COBISS: 1.01

LAYLA LAKES, SAUDI ARABIA: THE WORLD-WIDE LARGEST LACUSTRINE GYPSUM TUFAS

JEZERA LAYLA V SAUDSKI ARABIJI: NAJOBSEŽNEJŠE PODROČJE JEZERSKEGA SADRINEGA TUFA NA SVETU

Stephan KEMPE[1] & Heiko DIRKS[2]

Abstract UDC 911.2(532):553.556

Stephan Kempe & Heiko Dirks: Layla Lakes, Saudi Arabia: The world-wide largest lacustrine gypsum tufas

Throughout the center of Saudi Arabia the anhydrite upper Jurassic Heeth formation can be followed N to S. Locally it is punctured by hypogene karst sinkholes. The most prominent are the former Layla Lakes at 22.17°N 46.70°E. The lakes (17 originally) have been drained in the late 1980's, revealing 19 sinkholes, some of them composites of several subsidence centers. The largest is 1.1 km long, 0.4 km wide and about 40 m deep. Others are less than 10 m across and rather recent. The bottom of the former lakes and the flats around them are composed of thick layers of fine-grained lake chalks. The most striking feature of these sinkholes is the several meters thick tufa covering the vertical walls of the sinkholes. It formed subaqueous and is entirely composed of gypsum. Morphologically the tufa displays thick bulbous forms at the bottom changing to conical forms at middle depth to gour-, gutter-, or shovel-like forms near to the former lake surface. The mineralogy and morphology of this tufa appear to be singular world-wide.

Key words: Layla Lakes, Saudi Arabia, Heeth Formation, hypogene karst, sinkholes, tufa, gypsum tufa, paleolakes.

Izvleček UDK 911.2(532):553.556

Stephan Kempe & Heiko Dirks: Jezera Layla v Saudski Arabiji: najobsežnejše področje jezerskega sadrinega tufa na svetu

Skozi vso osrednjo Saudsko Arabijo, od severa proti jugu, je mogoče slediti zgornjejurski Heeth formaciji. Lokalno jo prekinjajo hipogene vrtače. Najpomembnejša so nekdanja jezera Layla na 22,170 severne zemljepisne širine in 46,700 vzhodne zemljepisne dolžine. Jezera (prvotnih 17) so bila v 80-tih letih prejšnjega stoletja izpraznjena in pokazalo se je 19 vrtač. Nekatere sestavlja več lokalnih področij pogrezanja. Največja vrtača je 1,1 km dolga, 0,4 km široka in okoli 40 m globoka. Ostale imajo manj kot 10 m premera in so precej mlajše. Dna nekdanjih jezer in uravnave okoli njih sestavljajo debele plasti drobnozrnate jezerske krede. Pri teh vrtačah najbolj presenečajo več metrov debele plasti oborine sadre, ki prekrivajo stene vrtač in so nastale pod vodo. V spodnjem delu je v obliki debelih gomoljev, ki v srednjem delu dobivajo konično obliko, proti vrhu, to je proti nekdanji jezerski gladini, pa prehajajo v ponvaste, žlebaste in lopataste oblike. Mineralogija in morfologija teh oborin sta edinstveni v svetovnem merilu.

Ključne besede: Layla jezera, Saudska Arabija, Heeth formacija, hipogeni kras, vrtače, lehnjak, sadra, sadrna oborina, nekdanja jezera.

INTRODUCTION

The Arabian plate is composed of crystalline basement in the west and of eastward dipping Phanerozoic strata in the east. In the center of the Kingdom of Saudi Arabia (KSA), a band of Jurassic and Cretaceous sediments crop out running nearly N-S throughout the entire country. Prominent escarpments are formed by middle Jurassic and lower Cretaceous limestone. The N-S extending plain in between the escarpments is partly formed by the upper Jurassic Heeth (or Hith) formation composed of a >150 m thick sequence of laminated and autobrecciated anhydrite forms a N-S extending plain. On it most of the inner-KSA cities are situated, including Riyadh, the

[1] Institut für Angewandte Geowissenschaften, Technische Universität Darmstadt, Schnittspahnstraße 9, D-64287 Darmstadt, kempe@geo.tu-darmstadt.de

[2] GTZ International Services, Riyadh, heiko.dirks@gtzdco-ksa.com

Received/Prejeto: 21.03.2008

capital of KSA with four million inhabitants. This band of anhydrite can be followed on satellite images, such as those provided by Google Earth, as a string of bright, almost white areas. Ground inspection showed that these areas are marked by gypsum caliche, presumably formed by ascending waters that left gypsum upon evaporation.

