profile, is a large piercing salt body that rose to the surface at the western edge of the deep block, along the north-south–oriented Sedom fault. The high-amplitude reflections within the layered salt, east and west of the diapir, are associated with clastic intercalations. The disordered seismic character of the diapir reflects internal deformation. The time of salt migration is indicated by seismic marker M1: The overburden above the marker thins toward the eastern flank of the Sedom diapir as a result of salt migration. For line location see Figure 1B. Alternatively (Martin Jackson, personal communication, 2006), the entire pre-M1 reflector cutoffs abut or onlap against the Sedom-diapir flank with no evidence for faults. This indicates that Sedom diapir was growing passively as an emergent diapir from the start of overburden accumulation. M1 marks when aggradation began to overtake diapiric rise because of salt depletion in its source layer. The prominent onlap surface in the east just above 1 s marks the time when Sedom diapir suddenly renewed its rise after increasing burial since M1. This sudden rejuvenation folded back the flap on its crest (active-style diapirism). This tilted flap was onlapped and buried, either because Sedom-diapir's rise declined, or because aggradation accelerated.



Figure 5. Geologic cross section through southern Mount Sedom. Based on paleomagnetic and structural analyses, the directions of salt migration during the emergence of the Sedom diapir are inferred and marked by thick solid arrows (after Weinberger et al., 1997). No vertical exaggeration. L-Lisan Formation; H-Hamarmar Formation; A-Amora Formation; S-Sedom Formation and its members: Sk-Karbolt Salt Member; Sl-Lot Salt Member; Sb-Benot Lot Shale Member; Sm-Me'arat Sedom Salt Member; Sh-Hof Shale and Salt Member. The suffix "c" in Smc, Slc, and Skc denotes caprock covering the different members.

particular, thickness variations and onlapping reflections are well observed above 1.4 s two-way traveltime (TWTT). They are less evident in the somewhat chaotic interval near the edge of the line, between 1.4 s TWTT and the M1 marker. Time-thickness variations above 1.9 and below 1.4 s TWTT are more clearly observed in a nearby parallel line (not shown here), thus supporting our interpretation of line RV-7003.

The parallel reflection series below the M1 marker represents deposition under stable conditions before the initiation of salt flow. The thickness of the undisturbed lower part of the overburden can be used to estimate the conditions and timing during the initial salt flow. Assuming a seismic velocity of 3150 m/s (ten Brink and Ben-Avraham, 1989) or 3200 m/s (Frieslander, 1993), the corresponding thickness between the top of the rock salt and the M1 marker in RV-7003 is 2400 m (1.5 s TWTT). Thus, the vertical growth of the Sedom diapir began when the sedimentary-fill at the center of the deep block exceeded ~2400 m (Fig. 4). At the western flank of the Sedom diapir, the sedimentary fill is tilted to the west and thickness variations are discerned only near its upper part.

The age of the M1 marker, which is related to the beginning of salt flow, is estimated from palynological data in the Melekh Sedom-1 drillhole (Horowitz, 1989; Levin, 1986), located southeast of the diapir (Fig. 3). Assuming a depth of 2800 m for the M1 marker in this drillhole, it may be correlated to palynozone QIc, the age of which was estimated by Horowitz (1989) to be 2.2 Ma.

By applying similar considerations, Al-Zoubi and ten Brink (2001) calculated that the salt migration beneath the Amatzyahu fault initiated when the overburden reached a thickness of  $\sim$ 1300 m (by using 0.8 s TWTT thickness and a seismic velocity of 3200 m/s).

Seismic and well data indicate that the thickness of the overburden is >1000 m throughout most of the southern Dead Sea area, from the Lisan Peninsula in the north to 40 km south of the Sedom diapir (Fig. 6) (Kashai and Croker, 1987; Al-Zoubi and ten Brink, 2001; Al-Zoubi et al., 2002). The situation is different, however, north of the Lisan Peninsula. A single-channel sparker seismic survey (Neev and Hall, 1979) shows the top of the salt (their "brown horizon") buried to depth of <800 m below the Dead Sea level of 400 mbsl. The same seismic survey revealed various salt swells and small salt diapirs at shallow depths. It is therefore estimated that salt migration initiated in the northern basin at a shallower depth of burial than in the southern basin.

Paleomagnetic data of the Sedom diapir indicates that the first emplacement phase of the salt diapir was associated with tilting of beds from a horizontal to vertical position about a horizontal axis (Weinberger et al., 1997). This phase took place sometime after the accumulation of ~2400 m of overburden at ca. 2.2 Ma, but before the Brunhes Normal chron of ca. 780,000 yr B.P. (Weinberger et al., 1997; see below).

#### II: Between 300,000 and 150,000 yr B.P.

The formation of caprock signifies the emergence of the Sedom diapir from great depth to the dissolution level near the surface. Zak and Freund (1980) attributed the formation of the caprock to the past 300,000–100,000 yr B.P. This suggestion is based on the observation that the fine laminae composing most of the Amora Formation are concordant throughout most of the sequence, while unconformities appear only in its upper part, where insoluble residue derived from the Sedom shales was redeposited (Zak, 1967; Zak and Bentor, 1972, p. 144).

At about this time, the Sedom Formation acquired secondary components of magnetization, mainly as chemical remanent magnetization (CRM). These components are carried by authigenic magnetite that might have formed during the migration of the Sedom diapir through the water table (Weinberger et al., 1997). All the secondary components have normal polarity and were acquired after the steep tilting of the beds. Hence, Weinberger et al. (1997) suggested that these components were acquired during the formation of the caprock during the Brunhes Normal chron, sometime after ca. 780,000 yr B.P. These secondary components show a ~30° counterclockwise rotation around a vertical axis of the eastern flank of Mount Sedom during this period.

