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Abstracts of selected papers

Listed by date of publication

Frumkin, A., Bar-Yosef, O., and Schwarcz, H. P. 2011, Possible paleohydrologic and paleoclimatic effects on hominin migration and occupation of the Levantine Middle Paleolithic. Journal of Human Evolution 60:4 p. 437-451.

ABSTRACT

This paper explores the impact of major glacial/interglacial paleohydrologic variations in the Middle- Paleolithic Levant on hominin migration and occupation. The climatic reconstruction is based primarily on the most straight-forward paleohydrologic records recently published. These terrestrial proxies convey direct paleoenvironmental signals of effective precipitation and aquifer recharge. The two main proxies are temporal changes of terminal lake levels in the Dead Sea basin and periods of deposition or non-deposition of speleothems. Other records, such as stable isotopes, if interpreted correctly, correspond well with these two direct proxies. All the records consistently indicate that the last two glacial periods in the central Levant were generally wet and cool, while the last two interglacials were dry and warm, so more water was available for the ecosystem and thus hominins during glacial periods than during interglacials. Some proxies indicate that the higher precipitation/evaporation ratio during glacial periods involved higher precipitation rather than only reduced evaporation. Beyond the general mean glacial/interglacial climate suggested here, variations occurred

at all temporal scales throughout glacial or interglacial periods. In the Sahara-Negev arid barrier, moister conditions occurred during Marine Isotope Stage (MIS) 6a-5e, when Anatomically Modern Humans apparently migrated out of Africa. We suggest that this migration, as well as the later Neanderthal expansion from Southeast Europe or the Anatolian plateau into the Levant during early MIS 4, could be facilitated by the observed major climatic variations.

Frumkin, A., Ezersky, M., Al-Zoubi, A., Abueladas, A.-R. (2011). The deadly hazard of the Dead Sea: geophysical assessment of salt sinkholes. Geomorphology 134, 102–117.

ABSTRACT

Sheffer, N., Cohen, M., Morin, E A geophysical approach is presented for analyzing processes of subsurface salt dissolution and associated sinkhole hazard along the Dead Sea. The implemented methods include Seismic Refraction (SRFR), Transient Electromagnetic Method (TEM), Electric Resistivity Tomography (ERT), and Ground Penetration Radar (GPR). The combination of these methods allows the delineation of the salt layer boundaries, estimating its porosity distribution, finding cavities within the salt layer, and identifying deformations in the overlying sediments. This approach is shownto be useful for anticipating the occurrence of specific sinkholes, as demonstratedon both shores of the Dead Sea. These sinkholes are observed mainly along the edge of a salt layer deposited during the latest Pleistocene,when Lake Lisan receded to later become the Dead Sea. This salt layer is dissolved by aggressivewater flowing from adjacent and underlying aquifers which drain to the Dead Sea. Sinkhole formation is accelerating today due to the rapid fall of the Dead Sea levels during the last 30 years, caused by anthropogenic use of its water.

Marder, O., Yeshurun, R., Lupu, R., Bar-Oz, G., Belmaker, M., Porat, N., Ron, H., and Frumkin, A. (2011). Mammal remains at Rantis Cave, Israel, and middle-late Pleistocene human subsistence and ecology in the Southern Levant. Journal of Quaternary Science 26(8) p. 769–780.

ABSTRACT

Rantis Cave is a recently discovered filled cave in central Israel, displaying a rich faunal accumulation of micromammals, ungulates and carnivores. U–Th dating assigns the beginning of accumulation to ca. 140 ka. The accumulation is culturally assigned to the late half of the Middle Paleolithic (MP) period. Single-grain optically stimulated luminescence measurements attest to a complex sedimentological history. We present the cross-disciplinary results of taphonomic and geomorphological analyses, which point to the cave serving as a natural pitfall trap for the large fauna, with little human or carnivore activity. The fauna is dominated by Dama among the ungulates and by Microtus among the micromammals. These data in conjunction with ungulate tooth mesowear analysis suggest a xeric Mediterranean environment on the eastern margin of the southern Levantine foothills. The relative taxonomic abundance of ungulate taxa shows some differences from anthropogenic MP sites, possibly reflecting the prey choice patterns of MP hunters. Overall, the natural accumulation scenario for Rantis Cave provides a rare paleoenvironmental and paleoeconomic reference to the rich anthropogenic MP faunas of the Southern Levant, enabling the reconstruction of a rich and diverse environmental setting for this important human dispersal route.

Zissu, B., Porat, R., Langford, B., and Frumkin, A., (2011), Archaeological Remains of the Bar Kokhba Revolt in the Te'omim Cave (M ŭghâret Umm et Tûeimîn), Western Jerusalem Hills. Journal of Jewish Studies 52,2, p. 262-283.

ABSTRACT

The Te′omim Cave is a large natural cave, located in the Jerusalem hills. The article presents the results of an archaeological survey in the hard-to-reach section of the cave. Archaeological finds, as hoards of coins, weapons, fragmentary human bones, pottery and oil lamps from the time of the Bar Kokhba Revolt were discovered *in situ*. The finds attest that the cave served as the last place of refuge for rebels who met there their death. The highlights of the survey were three hoards of coins. ‘Hoard A′ included 83 silver coins restruck by the Bar Kokhba administration. It is the only hoard of silver Bar Kokhba coins discovered thus far by archaeologists. ‘Hoard B′ included nine silver coins and a bronze *perutah*. ‘Hoard C′ included five Roman gold coins, 15 silver coins and four Roman bronze coins of Ascalon. The article discusses various numismatic and archaeological aspects of the finds.

Benami Amiel, R., Grodek, T., Frumkin, A. , 2010. Characterization of the hydrogeology of the sacred Gihon Spring, Jerusalem: A deteriorating urban karst spring. Hydrogeology Journal 18, 1465-1479.

ABSTRACT

The Gihon Spring, Jerusalem, is important for the major monotheistic religions. Its hydrogeology and hydrochemistry is studied here in order to understand urbanization effects on karst groundwater resources, and promote better water management. High-resolution monitoring of the spring discharge, temperature and electrical conductivity, was performed, together with chemical and bacterial analysis. All these demonstrate a rapid response of the spring to rainfall events and human impact. A complex karst system is inferred, including conduit flow, fissure flow and diffuse flow. Electrical conductivity, Na+ and K+ values (2.0mS/cm, 130 and 50mg/l respectively) are very high compared to other nearby springs located at the town margins (0.6mS/cm, 15 and <1mg/l respectively), indicating considerable urban pollution in the Gihon area. The previously cited pulsating nature of the spring was not detected during the present high-resolution monitoring. This phenomenon may have ceased due to additional water sources from urban leakage and irrigation feeding the spring. The urbanization of the recharge catchment thus affects the spring water dramatically, both chemically and hydrologically. Appropriate measures should therefore be undertaken to protect the Gihon Spring and other karst aquifers threatened by rapid urbanization.

Lisker, S., Vaks, A., Bar-Matthews, M., Porat, R., and Frumkin, A. 2010. Late Pleistocene palaeoclimatic and palaeoenvironmental reconstruction of the Dead Sea area (Israel) based on speleothems and cave stromatolites. Quaternary Science Reviews 29, 1201–1211.

ABSTRACT

Calcite speleothems are a hitherto hardly documented occurrence in the nowadays arid to hyper-arid rain-shadow Dead Sea area of eastern Israel. Speleothem ages (U–Th) from two caves on the Dead Sea Fault Escarpment and two caves from arid rain-shadow areas surrounding the Dead Sea, span the last three glacial cycles from ca 354 to 12 ka and suggest episodic moist local palaeoclimate mainly during glacial periods of Marine Isotopic Stages (MIS) 6 and 4 to 2. Previously reported U–Th ages of stromatolites deposited in the Late Pleistocene Lake Lisan and preserved in caves of the Dead Sea Fault Escarpment, suggest that regional relatively moist climate affected the lake catchment area during the late part of (relatively warm) MIS-3 lasting until middle (cold) MIS-2, as well as at the MIS-5 to 4 (interglacial–glacial) transition. Speleothem deposition periods spanning the 38.4 _ 0.5 to 16.4 _ 0.3 ka time interval, i.e. late MIS-3 to early MIS-2, representing moist periods in the lake area, are coeval to regional moist conditions inferred by the stromatolite record. A direct connection is thus implied between local and regional climate at the latest Pleistocene based on correlation between two independent data sets. This connection implies that glacial climate has generally been moister than interglacial climate during the last glacial–interglacial cycle at both local and regional scales around the Dead Sea and its predecessors.

Lisker, S., Porat, R., and Frumkin, A, 2010, Late Neogene rift valley fill sediments preserved in caves of the Dead Sea Fault Escarpment (Israel): palaeogeographic and morphotectonic implications, Sedimentology 57, 429–445

ABSTRACT

Evaporitic-lagoonal marl and dolomite laminar fill sediments are preserved in relict dry caves of the Dead Sea Fault Escarpment (Israel) which has been tectonically active since the Late Neogene. The hosting caves are located within Turonian massive carbonate bedrock and at higher altitudes than previously documented fill sediments of the Dead Sea depression. Based on the relative altitudes of the cave sediments, the 'reversed stratigraphy' of the Dead Sea depression fill sediments, possible partial correlation of the cave sediments with other fill sedimentary units of the depression, and sedimentary, geochemical and mineralogical characteristics, it is concluded that: (i) the cave sediments are among the oldest of the depression fill; and (ii) the deposition of the cave sediments took place in hypersaline dolomite-precipitating water bodies of Late Neogene age, during the initial morphotectonic stages of the depression formation. Variable and relatively low Sr/Ca and d34S ratios of the cave sediments (assuming precipitation from sea water) suggest variable fresh water input into the depositional brine. The present altitudes of the cave sediments reflect Late Neogene levels of water bodies in the depression, modified by vertical post-Late Neogene tectonic movements within the still active fault escarpment. According to these altitudes, a 50 to 250 m uplift of the western margins of the depression since the Late Miocene to Early Pliocene is inferred.

Gopher, A., Ayalon, A., Bar-Matthews, M., Barkai, R., Frumkin, A., Karkanas, P. and Shahack-Gross, R. 2010. The chronology of the late Lower Paleolithic in the Levant: U-series dates of speleothems from Middle Pleistocene Qesem Cave, Israel. Quaternary Geochronology 5, 644-656.

ABSTRACT

We present here the results of a U-Th dating project at Qesem Cave, a Middle Pleistocene, late Lower Paleolithic site in Israel. It provides 54 new MC-ICP-MS UeTh ages for speleothems from the cave. The results indicate that human occupation started sometime betweenw420 and 320 ka and ended between 220 and 194 ka. A survey of dates from culturally similar sites in the Levant indicates that the general range of ca. 400eca. 200 ka is an appropriate estimate for the life span of the Acheulo-Yabrudian Cultural Complex (AYCC).