The Heeth Formation is an aquitard, below which fossil groundwater is trapped that is extensively used for domestic and agricultural purposes. Consequently the ground water level has dropped in many areas by >100 m. This is best illustrated by the history of the deepest cave in KSA, Ain Heeth, a >160 m deep cave at the type location of the Heeth Formation near the town of Al-Kharj ca. 60 km south of Riyadh. The cave apparently formed by upward solution of the groundwater body in a hypogene setting sensu Klimchouk (2007, Fig. 16). In the 1930's the cave was a spring, allowing the deep groundwater to flow out freely. In the 1980's the cave formed a pool, often visited by locals for picnics. Then a pumphouse was installed and the water was used locally. In addition deep wells in the surrounding area tapped the underlying aquifer. In 2002 the lake had receded to a depth of 137 m (pers. comm. Greg Gregory) and divers explored a large chamber and a horizontal slowly, descending passage at its bottom. During the visits of the authors on February 19th, 2008, the large chamber (up to 70 m long and 20 m wide) at a depth of ca. 145 m was accessible, with the groundwater surface forming a lake at its bottom. The horizontal passages apparently were not yet free of water. The cave walls show the morphology typical of a convective cave formation in a phreatic setting in gypsum (e.g. Kempe, 2008). As one descends steeply over the boulders of the cave floor, one passes through almost all of the Heeth Formation, thus making it the only outcrop where it can be studied in detail. Above the entrance of the cave the transgressive contact of lower Cretaceous marl and platy limestone is well displayed.

Similar hypogene karstification appears in other places as well and has led to sinkholes. One of the areas is around the town of As Sulayyil, 500 km south of Riyadh, were several sinkholes have opened up. At least two have recently been filled by the farmers, but one rather recent one (at Umm Sulaim; N20.42414° E45.66311°), 47 m long and 27 m wide and about 1 m deep, was even venting hot and humid air through fresh circumferential and radial cracks, apparently rising from the deeper underlying aquifer. Similar sinkholes are also reported from the area north of Riyadh.

LAYLA LAKES SINKHOLES

The largest series of sinkholes is, however, found southeast of the town of Layla, 300 km south of Riyadh. Most of them were filled by lakes until the mid 1980's (Fig. 1). A hotel with bungalows and restaurant was build overlooking the largest lake in the south (Fig. 2). But it apparently never went into operation because here the same happened as in Ain Heeth: water was abstracted not only by pumping it directly from the northern end of the lake but also from the deep aquifer below. In the early 1990's the lakes dried up, revealing a series of text-book sinkholes (Fig. 3).

Fig. 1: Two of the smaller Layla Lakes still filled with water in the beginning of the 1980ies (Ministry of Agriculture and Water, 1984).

Google Earth provides a high resolution view of the northern sinkholes, while those in the south are barely perceptible once the ground situation is known (Fig. 4). Along the eastern side a prominent escarpment is visible, which is as much as 10 m high in places. Ground inspection shows, that it is accompanied by small graben structures with open cracks and small tectonic caves. Inspection also reveals that the rocks displaced are unconsolidated marls and not Mesozoic rocks. All in all (Table 1) 23 sinkholes can be listed of which some have several subsidence centers (Nos. 2, 4, 18 and 22). We were able to visit most of the sinkholes on February 21st and 25th in order to inspect them for tufa occurrence. The largest sinkhole is No. 4 with an N-S axis of 1.1 km and a width of 0.4 km and a depth of up to 40 m. The smallest ones have openings of less than 10 m across, but are bellowing out below, forming real sinkhole caves. Two of the sinkholes (18 and 19) are connected by a natural bridge. For a few sinkholes, we were not able to estimate the depth, because treir bottom was not visible. In

Table 1: *List of sinkholes near Layla. Sizes according to Google Earth and own field inspection.*

