THE PROBLEM OF CONDENSATION IN KARST STUDIES

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Condensation in karst occurs over a wide range of natural settings, at latitudes from 25º to 70º and altitudes from sea level to 2600 m. In summer (April through September), condensation introduces a significant amount of water into the karst massifs (from 0.1% to as much as 20% of the total dry-season runoff). Contrary to common belief, in winter evaporation does not withdraw appreciable amounts of water from the massifs. Evaporating at depth, the water condenses near the surface within the epikarstic zone or on the snow cover and flows back. Condensation can sustain springs during prolonged dry periods (such as summer and winter) when there is no recharge by liquid precipitation.

Condensation can play a significant role in speleogenesis, and many forms of cave macro-, meso-, and micromorphologies are attributable to condensation corrosion. It can be particularly efficient in the latter stages of hydrothermal cave development (during partial dewatering) when the temperature and the humidity gradients are highest. Coupled with evaporation, air convection, and aerosol mass transfer, condensation can play a crucial role in the formation of a number of speleothems, as well as create peculiar patterns of cave microclimate.

Early statements advocating the condensation of moisture in caves can be found in texts of the ancient Greek philosophers Thales of Miletus, Empedocles, and Aristotle (VI-IV BC). Marcus Vitruvius Pollio (I AD) stated his belief that the moisture can condense from the vapors of hot waters rising from depth of the Earth (Fedoseev, 1975). During the following fifteen centuries, the natural phenomena were interpreted in accordance with theological dogmas. Only in XVI-XVIII AD, the European philosophers Georgius Agricola, Rene Descartes, and Athanasius Kircher brought back into scientific use the ideas of ancient natural philosophy. Eventually, O. Volger offered a more or less comprehensive hypothesis about formation of groundwater by condensation process (Volger, 1877). The hypothesis, however, came under severe criticism (Hann, 1880) and, after relatively short debate, was abandoned. It was A. Lebedev who revived the ideas of Volger in a series of publications of 1908-1926. The latter went largely unnoticed outside Russia due to the unfavorable historic background: World War I and Russian revolutions.

According to the concept of Lebedev (1936), the vapor moves from areas with elevated partial vapor pressure and air temperature to the areas with lower values of these parameters. For more than 70 years, the concept of Lebedev provided the basis for studies of natural condensation; only recently several papers suggesting re-consideration of the concept have been published (Tkachenko, 1978; Kuldzhaev, 1989). Applied to karst, the concept of Lebedev implies that condensation should occur in caves during warm seasons, and that evaporation must prevail there during cold seasons (Fig. 1).

Shestakov (1989) compiled a bibliography of more than 1,000 papers on condensation. About 10% of the researchers believe that only evaporation of soil- and ground water occurs and that condensation of atmospheric moisture underground is not possible; 40% think that the input of water due to summer

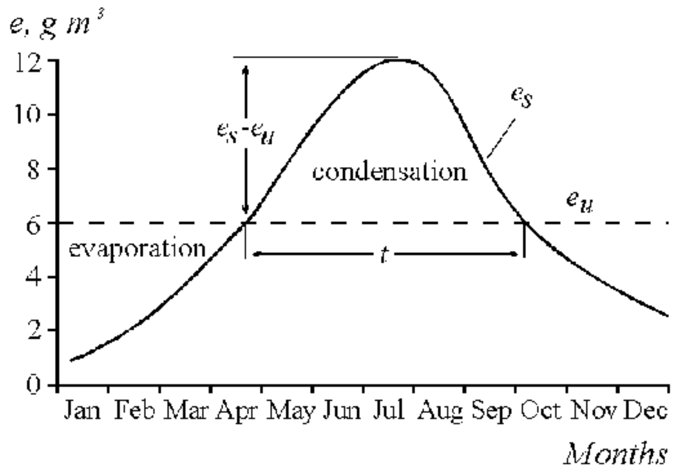

Figure 1. Potential of condensation and evaporation in the karst massifs of the Crimea Mountains (after Dublyankky & Lomaev, 1980; generalized). Many other karst massifs of the former Soviet Union exhibit similar patterns, though the concrete values of all parameters may vary. e_S is the absolute humidity on the surface; e_U is the absolute humidity underground; (e_S-e_U) - is the gradient of the absolute humidity of the air entering the cave; *t* - is the duration of condensation period. Condensation occurs when $e_s > e_u$.

condensation is balanced by water withdrawal due to winter evaporation; and ~50% consider the condensate an important component of the water balance, but abstain from numerical estimations.