Sheffer, N., Dafny, E., Gvirtzman, H., Navon, S., Frumkin, A., Morin, E., **2010.** Hydrometeorological daily recharge assessment model (DREAM) for the Western Mountain Aquifer, Israel: Model application and effects of temporal patterns**. Water Resources Research** 46.

ABSTRACT

Recharge is a critical issue for water management. Recharge assessment and the factors affecting recharge are of scientific and practical importance. The purpose of this study was to develop a daily recharge assessment model (DREAM) on the basis of a water balance principle with input from conventional and generally available precipitation and evaporation data and demonstrate the application of this model to recharge estimation in the Western Mountain Aquifer (WMA) in Israel. The WMA (area 13,000 km2) is a karst aquifer that supplies 360–400 Mm3 yr−1 of freshwater, which constitutes 20% of Israel's freshwater and is highly vulnerable to climate variability and change. DREAM was linked to a groundwater flow model (FEFLOW) to simulate monthly hydraulic heads and spring flows. The models were calibrated for 1987–2002 and validated for 2003– 2007, yielding high agreement between calculated and measured values (R2 = 0.95; relative root mean square error = 4.8%; relative bias = 1.04). DREAM allows insights into the effect of intra annual precipitation distribution factors on recharge. Although annual precipitation amount explains 70% of the variability in simulated recharge, analyses with DREAM indicate that the rainy season length is an

important factor controlling recharge. Years with similar annual precipitation produce different recharge values as a result of temporal distribution throughout the rainy season. An experiment with a synthetic data set exhibits similar results, explaining 90% of the recharge variability. DREAM represents significant improvement over previous recharge estimation techniques in this region by providing near real time recharge estimates that can be used to predict the impact of climate variability on groundwater resources at high temporal and spatial resolution.

Vaks, A., Bar-Matthews, M., Matthews, A., Ayalon, A. and Frumkin, A., 2010. Middle-Late Quaternary paleoclimate of northern Saharan-Arabian Desert: reconstruction from speleothems of Negev Desert, Israel. Quaternary Science Reviews 29, 1201–1211

ABSTRACT

Speleothems in arid and hyper-arid areas of Negev Desert, Israel, are used in paleoclimate reconstruction of northern margins of Saharan-Arabian Desert, focused on the following objectives: 1) precise UeTh dating of the timing of speleothem growth as an indicator of periods of humid climate, i.e. positive effective precipitation; 2) the origin of rainfall using the speleothem d18O and changes in spatial pattern of speleothem deposition and speleothem thickness along a northesouth transect; 3) changes of vegetation cover based on speleothem d13C variations. During the last 350 ka major humid periods, referred to herein as Negev Humid Periods (NHP), occurred in the central and southern Negev Desert at 350e310 ka (NHP-4), 310e290 ka (NHP-3), 220e190 ka (NHP-2), and 142e109 ka (NHP-1). NHP-4, NHP-2 and NHP-1 are interglacial events, whereas NHP-3 is associated with a glacial period. During NHP-1, 2 and 3 the thickness and volume of the speleothems decrease from the north to the south, and in the most southern part of the region only a very thin flowstone layer formed during NHP-1, with no speleothem deposition occurring during NHP- 2 and 3. These data imply that the Eastern Mediterranean Sea was the major source of the rainfall in northern and central Negev. More negative speleothem d18O values, relative to central parts of Israel (Soreq Cave) are attributed to Rayleigh distillation because of the increasing distance from the Mediterranean Sea. Speleothem deposition during the NHP-4 in the southern Negev was more intensive than in most of the central Negev, suggesting the prominence of the tropical rain source. Decrease in speleothem d13C during NHP events indicates growth of the vegetation cover. Nevertheless, the ranges of d13C values show that the vegetation remained semi-desert C4 type throughout the NHPs, with an additional significant carbon fraction coming from the host rock and the atmosphere. These observations, together with small thickness of the speleothem layers, favor that NHP events consisted of clusters of very short humid episodes interspersed with long droughts. NHP events were contemporaneous with climate periods with monsoon index of _51 (cal/cm2_ day) and with the formation of sapropel layers in the Mediterranean Sea. Such simultaneous intensification of the monsoon and Atlantic-Mediterranean cyclones is probably related to the weakening of the high pressure cell above sub-tropical Atlantic Ocean, which enabled more rainfall to penetrate into the Saharan-Arabian Desert from the north and south. The contemporaneous occurrence of the NHP events and the increased monsoon rainfall could have opened migration corridors, creating climatic “windows of opportunity” for dispersals of hominids and animals out of the African continent.

Frumkin, A. 2009, Active hypogene speleogenesis and groundwater system at the edge of an anticlinal ridge. In: Klimchouk, A., and Ford, D.C., eds., Hypogene Speleogenesis and Karst Hydrogeology of Artesian Basins. Ukranian Institute of Speleology and Karstology, Special Paper 1, p. 137-149.

ABSTRACT

It has been recently acknowledged that hypogenic caves are common in limestone terranes (e.g. KLIMCHOUK, 2000; AUDRA et al., 2002, 2007; AULER AND SMART, 2003; FORD AND WILLIAMS, 2007), with an extensive review by

KLIMCHOUK (2007). Anticlinal ridges provide large recharge areas through which meteoric water may flow into confined zones around the peripheries during their history of uplift and associated denudation. The spatially varying stratal dips may create preferred flow routes within the confined zone and consequently promote hypogene speleogenesis at the most suitable sites for the water to rise again and discharge. Active speleogenetic sites thus may be found around the edges of anticlinal ridges where the potentiometric levels in the confined zone are high enough to promote the rising, transverse flow. Further away towards the adjoining synclinal basin, impermeable cover may be too thick to allow rising flow. The preferred sites for speleogenesis may migrate away from the anticlinal axis during the uplift process and associated lowering of groundwater levels. The common occurence of relict isolated hypogene caves in the Judean anticlinorium (FRUMKIN AND FISCHHENDLER, 2005) have led to the discovery of similar caves actively forming today. The Yarkon Taninim regional aquifer is divided into lower and upper sub-aquifers, of which the lower one becomes (partly) confined near the anticlinal axis, while the upper subaquifer becomes confined at the western foothills. Upward flow is evident at the Ayalon Salinity Anomaly (ASA) where the upper sub-aquifer is still unconfined, so that rising water has much larger free space to fill in comparison with the nearby confined zone (FRUMKIN AND GVIRTZMAN, 2006). Approaching the watertable, the emerging rising flow can

Frumkin, A. 2009, Active hypogene speleogenesis and groundwater system at the edge of an anticlinal ridge. In: Klimchouk, A., and Ford, D.C., eds., Hypogene Speleogenesis and Karst Hydrogeology of Artesian Basins. Ukranian Institute of Speleology and Karstology, Special Paper 1, p. 137-149.

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It has been recently acknowledged that hypogenic caves are common in limestone terranes (e.g. KLIMCHOUK, 2000; AUDRA et al., 2002, 2007; AULER AND SMART, 2003; FORD AND WILLIAMS, 2007), with an extensive review by KLIMCHOUK (2007). Anticlinal ridges provide large recharge areas through which meteoric water may flow into confined zones around the peripheries during their history of uplift and associated denudation. The spatially varying stratal dips may create preferred flow routes within the confined zone and consequently promote hypogene speleogenesis at the most suitable sites for the water to rise again and discharge. Active speleogenetic sites thus may be found around the edges of anticlinal ridges where the potentiometric levels in the confined zone are high enough to promote the rising, transverse flow. Further away towards the adjoining synclinal basin, impermeable cover may be too thick to allow rising flow. The preferred sites for speleogenesis may migrate away from the anticlinal axis during the uplift process and associated lowering of groundwater levels. The common occurence of relict isolated hypogene caves in the Judean anticlinorium (FRUMKIN AND FISCHHENDLER, 2005) have led to the discovery of similar caves actively forming today. The Yarkon Taninim regional aquifer is divided into lower and upper sub-aquifers, of which the lower one becomes (partly) confined near the anticlinal axis, while the upper subaquifer becomes confined at the western foothills. Upward flow is evident at the Ayalon Salinity Anomaly (ASA) where the upper sub-aquifer is still unconfined, so that rising water has much larger free space to fill in comparison with the nearby confined zone (FRUMKIN AND GVIRTZMAN, 2006). Approaching the watertable, the emerging rising flow can easily travel laterally along the highly permeable karstified zone. The rising ASA water is comparable to artesian springs, which discharge in the zone of lowest head of the upper aquifer. In the case of the ASA, however, the upward flow does not reach the open land surface but instead disperses laterally near the watertable. It may thus be considered an “underground delta”. The conceptual model consists of four-segment flow route: (1) rainwater recharge through outcrops on the anticlinal ridge; (2) lateral confined flow down to a depth of ~-700 m; (3) pressurized upward flow through discrete sub-vertical conduits; and (4) multidirectional pervasive flow close to the water table, with restricted output in which the rising water mingles with the ‘normal’ water of the upper aquifer. Maze caves fed by vertical conduits are typical for such an “underground delta”, as they disperse the flow laterally in many similar routes. Dense cave formation is observed to be associated with the upward flow of aggressive water. Within the “underground delta” the aggressiveness is consumed over short distances

laterally away from the sub-vertical feeders. Such formation of large voids by dissolution far from the recharge zone implies renewed hydrochemical aggressiveness. The spatial location of the ASA is determined by three conditions that allow upward leakage from the deep sub-aquifer: (1) the location of the westernmost unconfined zone of the upper sub-aquifer, and its association with nearby confined regions; (2) the large upward head gradient; (3) spatial heterogeneities in the vertical permeability that are associated with tectonically disturbed zones.

Frumkin, A., 2009, Formation and dating of a salt pillar in Mount Sedom diapir, Israel: Geological Society of America Bulletin., v. 121, 1/2; p. 286–293

ABSTRACT

For at least two thousand years historians and travelers attributed a relict salt pillar in the Dead Sea area to the biblical myth of Lot's Wife, who "became a pillar of salt" (Genesis 19:26). Here the formation of the salt pillar is analyzed and dated, complemented by measurement of its uplift rate. Contrary to earlier assumptions that the salt pillar was formed by direct rainfall, the observed solutional notches and morphology of the neighboring chasm attribute the salt pillar to a karstic cave that collapsed ~4000 years ago. 14C dates from the highest cave level indicate that it had been active until ~2000 BCE, and collapsed soon afterwards. The measured uplift rate shows that when the pillar formed, it had been much closer to the travelers commuting along Mt. Sedom, and easily observable. This evidence suggests that the myth of Lot's Wife was originally based on one of the earliest geological observations: The sudden appearance of a salt pillar following a catastrophic earthquake, ~4000 years ago.