No	***North°***	***East°***	***Size (m)***	***Depth (m)***	***Type***	***Remarks (T = Tufa)***	***Qanat***
1	22.1689	46.7166	200*50	ca. 3-10	elongated	T, fresh circular cracks	no
2	22.1626	46.7034	400*100	ca. 5-30	elongated	T, fresh cracks; pit caves	no
2a	22.1628	46.7024	10*10	>20	narrow pit	T	no
2b	22.1626	46.7045	50*50	ca. 10	circular	T	no
2c	22.1632	46.4043	30*30	ca. 10	circular	T, fresh cracks	no
3	22.1634	46.7019	60*60	ca. 15	circular	post-lake	no
4	22.1681	46.7087	1100*400	ca. 30	elongated	T, former main lake, fresh cracks, terraces	channel
4a	22.1682	46.7077	50*50	ca. 10	circular	T, sand dune	no
4b	22.1686	46.7073	15*15	ca. 10	circular	T, sand dune at bottom	no
5	22.1706	46.7087	50*40	>20	circular	T ?, bottom not visible	no
6	22.1715	46.7087	60*60	ca. 30	circular	T, undercut, caves?	no
7	22.1744	46.7068	60*60	?	circular	not visited	no
8	22.1774	46.7133	70*70	ca. 40	circular	T	no
9	22.1771	46.7140	9*8	ca. 10	circular	overhanging, with sand pile	no
10	22.1769	46.7139	15*13	6	circular	overhanging, with sand pile	no
11	22.1776	46.7142	7*10	>25	circular	overhanging	
12	22.1785	46.7143	15*15	5	circular	half filled by dunes	no
13	22.1786	46.7146	16*14	6	circular	half filled by dunes	no
14	22.1807	46.7157	105*90	ca.40	irregular	T, sand dunes	yes
15	22.1820	46.7178	50*50	ca.50	circular	T	yes
16	22.1840	46.7256	100*110	35	irregular	T, collapse blocks	yes to 15 (80 m)
17	22.1853	46.7241	15*15	30	circular	overhanging	no
18	22.1865	46.7257	315*110	up to 25	elongated	T, composite of 3 sinkholes	channel to 17 (130 m)
18a	22.1857	46.7254	95*70	ca. 15	elongated	T, terraces	"
18b	22.1870	46.7257	112*85	ca. 15	irregular	T, terraces	"
18c	22.1872	46.7268	95*80	ca. 25	irregular	T, collapse blocks	"
19	22.1869	46.7273	51*25	ca. 20	elongated	T, natural bridge with 15c	yes
20	22.1884	46.7280	38*38	ca. 20	irregular	T, pit	channel to 19 (160 m)
21	22.1880	46.7287	26*22	?	elongated	not visited	yes
22	22.1897	46.7294	60*35	?	elongated	not visited	channel
22a	22.1897	46.7292	20*18	?	circular	not visited	"
23	22.2097	46.7345	48*38	?	circular	not visited, half filled by dunes	yes (?)

general the small, overhanging sinkholes are extremely dangerous because their margins are composed of loose material (lake marls). Many appear to have opened rather recently because they lack signs of tufa. All in all 19 of the structures (including the sub-sinkholes) have tufa, i.e. they are older and had standing water in them.

The Google Earth images also revealed that the lakes served as natural outlets of the deeper aquifer in as much as a series of parallel channels and qanats (Arabic for subterraneous water channels) conducted water over about 5 km to farms at Al Sayh in the north. This usage of the lake water was sustainable, since the qanats did only allow for gravitational outflow, thus only water that naturally flowed out of the aquifer was consumed.

Apparently most of the sinkholes were originally covered by water and thus not known at all. The water At-

Fig. 2: The Layla Lake Hotel overlooking the dried-up lakes in the southern section of the area.

las of Saudi Arabia lists 17 lakes (Ministry of Agriculture and Water, 1984). It also lists the electrical conductivities of the lake water that ranged from 2510 to 8600 µS/cm, i.e. the values are higher than expected for carbonate saturated waters. Some of the values appear to have been even higher than for gypsum (or anhydrite) saturated waters, but this may be due to ongoing evaporative concentration in shallow lakes. Thus the lake water most probably was high in sulphate as well as carbonate. This may explain why we only found two species of gastropods, quite a small number of species of molluscs for a freshwater habitat. The shells of one of the species are ubiquitous (Radix cf. natalensis, Krauss, 1848; Neubert, 1998; pers. com. H.-J. Niederhöfer, Stuttgart; also known as Lym-