Difficulties involved in quantifying the condensation are reflected in method and reference sources, which state that: "due to the fact that quantitative determination of condensation is difficult and time consuming, it is not expedient to take it into account in water balance studies" (Borevsky et al., 1976: 120); or: "due to practical difficulties in determining the condensation, the latter is conventionally lumped with the precipitation and the evaporation" (Pinneker, 1980: 89).

There is no agreement regarding the role of condensation among karst researchers, either. By way of example: Martel (1894) rejected the very possibility of it; Trombe (1952) and Gvozdetsky (1954) believed that it plays significant role in speleogenesis; and Gergedava (1970) assigned to condensation the leading role in speleogenesis.

By and large, the importance of condensation in karst and other hydrogeological processes seems to be underestimated. For instance, a fundamental review on karst geomorphology and hydrology by Ford and Williams (1989) only mentions seasonal condensation (p. 469) and condensation corrosion, mostly in hypogenic settings (p. 309). Meanwhile, the long-standing karst studies in the Crimea, Caucasus, and some other regions of the former Soviet Union reveal an important role of condensation in both formation of karst waters, and speleogenesis. Being published mostly in Russian, these data remain largely unavailable to the non-Russian researchers. This prompted us to prepare the present review.

Restricted volume of the paper does not allow us to present all pertinent references (many more references can be found in the bibliographic index by Shestakov, 1989), or to give detailed data on physical and geographical settings of studied objects (instead, we use statistical generalizations, such as the mean values and the coefficients of variation, C_v); as well as to provide all pertinent details about the methods used (in many instances we only outline their rationales). This should be viewed as an unavoidable shortcoming of a review paper.

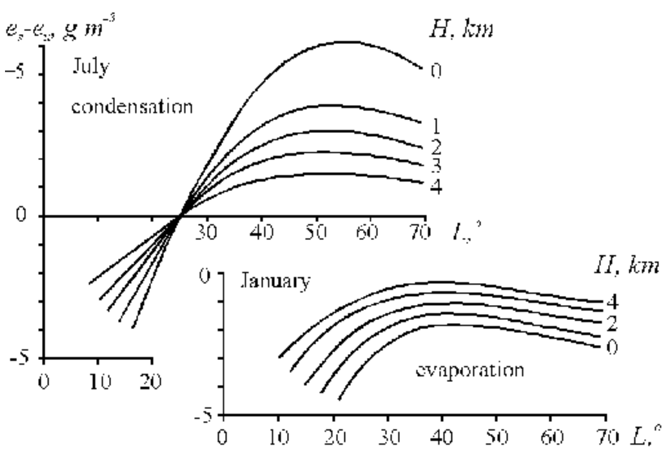

Fig. 2. Possibility of condensation in karst during warm (July) and cold (January) seasons at different latitudes L and altitudes above sea level H. Condensation occurs when (e_s - e_u) > 0 (after Dublyanskaya & Dublyansky, 1989).

DIFFERENT LEVELS OF CONDENSATION STUDIES

The discordant opinions about condensation, quite common in karst literature, often resulted from the difference in study methods and approaches. The latter strongly depend on the scale of studies. For the sake of simplicity, we will discuss separately four levels of condensation studies: global, regional, local, and object levels. It should be born in mind that the data and results obtained at one level cannot always be directly translated onto another level.

STUDY OF CONDENSATION ON THE GLOBAL LEVEL

The possibility of condensation can be assessed on the global scale in dependence on latitudes and altitudes. The attempt of such assessment was done by Dublyanskaya and Dublyansky (1989) (Fig. 2). They used data on latitudinal distribution of absolute humidity of the air (Khromov & Mamontova, 1963) along with the data on humidity in caves located at different latitudes and altitudes (by Moore and Sullivan (1978) with corrections by the data of other researchers). During the warm period (July) condensation can occur at latitudes from 25º to 70º; at lower latitudes evaporation prevails. During the cold period (January), evaporation prevails in caves at any latitude. The rates of condensation and evaporation change with altitude.