Frumkin, A., Karkanas, P., Bar-Matthews, M., Barkai, R., Gopher, A., Shahack-Gross, R., and Vaks, A., 2009, Gravitational deformations and fillings of aging caves: the example of Qesem karst system, Israel: Geomorphology, v. 106, p. 154–164.

ABSTRACT

The Qesem karst system may serve as an example for aging chamber caves. It includes two caves which have undergone several stages of natural and human-induced deposition, as well as subsidence and collapse. Natural deposits include calcite speleothems, bedrock collapse debris, and clay fill. Karst dissolution and associated sagging and decomposition have operated since the initial cave formation. Inclined sediments are attributed to several processes, mostly controlled by gravitation, affecting cave deposits and sometimes the host-rock. U-Th dating shows that speleothem deposition has been common during the mid-late Quaternary, but deposition sites shifted according to local conditions. The aging of caves occurs when they become totally filled by sediments and ultimately consumed by surface denudation, as documented in Qesem Cave.

Lisker, S. Vaks, A., Bar-Matthews, Miryam, Porat, R. Frumkin, A., 2009 Stromatolites in caves of the Dead Sea Fault Escarpment: implications to latest Pleistocene lake levels and tectonic subsidence, Quaternary Science Reviews, v. 28, 1-2, p. 80-92.

ABSTRACT

A varied assemblage of stromatolites was encountered within caves along the northern section of the Dead Sea Fault

Escarpment. The caves are situated at the lower part of the escarpment at altitudes -310 to -188 m relative to mean sea level, i.e. ca. 110 to 230 m above present Dead Sea level. The cave stromatolites are mainly composed of aragonite yielding U-Th ages of ~75 to 17 ka. The altitude, mineralogy and ages, as well as comparison with previously documented stromatolite outcrops in the area, ascribe the cave stromatolites to aragonite-precipitating hypersaline Lake Lisan - the Late Pleistocene predecessor of the Dead Sea.

The stromatolites are used as a lake level gauge, based on the algae being reliant upon the light of the upper water layer. Preservation of the original structure and aragonite mineralogy of the stromatolites, suggests a closed-system regarding the radioactive elements, enabling reliable U-Th dating.

A curve of Lake Lisan levels is constructed based on the stromatolite ages and the caves' elevations above m.s.l. The following points are noted: (1) Lake levels of -247 m relative to m.s.l. are recorded at ~75-72.5 ka; (2) Relatively high lake levels above -220 m relative to mean sea level, are achieved at ~41.5 ka, and are still recorded at ~17 ka; (3) The peak level is -188 m relative to mean sea level, at ~35.5-29.5 ka. These results indicate lake stands up to 80 m higher than previously accepted, for large parts of Lake Lisan time period. This difference is explained by tectonic subsidence of up to 2.2 m/ka within the Dead Sea depression since the latest Pleistocene. This subsidence rate is in the same order of magnitude with previously calculated subsidence rates for the Dead Sea depression (Begin and Zilberman, 1997). Unlike previous Lake Lisan level estimations, the new curve is measured at the relatively stable shoulders of the Dead Sea depression.

Frumkin, A., 2009. Stable isotopes of a subfossil Tamarix tree from the Dead Sea region, Israel, and their implications for the Intermediate Bronze Age environmental crisis Quaternary Research, v. 71, p. 319–328.

ABSTRACT

Trees growing on the Mt. Sedom salt diapir, at the southern Dead Sea shore, were swept by runoff into salt caves and subsequently deposited therein, sheltered from surface weathering. A subfossil *Tamarix* tree trunk, found in a remote section of Sedom Cave is radiocarbon dated to between ~2265 and 1930 BCE. It was sampled in 109 points across the tree rings for carbon and nitrogen isotopes. The Sedom *Tamarix* demonstrates a few hundred years of ^{13}C and ^{15}N isotopic enrichment, culminating in extremely high $\delta^{13}C$ and $\delta^{15}N$ values. Calibration using modern *Tamarix* stable isotopes in various climatic settings in Israel shows direct relationship between isotopic enrichment and climate deterioration, particularly rainfall decrease. The subfossil *Tamarix* probably reflects an environmental crisis during the Intermediate Bronze Age, which subsequently killed the tree ~1930 BCE. This period coincides with the largest historic fall of the Dead Sea level, as well as the demise of the large regional urban center of the 3rd millennium BCE. The environmental crisis may thus explain the archaeological evidence of a shift from urban to pastoral culture during the Intermediate Bronze Age. This was apparently the most severe long-term historical drought that affected the region in the mid-late Holocene.

Frumkin, A., 2009, How Lot's wife became a pillar of salt. Biblical Archaeology Review 35:3, p. 38-64.

ABSTRACT

A relict salt pillar in Mt. Sedom salt diapir, Dead Sea area, Israel, is shown to be preserved between an active fault plane and an unroofed dissolution cave (collapse sinkhole). The pillar was formed by a combination of processes: dissolution of salt by floodwater, active diapirism, and earthquake-triggered collapse. Radiocarbon dating, geodetic leveling and geomorphologic study are used in this study. Radiocarbon dates of wood remains in the preserved part of the cave suggest that the paleo-cave had been active (with ephemeral stream flowing in it) until ~4000 years ago. Consequently, its roof

was destroyed by collapse which isolated the pillar from its surroundings. The radiometric dating and the probable earthquake triggering of the collapse associate the pillar with the commonly proposed mechanism and age of the biblical Sodom and Gomorrah upheaval, ~ late Early Bronze or early Middle Bronze Age. This may suggest that the salt pillar is the origin of the ancient geological narrative, relating to Lot's Wife who "became a pillar of salt" (Genesis 19:26). The measured rising rate of the diapir, 6-9 mm/yr, suggests that following its formation, the salt pillar was close to the eastern foothills plain, attracting travelers who transferred the narrative as a living memory through time, until finally recorded in the biblical text. Therefore, this may be one of the oldest narratives that can be geologically attributed to a particular dated geological feature.

Ronen, A., Neber, A., Mienis, H. K., Horwitz, L. K., Frumkin, A., Boenigk, W., and Galili, E., 2008, Mousterian occupation on an OIS 5e shore near the mount carmel caves, Israel, in Sulgostowska, Z., and Tomaszewski, A. J., eds., Men – Millennia – Environment: Warsaw, Institute of Archaeology and Ethnology, Polish Academy of Sciences, p. 197-205

ABSTRACT

Humans have repeatedly camped on the last Interglacial sea shore at Atlit, a short distance from the Mount Carmel caves of Tabun and Skhul. Two small caves close to the shoreline were occupied, in all likelihood by archaic modern humans equipped with a Levantine Mousterian tool kit. The most intensive occupation occurred in the top/upper part of the beach sediment with only scanty remains left in the lower part. The occupants used hearths and exploited terrestrial and marine faunas. One of the caves contained most of the lithic artifacts while almost all the faunal and malacological remains were recovered in the other cave, indicating some degree of spatial organization. Atlit could have been a Middle Paleolithic coastal occupation providing for the Mount Carmel caves. It could have been equally well a stop on a dispersal route of modern humans out of Africa along the Last Interglacial coastline (Walter et al. 2000; Stringer 2000). If true, Atlit is likely to have been at the end of that dispersal route.

Fischhendler, I. and Frumkin, A. 2008. Distribution, evolution, and morphology of caves in southwestern Samaria, Israel. Isr. J. Earth Sci. 57: 311–322.

ABSTRACT

Karst has a significant role in the morphology of the Judean–Samarian mountains and may be associated with potential risk to groundwater pollution. Despite this, there is little knowledge of the pattern of karst in Samaria and its origin. The purpose of this research is to characterize the karst distribution and origin within southern Samaria. A karst survey was performed in a 25 km2 area, in which all the cavities above a volume of 5 m3 were mapped. In most formations in the Judea Group cavities appear in clusters. Each cluster consists of a big cavity and several other smaller ones. The distribution and intensity of cavities is partially explained by the percentage of insoluble residue in the different formations. Most cavities are small, isolated chambers characterized by limited vertical and horizontal development. The morphology of most cavities indicates that they were formed under shallow phreatic conditions, likely before the last major uplift of the backbone of central Israel.

Frumkin, A., Bar-Matthews, Vaks, A., 2008, Paleoenvironment of Jawa basalt plateau, Jordan, inferred from calcite speleothems from a lava tube, Quaternary Research, v. 70, 3, p. 358-367.

ABSTRACT

This paper explores the environmental conditions that faced the people of ancient Jawa during the Holocene, as well as previous prehistoric periods of the mid-late Pleistocene. Calcite speleothems in a lava tube are dated to marine isotopic stage 7 and stage 5/4 transition using the U-Th method. The available evidence indicates general aridity of the Black Desert during most of the mid-late Quaternary, punctuated by short wetter periods, when the Mediterranean cyclones systems intensified and penetrated the north Arabian Desert. These Mediterranean systems had a longer and more intense effect on the desert fringe closer to the Mediterranean and only rarely penetrated the Black Desert of Jawa. The results do not exclude some increase of rainfall which did not change water availability dramatically during the warm Holocene. The ancient Jawa city appears to have depended on technological ability to build elaborate runoff-collection systems, which became the prime condition for success.

Vaks, A., Bar-Matthews, M., Ayalon, A., Matthews, A., Halicz, L. and Frumkin, A., 2007, Desert speleothems reveal climatic window for African exodus of early modern humans, Geology v. 35:9, 831-834.

ABSTRACT

One of the first movements of early modern humans out of Africa occurred 130–100 thousand years ago (ka), when they migrated northward to the Levant region. The climatic conditions that accompanied this migration are still under debate. Using high-precision multicollector–inductively coupled plasma–mass spectrometry (MC-ICP-MS) U-Th methods, we dated carbonate cave deposits (speleothems) from the central and southern Negev Desert of Israel, located at the northeastern margin of the Saharan-Arabian Desert. Speleothems grow only when rainwater enters the unsaturated zone, and this study reveals that a major cluster of wet episodes (the last recorded in the area) occurred between 140 and 110 ka. This episodic wet period coincided with increased monsoonal precipitation in the southern parts of the Saharan- Arabian Desert. The disappearance at this time of the desert barrier between central Africa and the Levant, and particularly in the Sinai-Negev land bridge between Africa and Asia, would have created a climatic “window” for early modern human dispersion to the Levant.

Lisker, S., Porat, R., Davidovich, U., Eshel, H., Stein-Erik Lauritzen, S.E., Frumkin, A. 2007, Late Quaternary environmental and human events at En Gedi, reflected by the geology and archaeology of the Moringa Cave (Dead Sea area, Israel), Quaternary Research, v. 68, 203–212.