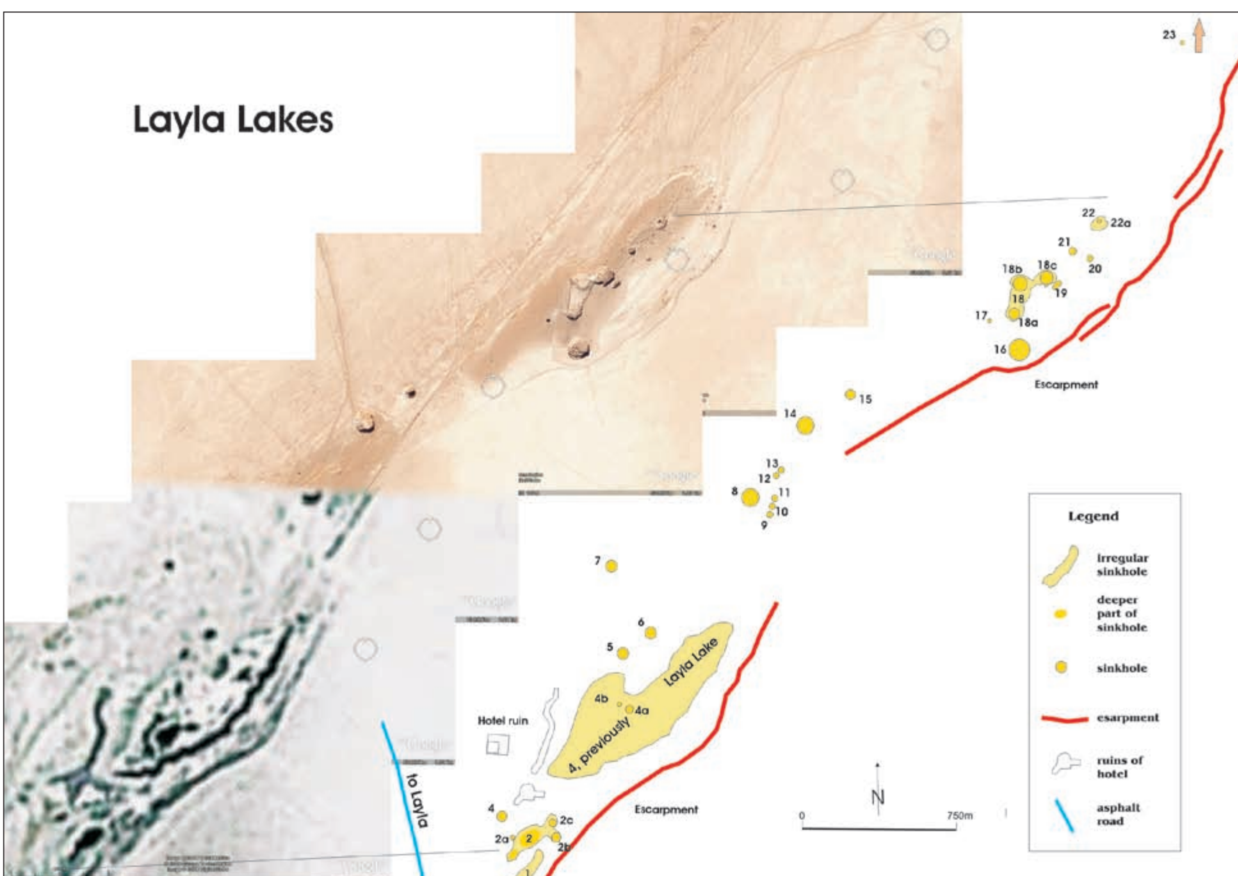

Fig. 4: Google Earth view of the Layla Lakes area and annotated map of sinkholes.

Fig. 3: Sinkhole No. 6, note tufa at bottom of lake and layered lake chalk profile near the top (car for scale).

Fig. 5: Shrinkage of lake-bottom chalk deposits has caused their subsidence by over one meter. The former contact of the sediment with the solid tufa is marked by a small ledge (Sinkhole 2, eastern side).

naea arabica; a very common fresh water snail) while the second one, (the cerithiid Melanoides cf. tuberculata, O. F. Müller, 1774; Krupp & Schneider, 1988; Neubert, 1998; pers. com. H.-J. Niederhöfer, Stuttgart; the species is salt tolerant and lives in warm waters), was found only in one place (half-way down in Sinkhole 2). The shallow lake bottoms (around the sinkholes) was occupied by reeds, the roots of which are still noticed everywhere.