Naturally, Figure 2 is a broad generalization; it depicts only the possibility of condensation. Processes occurring in real caves depend on climatic zone in which the cave is located, position of the cave within karst massif, passage of frontal systems, and many other factors. Also, Figure 2 implies that the input of water from summer condensation is counterbalanced by its withdrawal during winter evaporation. However, the local-level studies of condensation suggest that this does not happen in natural settings (see section "Winter condensation" below).

STUDY OF CONDENSATION ON THE REGIONAL LEVEL

The regional-level studies deal with condensation within mountainous constructions (e.g., the Crimea) or individual karst massifs (e.g., Chatirdag massif, one of nine karst massifs of the Crimea). At this level, the following features are suggestive of condensation.

Low-discharge springs. Such springs exist within isolated karst-erosional or structure-denudational remnants which are located close to mountain summits, crests, and passes. In such settings, the recharge via infiltration is insignificant, which suggest condensation as the source of waters (Slavianov, 1955;

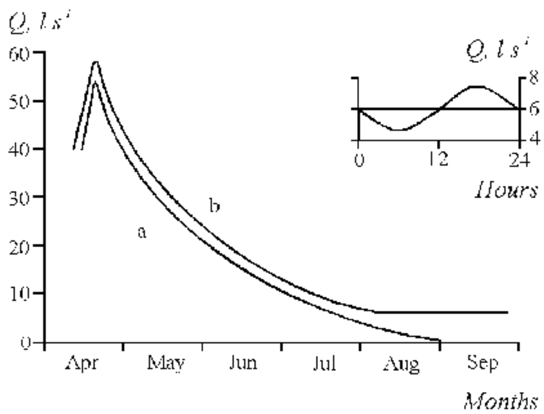

Figure 3. Discharge hydrographs (schematized). a - according to the model of the drainage of stored water; b - according to the condensation model. Inset shows the daily oscillations of the hydrograph during a period of condensation recharge (dry season; August-September on this graph). The values shown in the inset correspond to actual values measured for the Krasnopeshernaya River in the Crimea.

Protasov, 1959; Dublyansky, 1977; Dublyansky et al., 1985).

Constant summer discharges of karst springs. During summer dry season, karst springs display hydrographs which may be approximated by smooth recession curves. This type of hydrograph is normally interpreted by a model of drainage of karst in which water drains from storage in caves, fissures, and pores. A number of expressions approximate the observed recession curves; the one most frequently used is:

$$Q_t = Q_0 e^{-\alpha t} \qquad (1)$$

where Q is the discharge [m^3 s^{-1}] at times t and 0, t is the time elapsed [days], and α is the recession coefficient [T^{-1}] (Ford & Williams, 1989; p. 196). Quite often, however, after reaching a certain minimum at $n \cdot 10^{-2}$-$n \cdot 10^{0}$ l s^{-1}, the falling hydrograph limb levels off and remains horizontal (Fig. 3) for a long period of time (1 to 4 months). This has been reported by Jenko (1959) as a "precise constancy of dry-season discharges" in karst springs of the Dinaric Karst (Yugoslavia). Similar patterns were found for karst springs in the Crimea, the Caucasus, and some other karst areas of the former Soviet Union (Dublyansky et al., 1984; 1985; 1989).

The analysis of daily hydrographs of the Krasnopeshchernaya River in the Crimea (fed by karst springs withdrawing water from the Dolgorukov karst massif, with its 13.7-km-long Krasnaya Cave) performed for the period from 1963 through 1988 revealed a fine structure of dry-season discharges. Having average daily value of 6 l s^{-1}, the discharge exhibits regular daily variations, increasing from 4 to 8 l s^{-1} and then lowering again (Fig. 3, inset). Thus, the drainage of stored water is overprinted by a certain dynamic process, which stabilizes the discharge of springs at some level (specific to each spring) and governs the systematic daily variations around this level. A similar pattern was observed in springs located at different altitudes. It does not depend on the presence and composition of vegetation, which could induce "evapotranspirational" cyclicity of discharge. Also, the relation between the discharge of springs and the variations of the gravitational field caused by the interaction of the Earth, the Moon, and the Sun, reported by Kinzikeev (1993), has not been confirmed in the Krasnaya Cave area. Thus, we believe that condensation provides the most appropriate explanation for the observed patterns of the dry-season discharges.