At Nahal (Wadi) Perazim (Fig. 1B), the sediments of the Hamarmar Formation are divided into two members. The lower member is tilted  $15^{\circ}-17^{\circ}$  westward, and the upper member is tilted  $10^{\circ}-12^{\circ}$  westward. The age of this angular unconformity is  $150,000 \pm 20,000$  yr B.P. (Waldmann, 2002). This unconformity within the Hamarmar Formation is observed only in the vicinity of Mount Sedom at Nahal Perazim, Nahal Sedom, and 'En Hamarmar (Langozky, 1961, 1963; Waldmann, 2002) and is attributed to tilting of the beds by the piercing diapir.

# III: Between 150,000 and 70,000 yr B.P.

The unconformity separating the Hamarmar Formation from the Lisan Formation indicates another phase in diapiric rise. The age of this unconformity is ca. 70,000 yr B.P. at Nahal Perazim, based on the age of aragonite laminae 1 m above it (67,200 ± 1300 yr B.P.; Haase-Schramm et al., 2004). The angular relationships between the Hamarmar and Lisan formations decrease with increasing distance from Mount Sedom. At Nahal Perazim, the Hamarmar Formation is tilted westward 10°–17°, while the overlying Lisan Formation is horizontal (Weinberger et al., 2000). Adjacent to Mount Sedom at the Black Hill (Fig. 1B), the pre-Lisan sediments are tilted ~25°, while the overlying Lisan Formation dips gently (<5°) westward. A similar angular unconformity is seen along the southwestern rim of Mount Sedom (mapped there as the Amora Formation; Zak, 1967), as well as at the 'En Hamarmar area (Fig. 1B; Langozky, 1961, 1963).

#### IV: Between 70,000 and ca. 40,000 yr B.P.

Emergence and exposure of the Sedom diapir to subaerial conditions are recognized by an erosional unconformity between the Sedom diapir and the upper Lisan Formation (Zak, 1967), and the chemical and isotopic composition of aragonite laminae in the Lisan Formation in the vicinity of Mount Sedom.

# 1. Erosional Unconformity

On Mount Sedom, at White Hill (Fig. 1B), the upper member of the Amora Formation and the lower beds of the Lisan Formation are absent (Zak, 1967). The age of an aragonite bed in the lowermost Lisan sediments was determined to be 34,000 ± 4,000 yr B.P. (U-Th; Kaufman, 1971). This reported age has a large uncertainty estimate due to the analytical methods (alpha spectroscopy) available at that time. Weinberger and Bar-Matthews (2004) reevaluated the age of the Lisan sediments covering the White Hill through U-Th series using by multi-collector inductively coupled plasma-mass spectrometry. They found that the corrected age of an aragonite bed in the lowermost Lisan sediments, calculated using a 232Th/238U molar ratio of 0.85 (Haase-Schramm et al., 2004), is ca. 43,000 ± 370 yr B.P. (for uncorrected ages, see Weinberger and Bar-Matthews, 2004). A calibrated <sup>14</sup>C age of wood, found 10 m above the base of the section (correlative to 16 m above the base of a nearby section measured by Zak, 1967, p.86), was recently determined as ca. 30,000 yr B.P. (sample number GL-9; 14C date before calibration is  $27,550 \pm 280$  yr; M. Stein, 2004, personal commun.). In Nahal Perazim, only 1 km west of Mount Sedom, a complete section of the Lisan Formation underlain by the Hamarmar Formation was documented (Machlus et al., 2000). Based on comparison between these sections, we estimate that the lowermost ~20 m of the Lisan Formation is missing on the White Hill. This hiatus attests to a period of exposure of the Sedom diapir, and sediments were either not deposited or were deposited and then eroded. During the period between ca. 70,000 and 28,000 yr B.P, the Lake Lisan levels were between 350 and 280 mbsl (Bartov et al., 2002). Hence, before ca. 43,000 yr B.P., the top of Sedom diapir was higher than 350 mbsl and may have been even higher than 280 mbsl. Later, sometime during ca. 43,000–30,000 yr B.P, the deposition of lacustrine aragonite laminae at the White Hill indicates that the Sedom diapir was submerged below 280 mbsl.

# 2. Chemical and Isotopic Composition of Aragonite in the Lisan Formation

The Na/Ca ratio was determined for aragonite laminae in three sections of the Lisan Formation: at Deir Shaman, Massada, and Nahal Perazim (Fig. 1A and 1B; Katz et al., 1977; Machlus, 1996). This ratio reflects the sodium content of the upper water layer of Lake Lisan. The distribution coefficient of sodium between aragonite and the solution from which it precipitates depends on the salinity of the solution (Katz et al., 1977). Biological as well as Sr/Ca data show that the area of maximum salinity in Lake Lisan was near Massada (Begin et al., 2004). However, the variations of Na/Ca over time show the highest values at Nahal Perazim, near Mount Sedom (Fig. 7). While at Deir Shaman, 80 km north of Mount Sedom, Na/Ca values decrease after ca. 28,000 yr B.P., at the Massada and Nahal Perazim sections the Na/Ca values increase between ca. 40,000 and 20,000 yr B.P. Despite the large variability in the data, a Mann-Whitney test shows that Na/Ca values in Nahal Perazim, for samples younger than 34,000 yr B.P., are significantly higher than those older than that (the probability of random occurrence of such difference is 0.008).