Abstract

The Moringa Cave within Pleistocene sediments in the En Gedi area of the Dead Sea Fault Escarpment contains a sequence of various Pleistocene lacustrine deposits associated with higher-than-today lake levels at the Dead Sea basin. In addition it contains Chalcolithic remains and 5th century BC burials attributed to the Persian period, cemented and covered by Late Holocene travertine flowstone. These deposits represent a chain of Late Pleistocene and Holocene interconnected environmental and human events, echoing broader scale regional and global climate events. A major shift between depositional environments is associated with the rapid fall of Lake Lisan level during the latest Pleistocene. This exposed the sediments, providing for cave formation processes sometime between the latest Pleistocene (ca. 15 ka) and the Middle Holocene (ca. 4500 BC), eventually leading to human use of the cave. The Chalcolithic use of the cave can be related to a relatively moist desert environment, probably related to a shift in the location of the northern boundary of the Saharo-Arabian desert belt. The travertine layer was U–Th dated 2.46± 0.10 to 2.10±0.04 ka, in agreement with the archaeological finds from the Persian period. Together with the inner consistency of the dating results, this strongly supports the reliability of the radiometric ages. The 2.46–2.10 ka travertine deposition within the presently dry cave suggests a higher

recharge of the Judean Desert aquifer, correlative to a rising Dead Sea towards the end of the 1st millennium BC. This suggests a relatively moist local and regional climate facilitating human habitation of the desert.

Karkanas, P., Shahack-Gross, R., Ayalon, A., Bar-Matthews, M., Barkai, R., Frumkin, A., Gopher, A., and Stiner, M. C.,2007, Evidence for habitual use of fire at the end of the Lower Paleolithic: Site formation processes at Qesem Cave, Israel: Journal of Human Evolution, 53, 197-212.

Abstract

The Amudian (late Lower Paleolithic) site of Qesem Cave in Israel represents one of the earliest examples of habitual use of fire by middle Pleistocene hominids. The Paleolithic layers in this cave were studied using a suite of mineralogical and chemical techniques and a contextual sedimentological analysis (i.e., micromorphology). We show that the lower ca. 3 m of the stratigraphic sequence are dominated by clastic sediments deposited within a closed karstic environment. The deposits were formed by small scale, concentrated mud slurries (infiltrated terra rosa soil) and debris flows. A few intervening lenses of mostly in situ burnt remains were also identified. The main part of the upper ca. 4.5 m consists of anthropogenic sediment with only moderate amounts of clastic geogenic inputs. The deposits are strongly cemented with calcite that precipitated from dripping water. The anthropogenic component is characterized by completely combusted, mostly reworked wood ash with only rare remnants of charred material. Micromorphological and isotopic evidence indicates recrystallization of the wood ash. Large quantities of burnt bone, defined by a combination of microscopic and macroscopic criteria, and moderately heated soil lumps are closely associated with the woodash remains. The frequent presence of microscopic calcified rootlets indicates that the upper sequence formed in the vicinity of the former cave entrance. Burnt remains in the sediments are associated with systematic blade production and faunas that are dominated by the remains of fallow deer. Use-wear damage on blades and blade tools in conjunction with numerous cut marks on bones indicate an emphasis on butchering and prey-defleshing activities in the vicinity of fireplaces.

Porat, R., Eshel, H., Frumkin, A., 2007. Finds from the Bar-Kochba revolt from two caves in Ein Gedi: Palestine Exploration Quarterly, 139, 1, 35–53

Abstract

Finds from two caves that were excavated in Ein Gedi in 2002 are described. Eleven bronze coins of the Bar-Kokhba Revolt, twelve arrowheads and fragments of two papyrus documents were recovered in the Har Yishay Cave, located along the northern slopes of Nahal David. A hoard of nine silver coins, including a Bar-Kokhba tetradrachm, were found in the Sabar Cave. This is the second Bar-Kokhba tetradrachm to have been found in the context of a scientifically controlled archaeological project. Along with it were six Roman dinars and two dinars overstruck by Bar Kokhba. From the evidence of one of the Bar Kokhba documents dated to the third year of the revolt, it is possible to estimate that when this hoard was deposited in the cave, the total value of the coins exceeded that of a house!

Weinberger, R., Begin, Z. B., Waldmann, N., Gardosh, M., Baer, G., Frumkin, A., and Wdowinski, S., 2006, Quaternary rise of the Sedom Diapir, Dead Sea basin, in Enzel, Y., Agnon, A., and Stein, M., eds., New frontiers in Dead Sea paleoenvironmental research, GSA Special Paper 401: Boulder, GSA, p. 33-51

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 signifi cant growth of the Sedom diapir may have initiated only after this thickness exceeded ~2400 m in the Late Pliocene. The formation of the caprock signifi es 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 δ13C. 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 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.

Frumkin, A., and Gvirtzman, H., 2006, Cross-formational rising groundwater at an artesian karstic basin: the Ayalon Saline Anomaly, Israel: Journal of Hydrology, v. 318, 316–333

Abstract

It is proposed that a geothermal artesian karstic system at the central part of the Yarkon–Taninim aquifer creates the ‘Ayalon Saline Anomaly’ (ASA), whose mechanism has been under debate for several decades. A 4-year-long detailed groundwater monitoring was carried out at 68 new shallow boreholes in the Ayalon region, accompanied by a comprehensive survey of karstic voids. Results indicate the rising of warm-brackish groundwater through highly permeable swarms of karstic shafts, serving as an outflow of the artesian geothermal system. The ASA area contains ‘hot spots’, where groundwater contrasts with ‘normal’ water hundreds of meters away. The ASA temperature reaches 30 8C (w5 8C warmer than its surroundings), chloride concentration reaches 528 mg/l (50–100 mg/l in the surrounding), H2S concentration reaches 5.6 mg/l (zero all around) and pH value is 7.0 (compared with 7.8 around). Subsequently, the hydrothermal water flows laterally of at the watertable horizon through horizontal conduits, mixing with ‘normal’ fresh water which had circulated at shallow depth. Following rainy seasons, maximal watertable rise is observed in the ASA compared to its surroundings. Regional hydrogeology considerations suggest that the replenishment area for the ASA water is at the Samaria Mountains, east of the ASA. The water circulates to a great depth while flowing westward, and a cross-formational upward flow is then favored close the upper sub-aquifer’s confinement border.

Frumkin, A., and Shimron, A., 2006, Tunnel engineering in the Iron Age: geoarchaeology of the Siloam Tunnel, Jerusalem: Journal of Archaeological Science, v. 33, 227-237

Abstract

The Siloam Tunnel (ST) is the best-identified biblical structure that can be entered today. We use geological, structural, and chemical features of ST and its internal deposits to show that it is an authentic engineering project, without any pre-existing natural conduit that could have guided its excavators. Radiometrically and historically dated to w700 BCE, ST

pinpoints the technological advance in leveling techniques that was essential for the construction of such a long tunnel without intermediate shafts. A combination of geological and archaeological evidence demonstrates that the circuitous route of ST and the final meeting of the two excavating teams are associated with continuous modifications of the plan to allow acoustic communication between hewers and the surface teams. Hydraulic plaster was applied throughout the tunnel in order to seal voids of dissolution and tectonic origin. Organic material accidentally entrapped in the plaster was carbon 14 dated, and speleothems were dated by U-Th, both corroborating the historic and epigraphic evidence ascribing the engineering advance in tunneling techniques to the Judahite King Hezekiah.

Vaks, A., Bar-Matthews, M., Ayalon, A., Matthews, A., Frumkin, A., Dayan, U., Halicz, L., Almogi-Labin, A., and Schilman, B., 2006, Paleoclimate and location of the border between Mediterranean climate region and the Saharo–Arabian Desert as revealed by speleothems from the northern Negev Desert, Israel: Earth and Planetary Science Letters, v. 249, p. 384–399.

Abstract

Speleothem bearing karstic caves of the northern Negev Desert, southern Israel, provides an ideal site for reconstructing the paleoclimate and paleo-location of the border between Mediterranean climate region and the Saharo–Arabian Desert. Major periods of speleothem deposition (representing humid periods) were determined by high resolution 230Th–U dating and corresponding studies of stable isotope compositionwere used to identify the source of rainfall during humid periods and the vegetation type.Major humid intervals occurred during glacials at 190–150 ka, 76–25 ka, 23–13 ka and interglacials at 200–190 ka, 137–123 ka and 84–77 ka. The dominant rainfall sourcewas the EasternMediterranean Sea, with a possible small contribution from southern tropical sources during the interglacial periods. When the interglacial interval rainfall was of Eastern Mediterranean origin, the minimum annual rainfall was 300–350 mm; approximately twice than of the present-day. Lowerminimum amounts of precipitation could have occurred during glacial periods, due to the cooler temperatures and reduced evaporation. Although during most of the humid periods the vegetation remained steppe withmixed C3+C4 vegetation,Mediterranean C3 type steppe-forest vegetation invaded southward for short periods, and the climate in the northern Negev became closer toMediterranean type than at present. The climate was similar to present, or even more arid, during intervals when speleothem deposition did not occur: 150–144 ka, 141–140 ka, 117–96 ka, 92–85 ka, 25–23 ka, and 13 ka–present-day. Precipitation increase occurred in the northern Negev during the interglacial monsoonal intensity maxima at 198 ka, 127 ka, 83 ka and glacial monsoonal maxima at 176 ka, 151 ka, 61 ka and 33 ka. However, during interglacial monsoonal maxima at 105 ka and 11 ka, the northern Negev was arid whereas during glacial monsoonal minima it was usually humid. This implies that there is not always synchroneity between monsoonal activity and humidity in the region. Oxygen isotopic values of the northern Negev speleothems are systematically lower than contemporaneous speleothems of central and northern Israel. This part is attributed to the increased rainout of the heavy isotopes byRayleigh fractionation processes, possibly due to the farther distance from the Mediterranean coast.

Frumkin, A. Fischhendler, I. 2005, Morphometry and distribution of isolated caves as a guide for phreatic and confined paleohydrological conditions, Geomorphology, v. 67 p. 457–471.

Abstract

Isolated caves are a special cave type common in most karst terrains, formed by prolonged slow water flow where aggressivity is locally boosted. The morphometry and distribution of isolated caves are used here to reconstruct the paleohydrology of a karstic mountain range. Within a homogenous karstic rock sequence, two main types of isolated caves are distinguished, and each is associated with a special hydrogeologic setting: maze caves form by rising water in the confined zone of the aquifer, under the Mt. Scopus Group (Israel) confinement, while chamber caves are formed in phreatic conditions, apparently by lateral flow mixing with a vadose input from above.