Meteorological data. The senior author, for a number of years, monitored the discharges of several springs which were suspected to be fed by condensation, along with meteorological parameters (Dublyansky, 1977). A strong correlation was found between dry-season discharge (nil precipitation during 1 to 4 months), and meteorological parameters for 15 springs in the Crimea and 6 springs in Western Caucasus located at altitudes from 30 to 1800 m and having discharge from 0.012 to 8.660 L s^{-1}. Systematic diurnal variations of discharge, Q, and water temperature, T_w, which were correlated with changes in dynamic parameters of the air, controlling condensation (that is, temperature of the air, T_A, and its absolute humidity, e_s) were observed during warm seasons (June-August) over a period from 1965 through 1994. These relations have statistically significant values of the coefficient of correlation (0.77-0.99 ± 0.05-0.21). The response of Q and T_w to the changes of T_A and e_s is normally delayed; hence, a travel-time correction (retardation Δt) must be applied. The latter ranges from 1 to 15 hours for different springs (Fig. 4 and Table 1). T_w changes during a day almost synchronously with Q and does not show appreciable correlation with T_A. One may assume that water controls

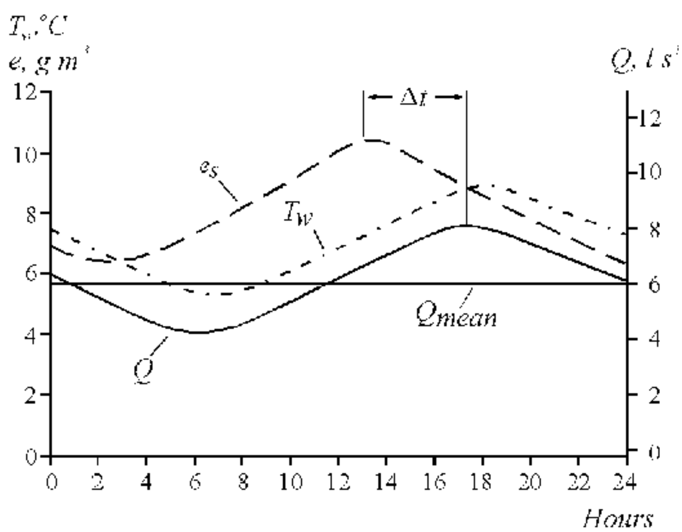

Figure 4. Daily variations of the discharge, *Q*, and the temperature, T_W, of a condensation-fed spring as compared with variation of absolute humidity of the atmospheric air, e_s. *t* - is the lag time (travel time).

Table 1
Discharge and water temperature in the condensation-fed springs in limestone massifs of the Crimea and Caucasus, and correlation between the discharge, Q, and absolute air humidity, e

Spring name	Altitude m	Period of observations	Mean discharge *Q* l s^{-1}	C_V	Mean T_W ºC	C_V	Lag time hours	Coefficient of correlation between Q and e
				Crimea				
Ay-Petri	1100	July 1-2, 1959	0.012	0.03	7.2	0.04	2	0.95±0.09
Beshtekne	1000	June 26-27, 1989	6.100	0.07	6.5	0.01	3	0.78±0.17
Beshtekne	980	July 8-9, 1989	0.770	0.05	7.7	0.03	3	0.72±0.11
Pahkal-Kaya	960	June 27-28, 1994	0.014	0.07	10.1	0.04	6	0.80±0.12
Chatirdag	920	June 20-21, 1995	0.008	0.20	12.4	0.26	4	0.57±0.16
Alushta	920	July 20-21, 1991	0.054	0.04	6.5	0.03	3	0.86±0.09
Alushta	730	July 20-21, 1991	0.181	0.02	8.5	0.03	3	0.85±0.13
Mangup	575	July 25-26, 1971	0.370	0.06	10.6	0.03	4	0.92±0.12
Kizil-Koba	550	Aug 24-25, 1965	8.560	0.22	9.8	0.04	15	0.81±0.07
Aleshina Voda	550	Aug 25-26, 1965	2.350	0.17	9.6	0.03	6	0.85±0.14
Red Cave #33	510	June 26-27, 1984	1.460	0.02	9.6	0.02	8	0.81±0.16
Petrovski-1	420	June 18-19, 1986	0.110	0.05	10.9	0.04	2	0.74±0.16
Preduschelnoye	380	Aug 2-3, 1989	0.700	0.01	10.5	0.01	4	0.83±0.21
Petrovski-2	330	July 9-10, 1991	0.104	0.02	11.2	0.02	14	0.75±0.18
Yanishar	160	May 1-2, 1988	0.020	0.02	-	-	18	0.96±0.02
Opuka	30	July 2, 1991	0.105	0.04	13.3	0.02	10	0.73±0.18
				Caucasus				
Bagia	1800	July 12-13, 1983	0.220	0.01	8.5	0.11	1	0.99±0.05
Gelgeluk	1780	July 19-20, 1984	1.400	0.03	4.1	0.02	5	0.92±0.09
Alek	960	Aug 5-6, 1971	0.220	0.03	9.2	0.06	5	0.88±0.07
Alek	920	Aug 6-7, 1971	0.170	0.04	9.6	0.05	5	0.92±0.09
Proval	600	Aug 21-22, 1975	0.830	0.04	30.0	0.03	16	0.72±0.19
Akhun	210	July 27-28, 1976	0.030	0.05	8.9	0.02	7	0.87±0.14
Mean	-	-	1.132	0.05	10.1	0.03	6	0.84±0.12