Another indication for the increase of sodium near Mount Sedom comes from the regression of Na/Ca on  $\delta^{13}$ C in the aragonite laminae of the Lisan Formation. A positive correlation between these variables is expected because  $\delta^{13}$ C reflects the degree of evaporation of Lake Lisan surface water while the Na/ Ca ratio in the aragonite increases with the salinity of the lake water (Katz et al., 1977). For data points representing beds of the Lisan Formation that are younger than 30,000 yr B.P., the aragonite laminae of the Nahal Perazim section near Mount Sedom show a significant increase of sodium relative to the mean value, as represented by the regression line (Fig. 8).

Both the Na/Ca time series and the relationship between Na/Ca and  $\delta^{13}$ C indicate rapid input of large quantities of sodium into Lake Lisan from a source near Nahal Perazim, probably by dissolution of halite from Mount Sedom. The feasibility of this pro-



Figure 6. Measured densities in Sedom-Deep 1 well (Fig. 3) and an average of the densities with depth (yellow line) (after Rybakov et al., 1995). Compaction curves of clay (red line) and sandstone (purple line) are shown. A compaction curve of mixed clay and sandstone (blue line) fits well the measured densities down to a depth of ~3700 m. At this depth, the density drops markedly, indicating the top of the rock salt.



Figure 7. Na/Ca time series in the Lisan Formation at Nahal Perazim (circles), 2 km from Mount Sedom; at Massada (triangles), 20 km from Mount Sedom; and at Deir Shaman (squares), 80 km from Mount Sedom. Note the increase in Na/Ca at the Perazim and Massada sections after ca. 40,000 yr B.P. (after Begin et al., 2004). Lake Lisan level (bottom) is after Bartov et al. (2003). Lines show fit for sixth degree polynomials.

cess is based on the high rate of solution of rock salt, 0.2 gr/s/m<sup>2</sup> at NaCl concentration in water of 300 gr/L (Alkattan et al., 1997). If we assume that rock salt was exposed in 20% of the area of Mount Sedom (3 km<sup>2</sup>), the resulting annual input of sodium from Mount Sedom would have been  $6.10^6$  tons. Assuming further that the thickness of the upper water layer of the lake was 40 m and that the relevant lake area is 1500 km<sup>2</sup> south of Deir Shaman, where no effect of increased sodium content is seen, the resulting assumed volume of the upper water layer is thus 6.10<sup>10</sup> m<sup>3</sup>. These values of sodium content and water volume are translated to an annual increase in concentration of 0.1 gr/L. This concentration should be compared with the assumed original sodium concentration of 20 gr/L, half of the current concentration of the Dead Sea. Thus, the 20% increase in Na/Ca values at Nahal Perazim and Massada (Fig. 7) may have been brought about by dissolution of salt within a few decades.

#### V. Between ca. 40,000 and 14,000 yr B.P.

Additional rise of the Sedom diapir is recognized by an angular (10°) unconformity 12 m above the base of the Lisan Formation section at White Hill (i.e., 18 m above the base in the nearby section of Zak, 1967). The age of aragonite laminae just above the angular unconformity was determined by the U-Th method to be 27,000  $\pm$  4,000 yr B.P. (Kaufman, 1971). The recently determined ca. 30,000 yr B.P. calibrated <sup>14</sup>C age for a bed lying 2 m below it (see above) constrains the age of the unconformity to younger than ca. 30,000 yr B.P. Zak (1988) attributed the angular unconformity within the Lisan Formation to faster uplift of the western flank of the Sedom diapir during deposition. Because the angular



Figure 8.  $\delta^{13}$ C versus Na/Ca for three sections in the Lisan Formation. A difference is seen between the three sections as to their Na/Ca values for data points younger than 30,000 yr B.P. (solid symbols) relative to the regression lines. At Deir Shaman (Fig. 1A), they are evenly partitioned below and above it; at Massada (Fig. 1A), 12 out of 18 are above the regression line; and at Nahal Perazim (Fig. 1B), the closest to Mount Sedom, all 10 of them are above the line. P—probability of a random occurrence of the clustering of data points younger than 30,000 yr B.P. around the regression lines. By definition, the probability for a single point to be above or below a regression line is 50%.

unconformity is accompanied by gravel derived from the Cretaceous bedrock exposed at the Dead Sea rift escarpment and from the Sedom Formation, this unconformity might attest to a period of topographic rise of the Sedom diapir above Ami'az Plain. Because at 28,000 yr B.P. Lake Lisan rose abruptly by ~100 m (Bartov et al., 2002, 2003), it seems that the unconformity and probably the topographic rise of the mountain occurred slightly earlier than that time, when the lake level was lower than 280 mbsl.

# VI. After 14,000 yr B.P

The rise of the Sedom diapir since the latest Pleistocene is recognized by five different types of evidence: (1) tilt of the youngest part of the Lisan Formation, (2) alluvial sediment on top of the Lisan Formation, (3) clastic dikes at the Ami'az Plain, (4) age of Mount Sedom caves, and (5) interferometric synthetic aperture radar (InSAR) and precise leveling. We discuss the first four types of evidence in the following subsections and the fifth in the next section.