Peeri, S., Zebker, H. A., Ben-Avraham, Z., Frumkin, A., Hall, J. K., Spatially-resolved uplift rate of the Mount Sedom (Dead Sea) salt diapir, from InSAR observations. Israel Journal of Earth Sciences, v. 53, p. 99-106

Abstract

Mt. Sedom, a diapiric “salt wall” southwest of the Dead Sea, was formed by extrusion of salt layers through passages in overlying sediments. Here we present the spatially resolved uplift rate of the salt body diapir derived from spaceborne Interferometric Synthetic Aperture Radar (InSAR) observations. Although the average uplift rate has been estimated earlier, spatially resolved uplift was not available due to the paucity of uplift observations. We processed 13 interferograms (InSAR deformation images) spanning time periods ranging from 421 to 1949 days, and calculate the spatial distribution of uplift rate for the two blocks that make up Mt. Sedom. We find average uplift rates of 8.27 ± 0.28 mm/yr and 6.88 ± 0.31 mm/yr for the northern and the southern blocks, respectively. These results represent relatively high values when compared to others measured in salt diapirs around the world (excluding certain domes in Iran). The tectonic processes in the area may influence these relative high values, and the division of the diapir into two blocks.

Frumkin, A., and Stein, M., 2004, The Sahara - East Mediterranean dust and climate connection revealed by strontium and uranium isotopes in a Jerusalem speleothem: Earth and Planetary Science Letters, v. 217, p. 451-464.

Abstract

This paper explores the potential of Sr and U isotope systems in speleothems as tracers of eolian dust transport and hydrological conditions. The study focuses on a speleothem from Jerusalem spanning the past 220 kyr. This speleothem provides a precisely dated record of dust flux from the Sahara to the East Mediterranean. Enhanced dust flux and Terra Rossa soil development is reflected by elevated $^{87}Sr/^{86}Sr$ ratios in the speleothem (0.7082-6), while lower $^{87}Sr/^{86}Sr$ ratios (~0.7078) indicate higher contribution of the local bedrock due to low dust flux and low soil accumulation. The strontium isotope system in the speleothem is a robust monitor of the Sahara monsoon-modulated climate, since dust uptake is related to development or reduction in vegetation cover of Sahara soil.

The $[^{234}U/^{238}U]$ activity ratios in the speleothem range between 1.12 and 1.0. The high activity values may indicate selective removal of ^{234}U from the soil while the low values converge to the bedrock . The migration of ^{234}U to the cave reflects mainly the regional hydrological conditions that are modulated by the North Atlantic-Mediterranean climate system. Thus, the speleothem provides a combined record of the Monsoon - North Atlantic climatic systems. Long-term stability in glacial $^{87}Sr/^{86}Sr$ ratios (0.7083±1 over the past 220 kyr) suggests an overall similarity in eolian dust-sources, and uniformity in the synoptic conditions that dominate the dust storm tracks during glacial periods.

Frumkin, A., Shimron, A., and Rosenbaum, J., 2003, Radiometric dating of the Siloam Tunnel, Jerusalem: Nature, v. 425, p. 169-171.

Abstract

The historical credibility of Biblical texts is often debated when compared with Iron Age archaeological finds. Modern scientific methods may, in principle, be used to independently date structures that seem to be mentioned in the Biblical text, in order to evaluate its historical authenticity. In reality, however, this approach is extremely difficult because of poor archaeological preservation, identification uncertainty, scarcity of datable materials, and restricted scientific access into well-identified worship sites. Due to these problems, no well-identified Biblical structure has been radiometrically dated prior to the present study. Here we report radiocarbon and U-Th dating of the Siloam Tunnel (ST), proving its Iron Age II date (Fig. 1a); we conclude that the Biblical text presents an accurate historic record of ST construction. Being one of the longest ancient water tunnels lacking intermediate shafts, dating ST is a key in determining where and when this technological breakthrough took place. ST dating also refutes a claim that ST was constructed at the 2nd century BCE.

Barkai, R., Gopher, A., Lauritzen, S. E., and Frumkin, A., 2003, Uranium series dates from Qesem Cave, Israel, and the end of the Lower Palaeolithic: Nature, v. 423, p. 977-979.

Abstract

Israel is part of a geographical “out of Africa” corridor for human dispersals. An important event in these dispersals was the possible arrival of anatomically modern humans in the Levant during the late Middle Pleistocene[1,2,3]. In the Levant the Lower Paleolithic ends with the Acheulo-Yabrudian complex, characterized by striking technological developments [4,5] including the introduction of advanced technological innovations such as systematic blade production and the disappearance of hand-axes . These reflect new human perceptions and capabilities in lithic technology and tool function, as well as innovative human adaptation[6]. Qesem Cave, discovered in 2000, has a rich, well-preserved Acheulo-Yabrudian sequence holding great promise for providing new insights into the period. Here we report the dates of this cave obtained by U-series of speleothems and their implications. The results shed light on the temporal range of the Acheulo-Yabrudian and the end of the Lower Paleolithic, suggesting a long and unique cultural phase between the Lower Paleolithic Acheulian and the Middle Paleolithic Mousterian, starting well before 350 kyr and ending at ca. 200 kyr.

Vaks, A., Bar-Matthews, M., Ayalon, A., Schilman, B., Gilmour, M., Hawkesworth, C. J., Frumkin, A., Kaufman, A., and Matthews, A., 2003, Paleoclimate reconstruction based on the timing of speleothem growth, oxygen and carbon isotope composition from a cave located in the 'rain shadow', Israel: Quaternary Research, v. 59, p. 182-193.

Abstract

High-resolution $^{230}Th/^{234}U$ ages and $\delta^{18}O$ and $\delta^{13}C$ compositions of speleothems in Ma’ale Efrayim Cave located to the east of the central mountain ridge of Israel enable us to examine the nature of the rain shadow aridity during glacial and interglacial intervals. Speleothem growth occurred during marine glacial isotopic periods, with no growth during the two last marine isotope interglacial intervals and during the peak of the Last Glacial Maximum. This contrasts with speleothem growth in caves located on the western flank of the central mountain ridge, in the Eastern Mediterranean semiarid climatic zone, which continued throughout the last 240,000 yr. Thus, during glacial periods water reached both sides of the central mountain ridge. A comparison of the present-day rain and cave water isotopic compositions and amounts at the Ma’ale Efrayim Cave site with those on the western flank shows that evaporation and higher temperatures on the eastern flank are major influences on isotopic composition and the lack of rainfall. The $\delta^{18}O$ and $\delta^{13}C$ profiles of the speleothems deposited between 67,000 and 25,000 yr B.P. match the general trends of the isotopic profiles of Soreq Cave speleothems, suggesting a similar source (eastern Mediterranean Sea) and similar climatic conditions. Thus, during glacial periods the desert boundary effectively migrated further south or east from its present-day location on the eastern flank, whereas interglacial periods appear to have been similar to the present, with the desert boundary at the same position. The decrease in overall temperature and a consequent reduction in the evaporation to precipitation ratios on the eastern flank are viewed as the major factors controlling the decay of the rain shadow effect during glacial periods.

Frumkin, A., 2003, Sedom salt karst, Israel, *in* Gunn, J., ed., Encyclopedia of cave and karst science: London, Routledge, p. 643-645.

Mount Sedom is the best studied salt karst region, containing the largest known salt cave. It is also the lowest and one of the most arid karst regions worldwide†(annual precipitation c. 50 mm). It has been explored systematically since 1981.

The exposed head of a diapir, composed of Neogene salt beds, forms the elongated (11 by 1.5 km) ridge of Mount Sedom within the Dead Sea Transform (**Figure 1,2**). It rises from -400 m (below MSL) up to -160 m. The mean estimated diapir rising rate is about 6-7 mm year-1†(Frumkin, 1996).

Salt karst has developed in the upper part of the diapir, where salt beds are vertical or steeply inclined (**Figure 2**). They often yield under the shear stress induced by salt tectonics and become minor fault plains (Zak and Freund, 1980). Horizontal fissures are rarely found in Mount Sedom.

Before its subaerial extrusion, the top of the rising diapir suffered dissolution by ground-water. Residual, relatively insoluble anhydrite, shales and dolomite accumulated above the salt, forming an up to 50 m thick cap-rock (Zak and Bentor, 1968). The top of cap-rock is a roughly tabular desert surface

Some 107 caves have been explored in Mount Sedom with a total length of c. 20 km (**Figure 1**). The caves have formed during the Holocene; the oldest cave passage is ^{14}C dated to ~8000 calendar years BP (Frumkin et al., 1991). Dating was performed on wood twigs carried and deposited by cave streams. The lower level of the caves is carrying floodwater during infrequent rainfall events.

The flood water flows from surface runoff from many small (up to 0.7 km^2) ephemeral catchments, developed on the cap-rock. The flow is captured into fissures which enlarge to form shafts. Sodium chloride concentration in flood flow increases dramatically within the caves, from ~10 gram/liter at stream sinks up to 200-350 gram/liter (Frumkin, 1994). Most flood waters remain chemically aggressive while flowing rapidly within cave passages. Apart from dissolution, cave development is promoted by physical erosion attributed to fast-flowing water, cutting into the soft salt.

After a short inception period, salt caves develop mainly by open-channel flow. The cave retains a downstream slope, supporting gravitational sediment-rich flow. The larger caves consist of a vertical shaft at the sink point or close to it, and a salt passage draining the shaft.

Shafts with a surface catchment area <200-300 m^2 usually do not have a draining passage; the small discharge infiltrates in the bottom of the shaft towards the water table. The common passage in Mount Sedom caves is a vadose canyon. The passages develop along a joint, bedding plane or fault within the salt.

Young passages are often steep, incised in bedrock, and follow the initial fissure closely. Older passages are often more sinuous, moderately inclined (a few %), and their floor is shielded by alluvium. Some wide passages with highly developed meander notches are indicative of flow without much downcutting; lateral migration of meanders sometimes causes destruction of earlier canyon walls.

Downward development of passages is achieved either by incision of a passage floor or by a stream capture to a lower-level passage. The older caves in Mount Sedom have several tiered levels above the modern channel.

Cave passages are either ingrowing vadose canyons or wide low passages with flat ceilings and corrosion bevels, developed by paragenetic dissolution (Frumkin 1998). Some cross sections are deformed by Holocene tectonics.

The development of a cave profile and morphological features such as meanders and notches is sometimes constrained by hardly soluble layers (dolomite, shales, anhydrite) interbedded within the salt. Nickpoints in a passage profile are often associated with insoluble beds. Dolomite beds are the most prominent, as they are much more resistant to both dissolution and erosion, relative to the salt.