The bottom of those sinkholes that contained lakes as well as the flats around the sinkholes is composed of very fine-grained marls or lake chalk (seekreide). Since the draining of the lakes, these deposits have dried out and shrank. Numerous meter-deep shrinkage cracks crisscross the lake bottoms and surround the sinkholes. They can not be differentiated from cracks caused by ongoing subsidence. The shrinkage of the lake bottom sediments has caused their subsidence; in places shrinkage amounted to more than a meter (Fig. 5) and opened over 10 m deep "shrinkage caves" between the sediment and the solid tufa (for example at the southern end of Sinkhole 2).

LAYLA LAKES GYPSUM TUFAS

The most important discovery, however, made in the Layla Lakes is the magnificent tufa that covers the vertical walls of the lake sinkholes (Fig. 6). Repeated test with 2nHCl, fingernail scratching and macroscopic inspection showed that the tufa is composed entirely of gypsum. In it numerous gastropod shells can be found immured at places. Even though the tufa surface is covered with fine-grained, cream-colored calcareous dust, the tufa itself is a sparitic selenite or a massive, fine-grained gypsum. Since no such site has – to our knowledge – been previously described in the literature, the term "tufa" is used even though it has so far exclusively been used for calcareous deposits (compare Ford & Pedley, 1996). The term "travertine" is avoided because it is more commonly used for hydrothermal and high pCO_2 sources of calcareous deposits. The expectation to find calcareous tufa or stromatolitic microbialites, as is common in $CaCO_3$-supersaturated lakes such as Plitvice (Kempe & Emeis, 1985) or Mono Lake, Pyramid Lake, Walker Lake and Searles Lake in the western USA (compare Kempe & Kazmierczak, 2008), Lake Van in eastern Anatolia (Kempe *et al.*, 1991), or in crater lakes such as Vai Lahi on Niuafo'ou (Kazmierczak & Kempe, 2006), was not met. An overview over calcareous tufa and travertine deposition in low temperature environments was given by Ford & Pedley (1996).

Apart from the singular mineralogy is the morphology of the tufa the most striking feature: the 20 to 30 m high walls of the sinkholes are covered with a several meter thick crust of tufa. There is a distinct morphological

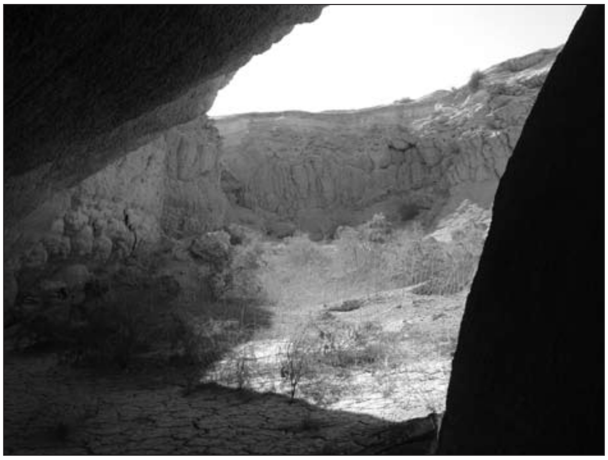

Fig. 6: View of the northern section of Sinkhole 2 from underneath the solid tufa showing the vertical tufa walls.

Fig. 9: Shell-like basin reminding of the large sea-shell in Boticelli's "Venus" (left, with one of the authors standing in it) and cup-like tufa (Sinkhole 5, southern wall). Note the terraces left by the sinking water level in the foreground.

Fig. 11: Tufa gours at the northern wall of Sinkhole 4b suggesting origin of tufa by water cascading down from the up-slope side of the sinkhole.