temperature during condensation, as the specific heat capacity of water (1 cal g^{-1} $degree^{-1}$) is 4 to 6 times as large as the specific heat capacity of karstifiable rocks (e.g., 0.16-0.24 cal g^{-1} $degree^{-1}$ for limestone and 0.20-0.25 cal g^{-1} $degree^{-1}$ for gypsum).

Geological engineering data. Much about condensation associated with construction works within karst terrains (residential and industrial buildings, asphalt and concrete covers, embankments, airdrome runways, etc.) has been published (Vedernikov & Larina, 1985). Condensation is viewed as a major factor in the rise of the groundwater (underflooding) within urbanized territories (Riazanova, 1987).

At the regional level, three groups of methods are used for quantitative determinations of condensation: (1) water balance studies; (2) calculation methods; and (3) microclimatic methods.

Water balance studies. A number of attempts have been undertaken for the Crimea Mountains to estimate condensation using water balance equation: [condensation = precipitation - (evapotranspiration+runoff)] (Golovkinsky, 1894; Vasilievski and Zheltov, 1932; Glukhov, 1963). The calculated values varied from 0.7 to 25.0% of the rainfall. This approach is inappropriate, as the calculated values are of the same magnitude as are estimated errors for other constituents of the water balance (15-20%).

Calculation methods. In 1938 through 1986 a number of researchers suggested methods for calculation of condensation within karst massifs. Most of those methods have important shortcomings: some of them contain terms which hardly can be determined; other are suitable for too general or, vice versa, too particular calculations. By way of illustration we present one of the suggested methods. Sitnikov (1986) studied the dynamics of moisture- and salt transfer in the aeration zone and suggested the following for estimation of condensation:

$$q(0,t) = -\frac{\beta\sigma(t)}{\gamma_L}\left\{P_W(0,t) - \left[P_L(0,t) - P_{AT}(0,t)\right]\right\}, \qquad (2)$$

where q is the condensation on or evaporation from a surface [m day^{-1}]; β is a coefficient accounting for the state of water on (from) the surface of which condensation (evaporation) occurs [m day^{-1}]; σ is a coefficient accounting for the effective surface of condensation (evaporation) [parts of unity]; γ_L is the density

Table 2. Condensation as related to recharge of some karst massifs of Ukraine, Russia, and Georgia (after Dublyansky, 1977; Dublyansky and Kiknadze, 1984; Dublyansky et al., 1985; and Vakhrushev, 1993). Calculations are by equation (3).