Many caves are integrated systems — they can be physically traversed along the full distance from sink to outlet (**Figure 3**). The largest ones, Malham Cave (the longest known salt cave; 5591 m long, 135 m deep) and Sedom Cave (1799 m long) drain to the south basin of the Dead Sea, the hydrologic base level of the region. They are branchwork caves, each

with several river passages joining undergroundÆ Residence time of flood water in these caves is short, measured in minutes up to a few hours in a single flow event. Integrated cave systems are developed along the margins of the rising diapir, where conditions are favorable: hydraulic gradients are high and fissures are long, open, and abundant because of lithostatic stress release.

Caves in the central portions of the mountain, terminating above the water table, appear to have no distinct outlet (**Figure 2**). These are referred to as 'inlet' caves. The downstream parts of inlet caves often contain silt and clay banks with no continuation of explorable passages. Water ponded in the bottom of these caves become saturated with salt within a few hours. This evidence suggests that the limit of exploration is also a hydraulic limit between two sequential modes of water flow: rapid turbulent floods prevailing from the sink to the cave bottom, and diffuse infiltration below the bottom of the explorable passage, down to the output boundary of†Mount Sedom. Three of the studied caves in northern Mount Sedom supported perennial brine ponds at least throughout the period 1984-1995. The ponds are perched some tens of m above the water table, and their level seems to be controlled by fissure width which decrease with depth. Water level in each lake also differs from the others by tens of meters. Both dissolution and precipitation features are observed on walls bordering ponds, as well as on cave walls where ponds have dried out. Horizontal notches indicate levels of aggressive water temporarily diluting the pond during floods. Large secondary halite crystals on some cave walls indicate supersaturation of the ponded water between successive floods. The ground plan of inlet caves range between three end members: elongated conduit, chamber and maze, depending on fissuring properties of the rock and the hydraulic head applied by flash floods.

Most integrated cave systems originated in the past as inlet caves, created by a capture of subaerial channel into a cap-rock fissure. Diversionary routes are common where earlier conduits are blocked by alluvium, until a connection is established with an output point and a stable condition is achieved in ground plan. If a connection to the output boundary is not established, the cave continues to evolve as an inlet cave.

Frumkin, A., and Elitzur, Y., 2002, Historic Dead Sea level fluctuations calibrated with geological and archaeological evidence: Quaternary Research, v. 57, p. 334-342.

Abstract

The Dead Sea, the Holocene terminal lake of the Jordan River catchment, has fluctuated during its history in response to climatic change. Biblical records, calibrated by radiocarbon-dated geological and archaeological evidence, reinforce and amplify the chronology of the lake-level fluctuations. There are three historically documented phases of the Dead Sea in the Biblical record: low lake levels c. 2000-1500 B.C.E. (Before Common Era); high lake levels c. 1500-1200 century B.C.E.; and low lake levels between c. 1000 and 700 B.C.E. The Biblical evidence indicate that during the dry periods the southern basin of the Dead Sea dried up, a fact that was not clear from the geological data.

Frumkin, A., and Elitzur, Y., 2001, The rise and fall of the Dead Sea: Biblical Archaeology Review, v. 27, no. 6, p. 42-50.

Abstract

The Dead Sea, the Holocene terminal lake of the Jordan River catchment, has fluctuated during its history in response to climatic change. Biblical records, calibrated by radiocarbon-dated geological and archaeological evidence, reinforce and amplify the chronology of the lake-level fluctuations. There are three historically documented phases of the Dead Sea in the Biblical record: low lake levels c. 2000-1500 B.C.E. (Before Common Era); high lake levels c. 1500-1200 century B.C.E.; and low lake levels between c. 1000 and 700 B.C.E. The Biblical evidence indicate that during the dry periods the southern basin of the Dead Sea dried up, a fact that was not clear from the geological data.

Frumkin, A., Kadan, G., Enzel, Y., and Eyal, Y., 2001, Radiocarbon chronology of the Holocene Dead Sea: Attempting a regional correlation: Radiocarbon, v. 43, no. 2C, p. 1179-1190.

Abstract

Sedimentary and geomorphic sequences from the Dead Sea region, Israel, are compared by correlation of more than 50 radiocarbon ages which provide the chronology of the region during the Holocene.

The chronology allows us to detect basin-scale events which are hard to detect in single-site records. We show the possible use of such correlations for paleoclimate reconstruction, indicated by the Dead Sea level. The Holocene Dead Sea apparently reached a relatively high level at the mid-Holocene around 4400 BP and 3000 cal BCE. Around 4000 BP and 2500 cal BCE it fell sharply and later fluctuated close to early 20th century levels.

The radiocarbon-based correlation is also used to estimate the rising rates of Mount Sedom salt diapir. The most probable average diapir rising rate is from 5 to 7 mm/yr.

Frumkin, A., and Raz, E., 2001, Collapse and subsidence associated with salt karstification along the Dead sea: Carbonates and Evaporites, v. 16, no. 2, p. 117-130.

Abstract

Two types of sinkholes are observed along the Dead Sea shore, Israel. The first is associated with vadose dissolution in Mount Sedom salt diapir. The second is associated with dissolution under the watertable along the retreating Dead Sea shore. The Dead Sea level is falling dramatically, mainly because of human activity. Simultaneously, the lake shores suffer tremendous impact since the late 1980s: The ground is collapsing and subsiding in hundreds of points along the lake, with people, roads and property being swallowed in the more catastrophic events. The collapse is believed to result from dissolution of salt by aggressive groundwater, following the retreat of Dead Sea level and the groundwater halocline. Geological evidence suggests that a previous major lake level fall occurred *naturally* ~2000 BCE. This may provide a new explanation for a curious historical-geological phrase in the book of Genesis, suggested to record formation of collapse sinkholes which occurred in response to the historic falling lake level, associated with climatic desiccation.

Frumkin, A., 2001, Karst and caves of Israel, *in* Juberthie, C., and Decu, V., eds., Encyclopaedia Biospeleologica: Moulis, Société de Biospéologie, p. 1840-1849.

Israel displays a gradient of karst features from the intensive karstification of Lebanon in the north to practically no karst in Elat region at the southern Negev desert (Gerson, 1976).

This is attributed mainly to the climatological gradient from alpine-Mediterranean climate in the Lebanon - Hermon mountains in the north, with precipitation >1000 mm/year, to the extremely arid southern Negev, with <50 mm/year. Another factor is the southward decrease in carbonates/clastics ratio of the phanerozoic stratigraphic section, due to the increasing distance from the Tethys Sea which deposited the significant carbonates.

Carbonate rocks outcrop in some 75% of the hilly regions of Israel. They are predominantly of Jurassic to Eocene age. However, much of the carbonates contain marls which inhibit extensive karst development, promoting the dominance of fluviokarst features. Another inhibiting factor is the abundance of faults in the Hermon, Galil and Shomeron regions. The faults are thought to constrain the temporal and spatial continuous underground flow, limiting the development of large caves in these regions.

Most limestone caves are relict phreatic conduits and voids, which do not show any genetic relation to subaerial topography. Today these caves are either dry or experience vadose dripwater. These caves have possibly developed under moister conditions than predominate today. Some of them have been sealed from the surface until opened by recent construction activity. They may contain valuable paleoclimatic records (Frumkin, et al., 1994).

Vadose caves are also common, and typically experience some water flow and active dissolution during the rainy season. These are mostly composed of vertical shafts with rare horizontal sections.

The unique rock salt karst of Mount Sedom exhibits the largest salt caves known in the world.

Some sea caves, attributed mainly to wave action with limited dissolution appear in the 'Kurkar' sandstone ridge along the Mediterranean coast.

Paleokarst is common in the stratigraphic section, and is probably related to humid paleoclimates.

Israel is especially rich in man made caves sustaining abundant fauna, but are beyond the scope of this review.

The major karst regions of Israel are briefly reviewed below.

1. Hermon

The higher part of Mount Hermon, on the northern end of Israel, displays distinctive alpine karst features. The elevation within Israel's border reaches 2220 m, and snow covers the higher parts several months a year. Massive Jurassic limestone, several hundred m thick, gives rise to developed holokarst with doline fields and poljes. However, the intensively fractured rock limit the number and extent of large caves. Only two caves are known above 2000 m MSL (Me'arat Pitulim and Me'arat Mizpe Shelagim), both vadose and only tens of meters long. The temperature in depth of these caves does not exceed a few degrees C even in summer, so they form a unique ecosystem in Israel. Known caves at lower elevations on Mount Hermon flanks are not larger than tens of meters too, but they include phreatic features, indicating longer evolution period.

The basaltic Ramat Hagolan, south of Mount Hermon exhibits some pseudokarst features (Inbar, 1984).

2. Galil

The Galil mountains is the major karst region of northern Israel, developed on Cretaceous to Eocene carbonates. Mediterranean fluviokarst is developed across the whole region, while the upper Galil, especially around Mount Meron, displays some mature karstified areas (Gerson, 1974). Of these, Mount Peqi'in is notable for its developed doline karst landforms with highest density of limestone vadose shafts in Israel. Two ponors drain large karst areas: Me'arat Pa'ar, in the bottom of a large doline, and Zomet Meron sink. The largest caves of the Galil (Fig. 1) are (1) Me'arat Sharakh; (2) Me'arat Alma - a tectonic cave altered by phreatic dissolution; (3) Me'arat Jermak - a vertical vadose shaft system, the deepest in Israel; (4) Me'arat Bereniqi - a relict phreatic maze.

The Galil is the only part of Israel where diving is needed to explore some caves. Me'arat En Nur (spring of Tabgha) is an underwater resurgence cave on the northwest coast of Yam Kinneret. Other short spring caves with perennial flow are Enot Enan, En Tamir and En Amal. Sea caves with dissolution features are developed in Rosh-Haniqra.

3. Karmel (Mt. Carmel)

The Karmel ridge is built mainly of Upper Cretaceous carbonates.

Fluviokarst is common, while karstic closed depressions are rare. A major active fault along the north-eastern edge of the ridge seems to inhibit karst development on this side. Relict phreatic caves are common mainly along the western border of the ridge, while vadose caves are less common. The longest cave is Me'arat Ornit - a dry phreatic maze.

4. Shomeron

Most karst landforms in Shomeron appear on Cretaceous limestone and dolomite. Western Shomeron is rich in small caves with relict phreatic and active vadose features. The largest cave is Me'arat Nahal Qana - a tectonic maze with a phreatic chamber (Frumkin, in press).

The Ram'alla anticline at eastern Shomeron is poor in large caves in its northern part, where it is dissected by large transversal faults. However, large caves do appear on its southern part, which is structurally similar to the Yehuda mountains. Of special interest is Nahal Delaya, where three large caves are grouped together (Frumkin, 1991).