#### 1. Tilt of the Youngest Part of the Lisan Formation

On top of Mount Sedom and on Black Hill, the Lisan Formation is tilted by ~5° northeastward (Zak, 1967) and ~5° westward, respectively. The tilting of the Lisan Formation on top of Mount Sedom resulted most likely from the rise of the diapir. The age of the youngest Lisan beds on Mount Sedom was determined to be 13,000  $\pm$  4,000 yr B.P. (Kaufman, 1971). Weinberger and Bar-Matthews (2004) reevaluated the age of Lisan beds 0.5 m below a gypsum layer that marks the top of the Lisan Formation at White Hill. They found that the corrected age of these layers is 15,500  $\pm$ 180 yr B.P. Hence, this phase of the diapiric rise is younger than 14,000 yr B.P., which is the estimated age of the top section of the Lisan Formation.

# 2. Alluvial Sediment on Top of the Lisan Formation

On top of Mount Sedom (e.g., at White Hill, 194 mbsl.), the Lisan Formation is covered by unconsolidated alluvial sediment, including rounded cobbles. They were deposited during the recession of Lake Lisan (Frumkin 1996b) and are therefore younger than the youngest beds of the Lisan Formation. The cobble lithologies indicate that they were derived from Cretaceous outcrops exposed in the western escarpment of the Dead Sea basin drained by the Nahal Hemar and Nahal Lot (Fig. 1B). The present topography would preclude such deposition on top of Mount Sedom, which is ~70 m higher than the Ami'az Plain (265 mbsl) that separates Mount Sedom from the Cretaceous outcrops. Hence, this alluvial sediment must have been deposited soon after 14,000 yr B.P. when the elevation of Mount Sedom was no higher than 265 mbsl. The alluvial sediment therefore implies a rise of at least 70 m since 14,000 yr B.P.

# 3. Clastic Dikes near Black Hill

Numerous opening-mode fissures filled with sediments (clastic dikes) cross the Ami'az Plain, forming a semi-radial and tangential network of fractures in the Lisan Formation (Zak, 1967; Marco and Agnon, 1996). The radial fractures converge at Black Hill (Fig. 1B), leading Marco et al. (2002) to suggest that the directions of the clastic dikes are dictated by stresses exerted by local doming at the Black Hill area. They hypothesized that this doming is due to the rise of an underlying salt diapir, which is perhaps a westward lobe of the Sedom diapir at depth. Because some of the clastic dikes crosscut the entire Lisan Formation and the beds of the Lisan Formation at the top of Black Hill are gently tilted, at least part of this postulated rise postdates the recession of Lake Lisan at ca. 14,000 yr B.P.

# 4. Age of Mount Sedom Caves

Due to the high solution rate of rock salt, caves develop in rock salt soon after its exposure to rainfall. Therefore, dating of the initiation of caves in Mount Sedom allows a reliable estimate of the timing of its most recent emergence above the Dead Sea base level. The caves were dated by wood debris found in alluvial sediment at different levels within the caves (Frumkin et al., 1991; Frumkin, 1996a). The ages show a systematic decrease from top to bottom of single cave systems, attesting to the timing of cave cutting. The oldest age of ca. 8000 cal. years B.P. was found in alluvial sediment close to the ceiling of a cave, indicating that the rock salt into which this cave is cut was exposed to meteoric water ca. 8000 cal. yr B.P. (Table 1 in Frumkin et al., 1991; Frumkin, 1996a). Before exposure of the rock salt to dissolving meteoric water, the Lisan Formation and its underlying caprock (combined maximum thickness of ~70 m) emerged first (Frumkin, 1996b). Assuming that the initial topographic rise of the entire sequence occurred later than 14,000 yr B.P., it took <6000 yr for the ~70m-thick veneer to be entrenched and the rock salt beneath to be exposed. The oldest cave (older than 8000 cal. yr B.P.) is found in the southern part of Mount Sedom, whereas the northern part of Mount Sedom was first exposed 3000 yr later (Frumkin, 1996b). This lag is in accord with the observation that there are fewer caves in the northern part of Mount Sedom. Following the initial topographic rise of Mount Sedom, a differential exposure was discerned: The base of the eastern flank of Mount Sedom rock salt was exposed at 6800 cal. yr B.P. in the south and at 3400 cal. yr B.P. in the north (Table 1 in Frumkin et al., 1991). Only later was rock salt exposed along the base of the western flank (Frumkin, 1996b).

#### UPLIFT RATES OF THE SEDOM DIAPIR

#### 1. Overall Average Rate

This is the crudest estimate due to the uncertainty concerning the time the diapir began to rise. The first tenet of this calculation is the thickness of the sedimentary fill above the salt of the Sedom Formation, assumed to be between 5200 and 5500 m in the southern Dead Sea basin (Fig. 3) (Al Zoubi and ten Brink, 2001). The height of the rock salt column that has been rising is equal to the thickness of the overlying sediments through which the diapir penetrated, plus the thickness of salt that was dissolved, estimated to be 600–800 m (Zak and Bentor, 1972), as indicated by the insoluble residue of the caprock. The second tenet is the time of the initial rise of the Sedom diapir, which is estimated to be 2.2 Ma if the M1 marker is accepted as an indication for the time of initiation (Milestone I). Hence, the overall average rate of rise is ~3 mm/yr. This slow rate relative to the rate of rise determined using more recent intervals (see below) may be partly attributed to the initial stage of the diapir rise, during which a relatively thin (~2400 m) overburden above the Sedom rock salt exerted low driving force on the diapir. In the latter stage, an additional ~2800-m-thick overburden accumulated, providing greater driving force by increasing both the buoyancy force and rate of salt flow due to increasing temperature and deviatoric stress.