Karst massif	Surface area km^2	The amount of condensed water: mm	% of yearly total precipitation	Contribution to runoff $l\ s^{-1}\ km^{-2}$: Annual	Per warm season
Western Carpathians					
Ugolsk	12.0	1	0.1	0.02	0.11
Crimea					
Aipetri	97.7	77	6.4	2.46	5.00
Dolgorukov	79.5	25	3.0	0.81	2.94
Karabi	217.4	27	3.2	0.86	3.09
Chatirdag	23.4	69	7.2	2.38	5.30
Inner Range	293.0	11	2.0	1.85	9.60
Opuka	2.7	36	9.1	1.15	1.70
Western Caucasus					
Kavminvody	495.0	8	1.2	0.25	0.68
Alek-Akhtsu	28.8	82	3.4	2.60	6.12
Dzikhra-Vorontsov	38.0	41	1.9	1.85	4.20
Akhshtir-Akhun	19.0	22	1.1	0.69	1.40
Arabika	517.8	134	5.6	4.27	9.36
Bzib	297.8	121	4.8	3.85	8.40
Khipsa	186.8	149	5.8	4.72	10.13
Gumishkha	263.5	61	3.1	1.95	4.37
Duripsh	40.9	4	0.1	0.12	0.28
Mean		54	3.5	1.86	4.54
Cv		0.87	0.73	0.79	0.75

of water [kg m^{-3}]; P_L and P_w are the pressure of water [Pa]; and P_{AT} is the atmospheric pressure [Pa]. This equation can be used for covered karst, but is not applicable to the directly exposed karst or to individual caves.

Microclimatic method. It is based on the equation introduced by Obolensky (1944) and modified by Dublyansky (1969):

$$A = V \varepsilon (e_s\text{-}e_u)\ t\ J \qquad (3)$$

where A is the amount of condensate [g]; V is the volume of the active part of the karst massif [m^3] (estimated from topographic and geologic maps and considering the depth of caves); ε is the fissuration and karst porosity [parts of unity] (estimated by geological, geophysical, or hydrochemical methods by density of fissuration and the volume of caves); (e_s-e_u) is the difference of absolute humidities on the surface and underground [g m^{-3}] (determined by meteorological and climate data; see Fig. 1); t is the duration of condensation period [day] (see Fig. 1); J is the frequency of air exchange [day^{-1}] (estimated by air flow velocities measured in caves and scaled to the average fissure and/or cave dimensions; Dublyansky, 1969).

This method has several apparent shortcomings. For instance, it is difficult to determine ε and J accurately. Also, the diffusion of water vapor, which does not depend on air movement, is not considered. In actual practice, nevertheless, it gives satisfactory results. It has been calibrated on a monitored massif of the Krasnaya Cave (the Crimea) and gave fair agreement (±10%) with the values obtained by an independent method (measurement of the dry-season spring discharges).

The microclimatic method was used to determine the role of condensation in recharge of karst waters within 16 karst massifs of the former Soviet Union (Table 2). The data imply that condensation accounts for 0.1 to as much as 9.1% of the total annual precipitation (mean 3.5%, C_v = 0.73). The average yearly condensation runoff is 1.86 l s^{-1} km^{-2} (C_v = 0.79). Because condensation occurs only during the warm season, it is worthwhile to calculate seasonal (warm-season) runoff. Its mean value for the massifs studied is 4.54 l s^{-1} km^{-2}. Calculated values show good correlation with the dry-season discharges of springs located within the massifs (coefficient of correlation r = 0.7-0.8).

Microclimatic calculations reveal some interesting peculiarities of condensation in karst massifs located at different altitudes (Fig. 5). Equation (3) comprises both static (V, e) and dynamic (t, e_s, e_u, and, J) members. The values of the term (e_s-e_u) decrease with increasing altitude, whereas those of t increase. The coupled effect is the appearance of the conden-