Few caves are known across the Eocene carbonates of the northern Shomeron syncline, although it serves as a major karst aquifer of Bet-She'an valley and Shekhem region. This region displays the largest tectonokarst feature in Israel - the Sanur polje.

The limited outcrop of Jurassic limestone display extensive karren features, but no caves. Karst landforms appear rarely in Neogene conglomerates of eastern Shomeron.

5. Yehuda

Karst features appear here on Cretaceous to Eocene carbonates Much of the upper erosion surface of Yehuda Mountains was formed by karst denudation (Frumkin, 1993) . Fluviokarst is most common, but north of Yerushalaim there are some areas of internal karst drainage, and also a doline field with 12 known vadose shaft systems (Frumkin, 1986). Lack of major faults has promoted the development of long and stable subsurface flow routes in the phreatic zone, allowing the development of the largest and most abundant limestone caves in Israel. The known phreatic caves are relict, sometimes forming three dimensional maze, such as Me'arat Hariton - the longest limestone cave in Israel, with some 4 km of mapped passages. Most large caves (Makukh, Hameraglim, El-Gai, Masaia, Pitria, Hariton, Qneitra) appear in massive Turonian limestone along the eastern monocline of Hebron anticline. The longest cave in the western monocline is Me'arat Tur Safa, near Hebron. The most studied cave in Israel is probably Me'arat Soreq (Bar-Matthews, et al., 1991; Even, et al., 1986)). This show cave is profoundly decorated with speleothems.

Natural caves in chalk are relatively rare. The longest is Me'arat Niqbot Hamaim in the Eocene chalk of Hashefela region (Frumkin, 1990). The largest limestone chamber in Israel (200x100 m) is Me'arat Atarot, in northern Yerushalaim.

6. Midbar Yehuda - Negev deserts

This region is arid, with precipitation lower than 200 mm/year. Therefore active karst processes are mostly limited to the micro scale.

Midbar Yehuda is a rain-shadow desert east of Yehuda mountains. The mountains (precipitation of up to 600 mm/year) are the input zone of groundwater discharging along Yam Hamelah. Such circulation has probably formed the relict phreatic caves found in Turonian limestone west of Yam Hamelah. The larger caves are Me'arat Ha'igrot, Qanna'im, Kidod and Zavoa.

Unlike Midbar Yehuda, the Negev Desert is part of the global Saharan arid belt. Large caves are rare, although carbonate rocks are common. Water was probably insufficient for karst development even during humid phases of the Pleistocene. The Largest cave is Me'arat Ashalim in the northern Negev - a ramiform relict system in Turonian limestone. Small caves in Ma'ale Hameshar are attributed to deep waters rising along faults. Karstic caves are not known in the extremely arid southern Negev.

Frumkin, A., 2001, The Cave of the Letters Sediments — Indication of an Early Phase of the Dead Sea Depression?

: Journal of Geology, v. 109, 1.

Abstract

The highest aquatic sediments along the shoulders of the Dead Sea depression have been found in the Cave of the Letters, Nahal Hever, Israel. The cave has acted as a sediment trap, preserving autogenic dolomite and detritic deposits. The dolomitic sediment may correlate with late Miocene dolomites within the rift valley. The morphostratigraphic setting of the sediment implies deposition within an early topographic low which existed in the Dead Sea region since ~10 to 7 Ma ago.

Frumkin, A., Ford, D. C. and Schwarcz, H. P., 2000, Paleoclimate and vegetation of the last glacial cycles in Jerusalem from a speleothem record: Global Biogeochemical Cycles, v. 14, 3, p. 863-870

Abstract

A speleothem isotopic record taken from Jerusalem is used to reconstruct regional climate over the last 170,000 yr. Glacial periods in Jerusalem were generally cooler and wetter than the present climate. Stage 5e in the desert margin of Jerusalem was extremely unstable, dry and warm, and instability persisted throughout the transition to glacial conditions. Climate after stage 5e became gradually cooler and wetter over a 20,000 yr interval and did not recover to interglacial conditions in stage 5c and 5a. $\delta^{13}C$ varied by up to 12‰, from glacial (stage 6, 4-2) values of -10 to -12‰ that reflect dense C_3 vegetation above the studied cave, up to 0‰ in early stage 5 when there was probably complete loss of vegetation. The climatic instability during interglacial periods is much larger than during glacial periods, and glacial/interglacial transitions do not behave the same in each climatic cycle in this region.

Frumkin, A., 2000, in: Klimchouk, A. B., ed., Speleogenesis — the Evolution of Karst Aquifers: U. S. National Speleological Society, p.169, 443-451.

Abstracts

Dissolution of salt

Halite, the main mineral of salt, dissolves physically, dissociating to Na^+ and Cl^-. Special features such as density stratification may arise from the high solubility, 360 gl^{-1}, while the rapid kinetics promotes intense karstification in short time scales. Salt water enhances limestone dissolution by the ionic strength effect. Other soluble salts reduce halite solubility through the common ion effect.

Speleogenesis in salts

Salt dissolution often occurs in deeply buried beds, where caves are hardly known. Caves are normally formed under selective dissolution along flow routes, rather than complete dissolution of the bulk salt mass. Most salt caves are found in diapirs, where open fissures drain meteoric water, rapidly enlarging to form vadose caves. Salt caves develop faster than other cave types, allowing their use as a natural laboratory for speleogenesis. Salt karst terrains exist mainly in arid climates where rock salt outcrops may escape complete destruction by dissolution. Known salt caves are mostly of Holocene age, while older ones are gradually destroyed by dissolution and collapse.

Speleogenesis in the Mount Sedom area, Israel

Mount Sedom salt diapir, with some 20 km of salt caves, is the most studied salt caves site. Its vadose caves are formed by captured ephemeral streams. Cave profiles are adjusted to base level, allowing reconstruction of the evolutional history of the region. Some 57% of Mount Sedom surface area is drained by the underground karst system. Waters in cave conduits do not reach saturation during flood flow, unless the water is ponded for at least several hours. Common cave features are vertical shafts, close to the cave inlet, and sub-horizontal passages,

leading to outlets at base level. Where no fissure connects the inlet with the margins of the mountain, an inlet cave is formed, capable of absorbing the flood discharge in a terminal pond. Water and solutes escape from the pond by slow seepage through narrow fissures to a regional aquifer.

Frumkin, A., 1999, Interaction between karst, water, and agriculture over the climatic gradient of Israel: International Journal of Speleology, v. 28B, 1, p. 99-110

ABSTRACT

The dry climate of Israel and the karstic nature of its rocks have imposed human innovation for utilization of water resources and agriculture. Large perennial karst springs are available only in the lowlands, but sophisticated water supply systems were built both in the lowland and highland regions. Marl layers interbedded within carbonates give rise to local perched springs and allow terrace construction. Deforestation has taken place for some 4000 years, causing intense soil erosion, but terraces have reduced this impact.

Frumkin, A., Ford, D. C. and Schwarcz, H. P., 1999, Continental oxygen isotopic record of the last 170,000 years in Jerusalem: Quaternary Research, v. 51, 3, p. 317-327.

Abstract

A long radiometrically dated oxygen isotopic record of continental climatic variations since the previous glacial period, was obtained from a stalagmite deposited in a sealed cave in Jerusalem. This record shows that speleothems have the potential of assigning dates to long and short-term climatic events, with possible refining of Milankovitch tuning of ice and marine records which are not datable themselves. Short-term (~1000 yr) events are very significant in the region, reaching ~50% of glacial/interglacial fluctuations. The Mediterranean Sea is shown to have been the most probable source of local precipitation throughout the last glacial cycle.

Frumkin, A., Carmi, I., Gopher, A., Tsuk, T., Ford, D. C. and Schwarcz, H. P., 1999, Holocene millenial-scale climatic cycle from Nahal Qanah Cave speleothem, Israel: The Holocene, v. 9, 6, p. 677-682.

Abstract

Nahal Qanah Cave, located in the east-Mediterranean region, has been inhabited by humans during several periods of the Holocene. These well-dated cultures are used here to establish the age of a speleothem growing over archaeological remains. $\delta^{18}O$ and $\delta^{13}C$ of a stalagmite through the last 6000 years display a 1-2 thousand years cycle. Depleted $\delta^{18}O$ and $\delta^{13}C$ values correlate well with high Dead Sea levels and increased arboreal pollen, suggesting common climatic control affecting the entire region.

Frumkin, A., 1998, Salt cave cross sections and their paleoenvironmental implications: Geomorphology, v. 23, p. 183-191.

Abstract

Salt caves respond rapidly to environmental changes. Direct measurement and ^{14}C dating show that complex cross sections may develop in a few hundred years. Two basic forms are discussed: (1) ingrowing vadose canyons where

changing width may correspond to changing discharge; (2) wide low passages with flat ceiling, developed by upward dissolution, which may indicate rising base level. Some cross sections are deformed by Holocene tectonics.

Frumkin, A., Shimron, A. E. and Miron, Y., 1998, Karst morphology across a steep climatic gradient, southern Mount Hermon, Israel: Zeitschrift für Geomorphologie Supplementband, v. 109, p. 23-40.

Abstract
The southern slopes of Mount Hermon display a multiphase karst system developed over a climatic and topographic gradient. The important factors are certain geologic features, altitude defining the climatic belts, the local slope gradient and the paleohydrological evolutionary history of the mountain. Doline density and cave depth tend to increase with altitude. Active vadose caves draining dolines are more common at the upper, alpine zone, while ancient phreatic caves appear in the lower altitude slopes. Intense fissuring of the authigenic karst surface favors diffuse seepage over concentrated flow, restricting conduit size.

Frumkin, A., 1997, The Holocene history of the Dead Sea levels: in Ben-Avraham, Z., Gat, Y. and Niemi, T. M., eds., The Dead Sea, the lake and its setting: Oxford, Oxford University Press, p. 237-248.

Abstract

The Dead Sea, as a terminal lake in an arid environment, may serve as an indicator to precipitation/evaporation ratio in its catchment throughout the Holocene. The Holocene Dead Sea level is reconstructed using the elevations of corresponding cave levels in Mount Sedom salt diapir. Thirty three 14C dates of wood fragments embedded in cave flood sediments provide the time frame. A gradual lowering of Dead Sea level is observed, with ten stages of fluctuation. The last major high level stage occurred from ~4200 to 2300 B.C.E, after which a major desiccation occurred. A good correlation exists between the lake level curve, Dead Sea sediments and pollen, as well as other evidence from the Dead Sea area. A fair correlation with lakes in eastern and northern Africa suggests a monsoonal climate influence during the first half of the Holocene.