Another possible reason for the relatively slow rate at the early stage of diapirism may be the fact that the overburden was not yet breached at that stage. Sometime after 100,000 yr B.P. (see below), when the overburden was breached, the diapir rose at a higher rate of rise than before.

# 2. Caprock Formation

As noted in the Milestone II section, Zak and Freund (1980) suggested that the caprock of the Sedom diapir formed during 300,000–100,000 yr B.P. As it is assumed to represent the insoluble residue of a vertical rock salt column of ~600–800 m that passed through the dissolution level (Zak and Freund, 1980), the average rate of rise for that time interval was between 2 and 8 mm/yr.

# 3. "Salt-mirror" Displacement

The salt mirror is thought to have "fossilized" between 14,000 and 11,000 yr B.P. The salt mirror is offset along the vertical rock salt bedding planes mainly at the marginal zones of the diapir (see Fig. 5). Along the eastern margin of Mount Sedom (Fig. 1B, salt quarry), the rock salt layers are consistently uplifted stepwise along successive bedding-planes relative to the more easterly beds (Zak and Freund, 1980). Here, the total displacement is 80 m, suggesting a rate of bedding-plane slip of between 5.5 and 7 mm/yr. This can be regarded as an approximation of the rate of rise of the Sedom diapir in the past 14,000 yr.

#### 4. Alluvial Sediment on Top of the Lisan Formation

The alluvial sediment on top of White Hill (Fig. 1B) indicates a ~70 m rise of the diapir, from 265 mbsl to 194 mbsl during the past 14,000 yr, with an average rate of ~5.0 mm/yr. Since the rate of surficial denudation of Mount Sedom (0.2 mm/ yr; Gerson, 1972) is more than an order of magnitude less than its uplift, it can be neglected in the rate calculation. Likewise, the top of northern Mount Sedom is found today at an elevation of 190 mbsl, and it is also covered by alluvial sediment (Frumkin, 1992).

# 5. Cave Formation

Observing that caves near the exposed border of the Sedom diapir are often multistoried, with high and dry levels hanging above the present base-level of the Dead Sea, Frumkin et al. (1991) and Frumkin (1996a, 1996b) concluded that a hanging passage adjusts rapidly to its concurrent base-level. Therefore, the present level of the caves relative to the present base-level of the Dead Sea is the result of two converging processes: the change in levels of the Dead Sea during the Holocene (Bookman et al., this volume) and the rise of the Sedom diapir. The oldest passage in Mount Sedom, dated to ca. 8000 yr B.P. (calibrated <sup>14</sup>C age), is 46 m above the current cave floor. For this and all other dated caves, the average down-cutting rate is ~6 mm/yr (Frumkin, 1996a). This would be equal to the rate of rise of the Sedom diapir, had the Dead Sea level not been lowered in the past 8000 yr. Since base-level did drop during this period, 6 mm/ yr should be considered a maximum value.

# 6. Dead Sea Lake Level

Lacustrine deposits along the western shores of the Dead Sea indicate that ca. 2600–3500 cal. yr B.P., the level of the Dead Sea was somewhat higher than 400 mbsl (Bookman et al., this volume). In Mount Sedom, a cave passage dated at 3100 yr B.P. is found today at an elevation of 365 mbsl. If the cave passage developed when it was draining into the Dead Sea at a level of ~400 mbsl (Frumkin, 1996b), then the cave rose up to 35 m during the past 3100 yr. This yields an average rate of Sedom diapir rise of ~11 mm/yr (Frumkin et al., 2001).

# 7. Geodetic Measurements

Frumkin (1992) and Pe'eri et al. (2003) measured the uplift rate of the Sedom diapir using a precise survey technique. Pe'eri et al. (2003) concluded that the southern Mount Sedom deformation is not uniform and the maximal rate of Sedom diapir rise averaged over two years of measurements is 6–8 mm/yr.

### 8. InSAR Measurements

The current rate of diapiric rise was also measured by InSAR, a technique that has recently become widespread for measurements of subtle displacements of the ground surface (e.g., Gabriel et. al., 1989; Massonnet and Feigl, 1998, and references therein; Baer et al., 2002a; Pe'eri et al., 2004). When two radar scans are made at different times from the same viewing angle, a small change in the position of the ground surface creates a detectable change in the phase of the backscattered signals. This phase change is proportional to the path difference between the two signals, and may thus be translated to ground displacement along the satellite-to-ground line of sight. A component of this phase change is always generated by the topography in the target area, the topographic effect increasing with the growing ground-parallel separation ("perpendicular baseline") between the two viewing antenna. To minimize this topographic phase contribution, we use in our analysis pairs with minimal perpendicular baselines (Table 1). The topographic phase is removed by projecting an independent, or an InSAR-made, digital elevation model (DEM) into the radar coordinates and subtracting it from the interferogram. Each fringe cycle in the topography-corrected interferogram corresponds to contours of 28 mm ground displacement along the satellite-to-ground line of sight. For pure vertical movements, each cycle corresponds to 31 mm vertical displacement.

InSAR has been applied to study the rate of Sedom diapir rise (Baer et al., 2002b; Pe'eri et al., 2004). SAR data used for this study were collected by the European Space Agency Remote Sensing Satellites ERS-1, which imaged the area between April 1992 and October 1997, and ERS-2, which has been imaging the area since July 1995. The SAR operates in C-band at a wavelength of 56.5 mm, with a nominal orbital cycle of 35 days for each satellite. During the overlapping period of the two satellites (1995–1997), they performed tandem missions at oneday intervals. Change (deformation) interferograms were generated for 10 different time intervals of 3–89 months between 1992 and 2001.