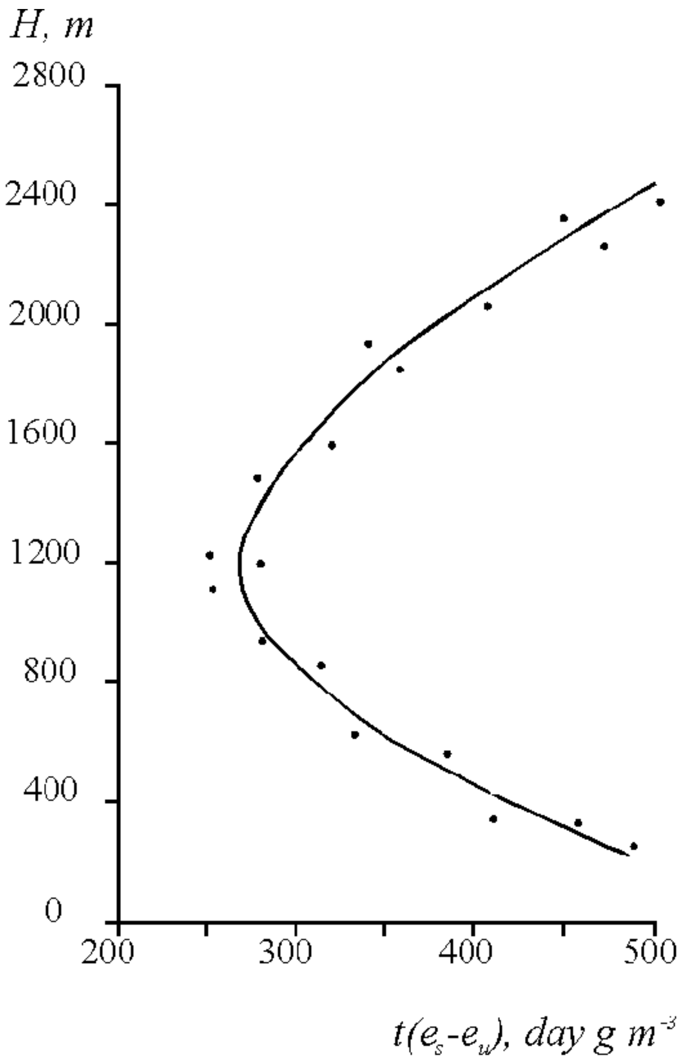

Figure 5. The dynamic parameter of condensation, t (e_S-e_U), as related to altitude above sea level, H. Data for the Bzib massif, Western Caucasus.

sation minimum at 800-1600 m and of two maximums below 800 and above 1600 m.

Naturally, the results presented in this section do not give an exhaustive account of all aspects of regional level condensation studies. For instance, of particular interest are the annual patterns of condensation in karst massifs located within different altitude zones having different vegetation cover; condensation in high altitude karst massifs; change of condensation pattern due to passage of frontal systems, etc. These problems are not yet explored adequately.

STUDY OF CONDENSATION ON THE LOCAL LEVEL

The local level deals with individual caves as well as with small karst remnants feeding karst springs.

Historical and archeological data. Water which condensed on naturally collapsed rock or within man-made piles of gravel was used for water supply in ancient and medieval settlements in Southern Europe and Central Asia (Zibold, 1904; Tugarinov, 1955; Klimochkin, 1973; Firsov, 1990; Vakhrushev, 1993). Destruction of such structures, as well as destruction of small isolated limestone remnants (e.g., their quarrying for gravel during road construction) led to decrease in discharge or even cessation of condensation-fed springs (e.g., Gaspra Isar and Morcheka springs in the Crimea).

Observations and microclimatic studies in caves. Studies through the past thirty years have revealed condensation in caves of varied location, morphology, and microclimate, as well as in underground mines (Ustinova, 1956; Protasov, 1959; Prokofiev, 1964; Lukin, 1969; Andrieux, 1970; Eremenko & Kolpashnikov, 1974; Dublyansky, 1977; Ginet, 1977; Racovitca & Viemann, 1984).

The possibility that there may be condensation occurring in a cave may be estimated by measuring the difference between absolute humidity on the surface and underground (e_s-e_u). Microclimatic observations from 290 caves of the Crimea and Western Caucasus (more than 10,000 measurements and 5,000 continuous daily records of air pressure, temperature, and humidity) demonstrated the existence of condensation and revealed its daily, weekly, and monthly variations (Dubljanski & Sockova, 1977; Tsikarishvili, 1981; Dublyansky et al., 1989). Condensation was observed in caves during the warm season (maximum in July and August). Evaporation prevails during the cold season, though in some particular settings condensation also can occur. The diurnal pattern of condensation is controlled by change of the temperature and humidity on the surface (maximum at 10 a.m. - 4 p.m. and minimum at 10 p.m. - 2 a.m.).

Condensation and chemosorption in caves and underground mines in hygroscopic rocks (massive halite and potash deposits) were reported by Maksimovich (1963), Eremenko and Kolpashnikov (1974), and Beltukov (1989). Korotkevich (1970) demonstrated that at relative humidity close to 100%, the rate of condensation there may be as high as 180-225 mm yr^{-1}.