Frumkin, A., 1996, Ariel Cave, Israel, Survey and ground penetrating radar study (in Hebrew, English abstract): in Eshel, Y., eds., Judea and Samaria research studies, 6'th annual meeting, Ariel, The College of Judea and Samaria, p. 321-328.

Abstract

A phreatic chamber cave, 26x17x15 m in size was truncated by construction works in Ari'el, western Samaria. The cave probably developed below the regional water table, prior to the Quaternary uplift of the region which drained the cave. A geodetic survey of the cave interior combined with ground penetrating radar sections indicate that the cave chamber was larger in its geologic history, becoming gradually filled by breakdown debris, speleothems and Terra-Rosa clays.

Frumkin, A., 1996, Uplift rate relative to base level of a salt diapir (Dead Sea, Israel), as indicated by cave levels: in Alsop, I., Blundell, D. and Davison, I., eds., Salt Tectonics, Special Publication no. 100: London, Geological Society, p. 41-47.

Abstract

Rapid downcutting rates in the extremely soluble salt of Sedom diapir allow cave channels to become rapidly graded with respect to base level . Diapir uplift leaves the older passages high and dry above present base level. Dating these passages by 14C allows us to estimate diapir uplift rates, taking into account previous Dead Sea levels. Maximum mean Holocene uplift rates are 6-7 mm/y along the eastern fault of Mount Sedom.

Frumkin, A., 1996, Structure of northern Mount Sedom salt diapir (Israel) from cave evidence and surface morphology: Israel Journal of Earth Sciences, v. 45, p. 73-80.

Abstract

Mount Sedom salt diapir, at the south-western edge of the Dead Sea, is covered by a residual caprock, concealing its internal structure. Internal structure observed within karstic caves is correlated here to surface lineaments on top of the caprock. The structural evidence suggests that the northern part of the diapir consists of two salt walls rising from the east and the west. The border between the two walls is observed in caves along the northwestern part of the mountain. The layers are highly deformed along this border, while on both limbs the beds are relatively undeformed, dipping in different directions. The eastern limb comprises most of the width of the elongated northern part of the diapir.

Frumkin, A., 1996, Determining the exposure age of a karst landscape: Quaternary Research, v. 46, p. 99-106.

Abstract

An extensive salt karst system has developed in Mount Sedom salt diapir, Israel, during the Holocene. Multi-level vadose caves were 14C dated using wood fragments embedded in alluvial deposits. The oldest date of each cave is used to constrain the age of the salt exposure. The upper portion of the southeastern escarpment was the first to rise above base level ~7100 yr B.P. Caves in the surrounding area indicate gradual landscape exposure around this initial karstified area between 7000 and 4000 yr B.P. The northern part of the mountain experienced a similar exposure history, lagging some 3000 yr after the southern part. This lag may be attributed to the narrow width of the diapir in the north, which increases viscous drag at the borders of the rising diapir.

Frumkin, A. and Ford, D. C., 1995, Rapid entrenchment of stream profiles in the salt caves of Mount Sedom, Israel: Earth Surface Processes and Landforms, v. 20, p. 139-152.

Abstract

Rock salt is approximately 1000 times more soluble than limestone and thus displays high rates of geomorphic evolution. Cave stream channel profiles and downcutting rates were studied in the Mount Sedom salt diapir, Dead Sea rift valley, Israel. Although the area is very arid (mean annual rainfall ^{a} 50 mm), the diapir contains extensive karst systems of Holocene age. In the standard cave profile a vertical shaft at the upstream end diverts water from a surface channel in anhydrite or clastic cap rocks into the subsurface route in the salt. Mass balance calculations in a sample cave passage yielded downcutting rates of 0.2 mm/sec during peak flood conditions, or about eight orders of magnitude higher than reported rates in any limestone cave streams. However, in the arid climate of Mount Sedom floods have a low recurrence interval with the consequence that long term mean downcutting rates are lower: an average rate of 8.8 mm/y was measured for the period, 1986-1991, in the same sample passage. Quite independently, long term mean rates of 6.2 mm/y are deduced from 14C ages of drift wood found in upper levels of twelve cave passages. These are at least three orders of magnitude higher than rates established for limestone caves. Salt cave passages develop in two main stages: (I) an early stage characterized by high downcutting rates into the rock salt bed, and steep passage gradients; (II) a mature stage characterized by lower downcutting rates, with establishment of a sub-horizontal stream bed armored with alluvial detritus.

In this mature stage downcutting rates are controlled by the uplift rate of the Mt. Sedom diapir and changes of the level of the Dead Sea. Passages may also aggrade. These fast-developing salt stream channels serve as full-scale models for slower developing systems such as limestone canyons.

Frumkin, A., 1994, Hydrology and denudation rates of halite karst: Journal of Hydrology, v. 162, p. 171-189.

Abstract

Salt karst terrains exist mainly in arid climates where rock salt outcrops may escape complete destruction by dissolution. Such is the case with Mount Sedom, on the southwestern shore of the Dead Sea, one of the most arid parts of Israel. Many small catchments developed over the relatively insoluble cap rock which overlies the highly soluble rock salt. The catchments were surveyed and classified. Some 57% of the surface area is drained by an underground karst system. Water samples from different points in the system were analyzed, and water development was inferred. Waters in cave conduits do not reach saturation during flood flow, unless the water is ponded for at least several hours. Based on the available evidence, regional karst denudation is tentatively estimated to be about 0.5-0.75 mm/year, occurring mainly within the rock salt.

Frumkin, A., 1994, Operating an experimental catchment in an arid karst environment: in Pulido-Bosch, J. R., Fagundo, J. E. and Rodriguez, R., eds., El karst y los acuiferos Karsticos: Granada, Universidad de Granada, p. 269-278.

Abstract

During the years 1986-1991 an experimental catchment area was operated for a karst study in the Mount Sedom salt diapir, Israel. Interim results and methodologies are discussed, suggesting ways for operating observation networks in environments with long dry periods between floods and where there are high concentrations of suspended load.

Frumkin, A., 1994, Morphology and development of salt caves: Journal of caves and karst studies (NSS Bulletin), v. 56, p. 82-95.

Abstract

Morphology and origin of salt caves are discussed, based on a study of 105 caves in Mount Sedom salt diapir, Israel. High solubility of rock salt has favoured the development of allogenic caves under arid climate. Caves along the margins of the mountains are integrated systems with open outlets at base level. Central caves lack such an outlet, discharging slowly through narrow fissures to a regional aquifer. Cave profiles are adjusted to base level, allowing reconstruction of the evolutional history of the region.

Frumkin, A., Carmi, I., Zak, I. and Magaritz, M., 1994, Middle Holocene environmental change determined from the salt caves of Mount Sedom, Israel: in Bar-Yosef, O. and Kra, R., eds., Late Quaternary chronology and paleoclimates of the eastern Mediterranean: Tucson, The University of Arizona, p. 315-322.

Abstract

Paleoclimatic sequence for the Middle Holocene was constructed, based on Mount Sedom salt caves, and other evidence. Mount Sedom is a salt diapir, on the southwestern shore of the Dead Sea, which has been rising above the local base level throughout the Holocene. Allogenic karst development has kept pace with the rising, forming vadose caves. Wood fragments found embedded in flood sediments that were deposited in sub-horizontal cave passages yielded 14C ages from 7090 to 200 YBP. The paleoclimatic sequence is based on parameters that include: relative abundance of plant types or floral communities, the elevations of the corresponding relict cave passages and the ratio of their width to present passage width. Moister climatic stages are indicated by relatively abundant wood remains, by wide cave passages and by higher-level outlets, indicating high Dead Sea levels. Arid periods are marked by a scarcity of wood remains, by narrow cave passages and by low-level outlets. The results were correlated to other middle-Holocene evidence and temporal settlement changes. The Early Bronze period in Israel was the moistest period during the last 6000 years and as such it encouraged cultural development. It was followed by a considerable desiccation that caused a cultural deterioration.

Frumkin, A., Schwarcz, H. P. and Ford, D. C., 1994, Evidence for Isotopic equilibrium in stalagmites from caves in a dry region: Jerusalem, Israel: Israel Journal of Earth Sciences, v. 43, 3-4, p. 221-230.

Abstract

Paleoclimatic inference from stable isotopes of cave deposits is possible where the deposition occurred under isotopic equilibrium. Seven stalagmites from three caves in the Jerusalem region are tested for equilibrium deposition, by determining d18O and d13C along growth layers. The heavy isotopes are rarely enriched and there is hardly any correlation between d18O and d13C along the flow line. This indicates that equilibrium deposition has been common in the studied caves which sustained high humidity and scarcely any air movement as they lacked natural entrances.

Frumkin, A., 1993, Karst origin of the upper erosion surface in the Northern Judean Mountains, Israel: Israel Journal of Earth Sciences, v. 41, p. 169-176.

Abstract

The upper erosion surface in the northern Judean Mountains is actively karstified, in the vadose zone and on the surface. The karst valleys become gradually covered with Terra Rossa which inhibits further denudation underneath the impermeable cover. Higher solution rates in the elevated areas keep the erosion surface relatively flat. The main characteristics of the area which dominate karst processes are fissured carbonate rocks with some insolubles and aeolian contribution, non arid climate and moderate relief. The erosion surface developed probably since the Oligocene regression. The Pleistocene uplift of the mountain backbone increased the relief and reduced the area of the karst plateau.

Frumkin, A., Magaritz, M., Carmi, I. and Zak, I., 1991, The Holocene climatic record of the salt caves of Mount Sedom, Israel: The Holocene, v. 1, 3, p. 191-200.

Abstract

Mount Sedom is a salt diapir, on the southwestern shore of the Dead Sea, which has been rising above the local base level throughout the Holocene. Karst development within the salt body has kept pace with the rising, forming sub-horizontal cave passages with vertical shafts. Wood fragments found embedded in flood sediments that were deposited in the cave passages yielded 14C ages ranging from ca. 7100 to 200 YBP. A paleoclimatic sequence was constructed, based on parameters that include: relative abundance of plant types or floral communities, the elevations of the corresponding cave passages and the ratio of their width to present passage width. The results were correlated to the Holocene sedimentary sequence of the Dead Sea Basin, and other features associated with shifting lake levels. Moister climatic stages are

indicated by relatively abundant wood remains, by wide cave passages and by elevated outlets, indicating high Dead Sea level. Arid periods are marked by a scarcity of wood remains, by narrow cave passages and by low-level outlets. The Holocene sequence of Mount Sedom is subdivided into ten climatic stages: A moist stage in the early Holocene, older than 7000 YBP, and nine subsequent stages of drier climate, fluctuating between conditions that are somewhat drier, up to somewhat moister than those of today. The Dead Sea Level dropped from ca. -300 MSL during the early moist period to -400 MSL or lower during the subsequent arid periods.