The uplift for each period is measured by counting the fringes (color cycles) in each interferogram from the background color (in the Ami'az Plain and/or along the Dead Sea shoreline) to the top of the two parts of Mount Sedom (Fig. 9). Figure 10 shows the cumulative uplift with time for the northern and southern part of Mount Sedom. Some of the interferograms overlap in time. A smaller uplift is generally seen in the long-term (1993–2001) interferogram relative to the added uplifts in the short-term interferograms (Fig. 10). We thus present two uplift paths for each part of Sedom diapir, one derived from the long-term interferogram, representing the minimal uplift rate, and the other composed of the cumulative uplift values in the short-term interferograms, representing the maximum uplift rate. The minimum and maximum rates for the northern part of Mount Sedom are 6.5 and 9.0 mm/yr; the minimum and maximum rates in the southern part of Mount Sedom are 5.0 and 7.0 mm/yr.

# DISCUSSION: CAUSES AND RATES OF THE SEDOM SALT DIAPIRISM

Initiation of diapirs in general and that of Sedom diapir in particular is one of the least understood aspects of salt tectonics in the Dead Sea basin. Two main characteristics of rock salt enable salt diapirism in several different scenarios: its ability to flow at a relatively high strain rate of up to  $10^{-12}$  s<sup>-1</sup> (Carter et al., 1982) and its relatively low density (2150 kg/m<sup>3</sup>). Below we consider their significance for Sedom salt diapirism.

There seems to be a discrepancy between the actual overburden under which the Sedom salt started its rise and the minimum thickness of overburden that is needed in order to provide buoyancy force to the Sedom salt. The minimum overburden thickness that allows buoyancy to become an upward driving force of the Sedom salt is determined by the stratigraphic level in which the average density of the entire overburden becomes larger than the density of the rock salt. Weinberger (1992) calculated the density profile of the Dead Sea basin sedimentary fill for different compositions following compaction curves of Baldwin and Butler (1985) and assuming that all pores are filled with brine of density 1235 kg/m<sup>3</sup> (the density of the saline Dead Sea water). The minimum thickness of overburden required for density inversion was calculated to be between 550 and 1650 m with a likely value of ~1000 m for an overburden composed of mixed shales and sandstones. This estimate agrees with the density log of the Sedom-Deep 1 drillhole (Rybakov et al., 1995), which indicates that the average overburden is denser than the Sedom salt (now at depth between 3700 and 4800 m) once the overburden thickness is thicker than 1000 m. Thus, the conditions for salt buoyancy exist both in the intermediate block

Orbit no. (reference–repeat)	Dates	Time (mo.)	Perpendicular baseline (m)	Uplift N-Sedom (mm)	Uplift S-Sedom (mm)	Rate N-Sedom (mm/yr)	Rate S-Sedom (mm/yr)
04732–22110	06/92-10/95	40	-40	25	20	7.5	6.0
10744–03439	08/93–12/95	28	26	25	20	10.7	8.6
10744–06445	08/93-07/96	35	-59	25	15	8.6	5.1
10744–12958	08/93-10/97	50	18	30	20	7.2	4.8
10744–29992	08/93-01/01	89	-13	45	35	6.0	4.7
01435–22611	07/95–11/95	3	-6	LD*	LD	LD	LD
01435–09451	07/95-02/97	18	-4	12	10	8.0	6.6
22611–09451	11/95-02/97	15	2	10	10	8.0	8.0
03439–12958	12/95-10/97	22	-8	15	15	8.2	8.2
13960–20473	12/97-03/99	15	14	10	5	8.0	4.0

Note: InSAR-interferometric synthetic aperture radar.

\*LD—less than the detection limit of 5 mm.



Figure 9. (A–I) Mount Sedom interferograms for periods of 15–89 months. Note the difference in number of interference rings between the northern and southern parts of Mount Sedom and the increasing uplift with time. For actual times of each pair, see Table 1.

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below the Ami'az Plain and in the deep block below the Dead Sea (Figs. 2 and 3), where overburden thicknesses are more than 1700 m (Ami'az 1 drillhole) and 3700 m (Sedom-Deep 1 drillhole).

However, the interpretation of seismic lines presented above indicates that more than 2400 m had been accumulated in both blocks before a significant rise of the diapir took place. This discrepancy indicates that the buoyancy force did not play the only role in Sedom salt diapirism. It can be explained by considering that the Sedom salt must have migrated from the center of the Dead Sea basin to the Sedom-fault conduit at its margins. Such lateral migration indicates that the salt flowed at a depth of ~2400 m. Indeed, this is the depth at which flow of rock salt may become important (Carter et al., 1982; Carter et al., 1993), and evidence for flow of rock salt is found in Mount Sedom. Detached boudins of dolomite and salt squeezed into the gaps between them indicate a finite strain of up to 1.6 at a depth probably >2000 m (Zak and Freund, 1980). Since, as deduced above, the Sedom diapir started its ascent ca. 2.2 Ma, and assigning that strain to this whole period, the minimum strain rate is  $3 \cdot 10^{-14} \text{ s}^{-1}$ . This strain rate is in accord with steady-state calculations under a temperature of 70 °C and deviatoric stress of 0.5-1.0 MPa (Carter et al., 1982, 1993; Talbot and Jackson, 1987). These values are realistic for the Sedom salt at an overburden depth of ~2400 m. For comparison, Jackson and Talbot (1986) show that in order to initiate salt pillow growth within a reasonable time frame for the tectonic evolution of the Gulf Coast, the calculated strain rate is at least 10<sup>-16</sup> s<sup>-1</sup>. Hence, we suggest that salt flow and the associated strain rate resulting from the load of overburden have been an important factor in the migration of the Sedom salt and the formation of the Sedom diapir. Moreover, bedding-plane slip displacements observed in the salt mirror (Fig. 2B) add 0.4 slip strain that developed since the salt mirror ceased to form at 11,000 yr B.P. (Zak and Freund, 1980). This finite strain, which appears at the surface of the diapir, indicates a high strain rate of 10<sup>-12</sup> s<sup>-1</sup> that is associated with the extrusive stage of the Sedom salt diapir. This high strain rate during the latter stage of Sedom diapirism is in accord with the results of Talbot and Jackson (1987; Fig. 1A), who reported that during salt extrusion, strain rates are 3-4 orders of magnitude greater than strain rates calculated for diapirism at depth.