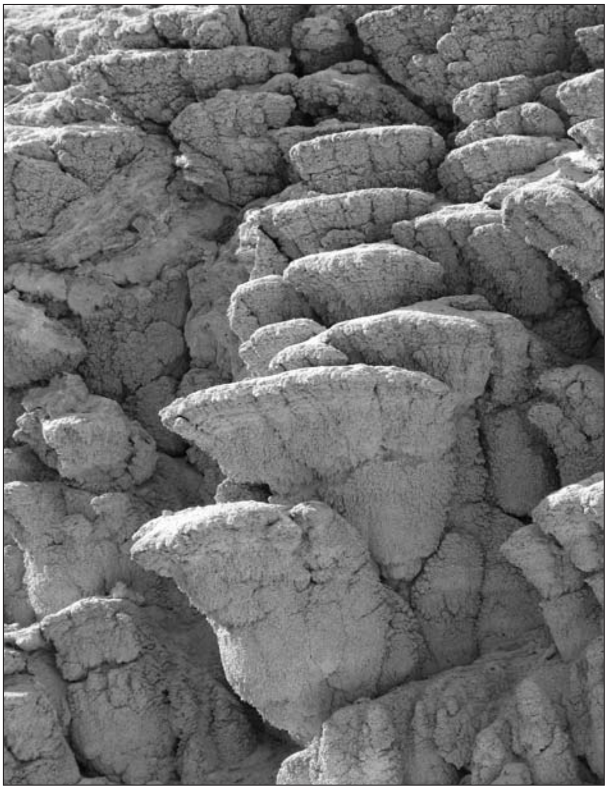

Fig. 8: Upward oriented, shovel-like cups of tufa, typical for the forms near to the former lake surface (Sinkhole 2, western wall, ca. 7,4 m).

Fig. 7: Panorama view of the eastern wall of Sinkhole 2, showing clear vertical change in the morphology of the tufa.

Fig. 10: Panorama of a step-like assemblage of gour-like tufa forms in the northern part of Sinkhole 4. Since the lakes dried up, sand started to drift in. Note the ripple marks on the dune slopes accentuated by white gypsum dust (length of view ca. 50 m).

change from bottom to top (example Sinkhole 2, eastern wall; Fig. 7): At the bottom the crust forms a solid, overhanging panel with only shallow vertical groves. Above, the crust is more segmented into m-sized bulbous, inverted cones and further up (left on Fig. 7) the tufa forms protruding, upward-oriented, shovel-like bowls or cups (Fig. 8). Some of the cups are more delicate than in other places and can form large shell-like basins (Fig. 9). The rims are often less than 10 cm thick and the cups are partially filled with loose sediment. In a sense, they remind of speleothem gours. In places where the sinkhole does not display vertical walls, such as in the center of Sinkhole 4, we find rather regular rows of cup-like structures forming steps (Fig. 10). A specifically regular tufa display was found at the northern wall of Sinkhole 4b (Fig. 11). Overall this triple division of the gross morphology of the tufa is found in all of the sinkholes.

GENETIC CONSIDERATIONS

It is clear, that we will never be able to fully understand the genesis of this special form of tufa because the lakes and their physico-chemistry in which they grew are gone forever. We thus can only speculate on these conditions. The observation that the conductivities were high, i.e. in or even above the range of gypsum-saturation, and from the fact that these tufa forms exist, we must conclude, that the Layla Lakes were saturated with respect to gypsum. In contrast to calcite, gypsum cannot be highly supersaturated but precipitates at saturation. Apart from evaporation two more processes govern gypsum saturation, best explained by Wigley (1973) and exemplified for a gypsum karst setting by Brandt *et al.* (1976). These processes are: co-dissolution or co-precipitation of calcite and temperature alteration. Thus several processes can be discussed that may have caused the gypsum precipitation along the walls of the lakes:

a) *Concentration by evaporation.* It is conceivable that on the wide flats that surrounded the deeper sinkhole centers of the lakes evaporation would concentrate the water much faster than over the deep sinkhole sections of the lakes. Higher concentrated solutions may have run down along the floor and cascaded underwater over the lips of the walls of the sinkhole, bringing saturated solutions into contact with the crystals already growing on the walls (precipitation upon reaching nucleation sites).

b) *Calcite co-dissolution.* Concentration on the flats by evaporation and degassing of CO_2 causes a precipitation of $CaCO_3$ (calcite and/or aragonite). Downward cascading solutions bring the water into deeper water layers with a higher pCO_2. There, the co-transported fine-grained lake chalk is being dissolved, pushing (because of the common ion effect of the increasing calcium activity) the gypsum over the saturation limit and causing its crystallisation along the walls.

c) *Temperature change.* Ascending water from the deep aquifer, delivering gypsum-saturated solutions warmer than the lake temperatures, cools in the lake and gypsum crystallises along the walls.