The location of the diapir was probably dictated by the existence of normal faults in the margins of the basin, one of which (Sedom fault) acted as a preferred conduit for the upward migration of salt that arrived from the two subbasins, east and west of the diapir. The Sedom fault has been active since the Miocene (Al-Zoubi and ten Brink, 2001); uplifting of the Sedom diapir, however, did not start before 2400 m of overburden has been deposited in the Plio-Pleistocene. This time table indicates that the Sedom diapir was an active one, the forceful intrusion of which into an already existing fault system was governed by the thickness of overburden. Hence, it seems to us that the model of reactive diapirism (Vendeville and Jackson, 1992; Jackson and Vendeville, 1994), in which rising followed faulting due to exten-



Figure 10. Cumulative uplift of Mount Sedom between 1992 and 2001. Two lines are shown for each part of the mountain, representing the maximum and minimum uplift measured in the short- and long-term interferograms, respectively (see text for additional explanation). Numbers denoting annual rates of uplift are presented in Table 1.

sion as adopted by Al Zoubi and ten Brink (2001), does not apply to Sedom diapir.

Angular unconformities within the pre-Lisan and Lisan formations are observed mainly near Mount Sedom. It is suggested above that these unconformities are due to upward migration of salt beneath and that the salt is connected at depth to the main body of the Sedom diapir. As presented above, the amount of bed tilting at the Ami'az Plain declines away from Mount Sedom. We suggest that these gradual tilting variations are due to spatial and temporal variations of salt diapir emplacement. It is likely that rock salt is closer to the surface and was emplaced later beneath Black Hill than beneath Nahal Perazim. In such a case, the migrating salt concentrated along the north-south–trending Sedom fault, piercing and differentially tilting the overlying beds.

The Late Quaternary uplifting of the Sedom diapir top is constrained by only one date, at 14,000 yr B.P. At that time (Fig. 11, point 5), the Sedom diapir (namely, the salt top and a veneer of the caprock and Lisan Formation) was still lower than 265 mbsl. For an earlier time, a weaker indicator comes from the timing of inundation of the diapir by Lake Lisan. After this inundation, the Sedom diapir was at least partly stripped of its covering caprock and the lower Lisan Formation. It seems reasonable to assume that the aragonite at the base of the Lisan section on the top of Mount Sedom is associated with the lake



Figure 11. Tentative reconstruction of the elevation of Sedom diapir against the background of a curve illustrating the level of Lake Lisan. (1–2) Sedom diapir elevation was limited by Lake Lisan, which dissolved the rising salt. (2) Inundation of the Sedom diapir by the rising Lake Lisan and accumulation of aragonite at ca. 43,000 yr B.P. (3) Emergence of Sedom diapir and formation of unconformities. (4) Inundation and beginning of rocksalt dissolution. (4–5) Fast dissolution of rock salt lowers the top of Mount Sedom. (5) Reemergence of the Sedom diaper. (6) The present position of Mount Sedom. Lake Lisan level is after Bartov et al. (2003); Holocene lake level is after Yechieli et al. (1993).

level rise at ca. 43,000 yr B.P. (Bartov et al., 2003), and at that time at least parts of the Sedom diapir were lower than 280 mbsl (Fig. 11). At a later stage, the Sedom diapir top was lowered rapidly by dissolution as reflected by the increased Na/Ca ratio within the aragonite laminae of the Lisan Formation after 34,000 yr B.P., at a possible rate as high as 3 m/yr (calculated after Alkattan et al., 1997). This dissolution could later cease, when a sufficiently thick veneer of the Lake Lisan sediments, which are impermeable (Arkin and Starinsky, 1981; Katz and Kolodny, 1989), accumulating at a rate of more than 1 mm/ yr, covered the Sedom diapir. This then permitted the buildup of Mount Sedom topography under Lake Lisan water, until it reached an elevation somewhat lower than 265 mbsl at ca. 14,000 yr B.P.

This tentative reconstruction indicates the possibility that the topographic rise of Mount Sedom is related to the variation in lake level during the late Pleistocene. Even though the conditions have constantly promoted the upward migration of salt, a substantial topographic rise took place mainly since the early Holocene. At that time, lake level drop freed the rock salt from the lake water and underground water that had previously caused its rapid solution and prevented its topographic rise.