The possibility exists that all three of the processes may be applicable, each in a different season of the year. In any case is the continued delivery from the underlying aquifer of nearly gypsum saturated water the key condition. These solutions may either have risen slowly through the sediments of the lake bottoms or through distinct vents. One of such vents may have been adjacent to Sinkhole 2. Another vent may have been located at the NW-end of Sinkhole 4 and in the western wall of Sinkhole 20.

The situation seen today is the product of a long geological history. At this point one can only guess what this history is. One of the clues is the fact that all of the sinkholes seem to occur in unconsolidated lake chalks.

Thus the outflow of deep aquifer water over long periods refills any subsidence holes with chalk. During times of wetter climate the groundwater is recharged and the lakes expand. During dry climate periods, the groundwater flows out only sparingly and the lakes retreat to the immediate vicinity of the sinkholes. Where the gypsum tufa has collapsed from sinkhole walls, we find over 10 m high profiles of laminated or layered lacustrine chalks. Similar, albeit older, deposits are exposed along the eastern escarpment. These offer the possibility to do paleoclimate research, an aim we will try to pursue next. The apparently dozens of meter thick calcareous chalks (lime muds) should be listed as an own Pleistocene formation: the Layla Lakes Marls.

ACKNOWLEDGEMENTS

The authors are grateful to Dr. Randolf Rausch, Technical Director for GTZ International Services at Riyadh, who not only advised us to visit Layla Lakes but also financed the stay of the first author in KSA in February 2008. The authors thank also Paolo Forti, Bologna, for helpful remarks and H.-J. Niederhöfer, Stuttgart, for his determination of the gastropod shells.

REFERENCES

Brandt, A., Kempe, S., Seeger, M., & Vladi, F., 1975: Geochemie, Hydrographie und Morphogenese des Gipskarstgebietes von Düna/Südharz. – Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Geol. Jahrbuch, Reihe C, 45: 55 pp.

Ford, T.D. & Pedley, H.M., 1996: A review of tufa and travertine deposits of the world. – Earth Science Reviews 41: 117-175.

Kazmierczak, J. & Kempe, S., 2006: Modern analogues of Precambrian stromatolites from caldera lakes of Niuafo'ou Island, Tonga. – Naturwissenschaften 93: 119-126.

Kempe, S., 2008: Vom Urkanal zur unterirdischen Kathedrale, Höhlenformen und ihre Entstehung. – In: Kempe, S. & Rosendahl, W. (eds.), Höhlen: Verborgene Welten; Wissenschaftliche Buchgesellschaft Darmstadt, Darmstadt: 54-64.

Kempe, S. & Emeis, K., 1985: Carbonate chemistry and the formation of Plitvice Lakes. – In: Degens, E.T., Kempe, S. & Herrera, R. (eds.) "Transport of Carbon and Minerals in Major World Rivers", Pt. 3, Mitt. Geol.-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP Sonderband 58: 351-383.

Kempe, S., Kazmierczak, J., Landmann, G., Konuk, T., Reimer, A. & Lipp, A., 1991: Largest known microbialites discovered in Lake Van, Turkey. – Nature 349: 605-608.

Kempe, S., & Kazmierczak., J., 2008: Soda lakes. – In: Reitner, J., and Thiel, V. (eds.) Encyclopedia of Geobiology, Springer, submitted.

Klimchouk, A., 2007: Hypogene Speleogenesis, Hydrogeological and Morphogenetic Perspective. – Nat. Cave and Karst Res. Inst. Spec. Pap. No 1, 106 pp.

Krupp, F. & Schneider, W., 1988: Die Süßwasserfauna des Vorderen Orients. - Natur und Museum 118: 193-213.

Ministry of Agriculture and Water of the Kingdom of Saudi Arabia, 1984: Water Atlas of Saudi Arabia. – Saudi Arabian Printing Company, 112 pp.

Neubert, E., 1998: Annotated checklist of the terrestrial and freshwater molluscs of the Arabian Peninsula with descriptions of new species. – Fauna of Arabica 17: 333-461; Basle, Switzerland.

Wigley, T.M.L., 1973: Chemical solution of the system calcite-gypsum-water. – Canadian J. Earth Sci. 10: 306-315.