The rate of rise of the Sedom diapir is estimated here by six different approaches and methods, covering time spans of six orders of magnitudes. For the past 14,000 yr, after the Sedom diapir had breached the overburden, the uplift rate has varied between 5 and 11 mm/yr, not too far from the overall rate of ~3 mm/yr, which pertains mostly to the long pre-emergent period. Even the highest estimated rate of Sedom diapir is an order of magnitude lower than the rate found in some Iranian diapirs (Talbot et al., 2000; Talbot and Aftabi, 2004).

No evidence has been found that the Sedom diapir has ever fountained and formed "salt glaciers" at its flanks, such as observed in Iranian diapirs (Talbot et al., 2000; Talbot and Aftabi, 2004). Although it is well appreciated that such evidence is hard to come by, it is noteworthy that the rate of uplift as deduced from measurements taken at present—in which the Sedom diapir clearly does not fountain—is very similar to rates estimated for past stages of diapirism. In addition, the rate of salt dissolution in either lake water or groundwater (up to 3 m/yr), in comparison to the maximum estimated uplift rate of the Sedom diapir (~10 mm/yr), precludes the possibility that the diapir fountained as it approached the surface, after ca. 300,000 yr B.P. It should also be noted that there are no indications of salt layers (i.e., salt glaciers) in the Melekh Sedom-well located near and to the east of the diapir (Fig. 3).

The Sedom diapir shall not rise forever. At present, the buoyancy force that the minimum 5500 m overburden exerts on the source Sedom salt layer beneath it (Fig. 3) is not balanced by the force exerted by the salt column of the same height. The potential height of the Sedom diapir may be simply calculated by equating the weight of the overburden column ( $\rho_{overburden}gh_{overburden}$ ) with the weight of the salt column ( $\rho_{salt}gh_{salt}$ ), where  $\rho$  is the density (kg m<sup>-3</sup>), g is the acceleration due to gravity (m s<sup>-2</sup>), and h is the column height (m). Hence,  $h_{salt} = \rho_{overburden}h_{overburden}/\rho_{salt}$ . Applying such calculation to Mount Sedom by taking an average density of the overburden (Fig. 5):

$$h_{\rm mat} = (2300 \text{ kg m}^{-3} \times 5500 \text{ m})/(2150 \text{ kg m}^{-3}) = 5884 \text{ m}$$

This result implies that the salt column (i.e., Mount Sedom) may reach a height of 5884-5500 = 384 m above the Dead Sea. Because Mount Sedom currently rises 250 m above the Dead Sea, it may gain an additional ~130 m. Assuming a rate of rise between 5 and 10 mm/yr, this may take 15,000–30,000 yr. However, the rate of rise may decline because (1) the source salt layer will thin; based on the seismic data (Fig. 4), this later stage has not yet been reached; and (2) the buoyancy potential will approach exhaustion. Thus, the ultimate height of Mount Sedom may be reached much later than 30,000 yr from the present.

#### SUMMARY AND CONCLUSIONS

The following milestones in the rise of the Sedom diapir have been discerned (Table 2).

- 2,200,000–300,000 yr B.P.: The diapir began to rise at ca.
  2.2 Ma and the salt layers rotated to vertical about horizontal axes trending north-northeastward.
- 2. 300,000–150,000 yr B.P.: The diapir reached a near surface level at ca. 300,000 yr B.P. At that time, the dissolution of a rock salt column of 600–800 m left the insoluble

#### Quaternary rise of the Sedom diapir

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No.	Method	Time span (years)	Height difference (m)	Uplift rate (mm/yr)	Source	
1	Overall diapir rise	2,200,000	5200 to 5500	3	This study	
2	Caprock formation	100,000 to 300,000	600 to 800	2–8	Zak and Freund, 1980	
3	Alluvial sediment on Mount	14,000	75	5 (south)	Zak, 1967; this study	
	Sedom	14,000 to 10,000	70	5–7 (north)		
1	Salt mirror	11,000	80	7	After Zak and Freund, 1980	
5	Cave formation	8,000	46	6 (max.)	Frumkin et al.,1991; Frumkin, 1996	
6	Dead Sea lake levels	3,100	35	11	Frumkin et al., 2001	
,	InSAR	7.5	0.035	5–7 (south)	This study	
		7.5	0.045	6–9 (north)		
3	Precise leveling	2	0.012 to 0.016	6–8	Frumkin, 1992; Pe'eri et al., 2003	

TABLE 2. SUMMARY OF RATES OF SEDOM DIAPIR RISE AS ESTIMATED BY DIFFERENT METHODS

residue as a caprock on a salt mirror. The arrival of the diapir at that level tilted the lower member of the Hamarmar Formation in the margins of the diapir. At the southeastern flank of Mount Sedom, the salt layers rotated  $\sim 30^{\circ}$  counterclockwise about vertical axes.

- 3. 150,000–70,000 yr B.P.: Additional uplift of the Sedom diapir tilted the pre-Lisan formations.
- 4. 70,000–ca. 40,000 yr B.P.: The Sedom diapir breached the surface; its veneer of sediments was eroded, thus exposing some of the rock salt to further dissolution.
- 5. Circa 40,000–14,000 yr B.P.: The Sedom diapir was inundated by Lake Lisan and exposed rock salt dissolved. The top of the diapir was lower than 265 mbsl.
- 6. Since 14,000 yr B.P.: The level of Lake Lisan fell below 280 mbsl and the Sedom diapir emerged again above the Ami'az Plain. Continued uplift led to the present maximum elevation of 164 mbsl. The rock salt is slowly dissolved under the very low rainfall.

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