Calculations of the amount of condensation in Kungur Ice Cave, Urals were performed by Lukin (1969). He calculated that some $2 \cdot 10^5$ m^3 of air passes through a cave per day. Each cubic meter of air leaves behind some 4.6 g of condensed water (which yields on a daily basis 920 kg). For five caves in the Crimea, Ustinova (1956) obtained somewhat lower values of 3 g m^{-3} at a rate of air exchange of $0.3 \cdot 10^5$ m^3 day^{-1}.

Detailed microclimatic studies carried out between 1960 and 1970 in 157 caves of the Crimea (Dublyansky et al., 1989) yielded an average value of condensation 19.9 g m^{-3} (C_v = 1.45). Condensation reaches a maximum of 75.8 g m^{-3} in July in vertical shafts; values of 0.7-4.0 g m^{-3} were measured in open caves located on the plateau, which agrees with earlier results by Ustinova (1956). Jameson and Calvin Alexander (1989) reported condensation rates of 30-90 g m^{-2} day^{-1} on vertical surfaces and 45-200 g m^{-2} day^{-1} on horizontal surfaces in Snedegar's Cave in West Virginia. Similar studies have been carried out in caves of Romania, France, and some other countries (Andrieux, 1970, Racovitca & Viemann, 1984).

Calculations of condensation. Several methods of condensation calculation in caves have been suggested; each method based on different theoretical premises. Mucke, Völker, and Wadewitz (1983) suggested an empirical equation for calculation of condensation:

$$m = (25 + 20W)(X_S - X_L), \qquad (4)$$

where m is the condensation rate [g m^{-2} $hour^{-1}$]; W is the velocity of the air motion [m s^{-1}]; X_s is the saturation humidity in the boundary layer between air and cave wall [g kg^{-1}]; and X_L is the humidity of the bulk of the air at the same temperature [g kg^{-1}].

Eraso (1969) pointed out that when warm air enters a cave, it cools down and a part of its moisture can condense. The decrease of the temperature is defined as:

$$\Delta T = (K - I)(1000 c_P \gamma)^{-1} \qquad (5)$$

where ΔT is the decrease of temperature [ºC]; K and I are the heat content of moist- and dry air masses [kcal m^{-3}]; C_P is the specific heat capacity of the air [cal g^{-1} $degree^{-1}$]; and γ is the air density [kg m^{-3}]. A similar approach was independently developed by Dublyansky and Iliukhin (1981).

Golod (1981) has developed a mathematical model of coupled aero-, thermo-, and hydrodynamic processes in caves. He assumed that condensation, being a low-intensity process, occurs at an equilibrium (along the curve of saturation). This allows calculation of condensation by:

$$P_H = P_0 \exp [\mu_n L_K/R] [(T_B - T_0)/(T_B T_0)] \qquad (6)$$

and

$$dQ_K = \rho_L L_K dV_K, \qquad (7)$$

where P_H is the pressure of saturated vapor; P_0 and T_0 are the pressure and the temperature at the triple point; μ_n is the molecular weight of the vapor; L_K is the specific heat of condensation; R is the universal gas constant; T_B is the absolute temperature; dQ_K is the heat released in process of condensation; dV_K is the amount of condensed water; and ρ_L is the density of the liquid phase.

Comprehensive thermodynamic calculations of condensation processes were performed by Bruent and Vidal (1981) in order to develop methods of protecting the Paleolithic paintings in the Lascaux Cave, France. The air conditioning system was constructed in the cave on the basis of these calculations.

Winter condensation. The local-level studies of condensation fostered some fundamentally new ideas about the formation of ground waters. The problem of special interest is the winter condensation (distillation). The warm-season condensation in caves is accompanied by an input of moisture from the outside atmosphere. The cold-season evaporation, however, does not remove all moisture from the rocks: the water evaporated deep within a karst massif condenses within the epikarstic zone or on the snow pack (Fig. 6). Thus, there occurs an "internal circulation of moisture", which does not increase the total amount of water stored in the massif, but significantly increases the residence time of water in the rock and thus enhances condensation-related karstification. Winter condensation sustains the runoff from high-mountain karst massifs during periods when they are devoid of recharge by liquid precipitation.

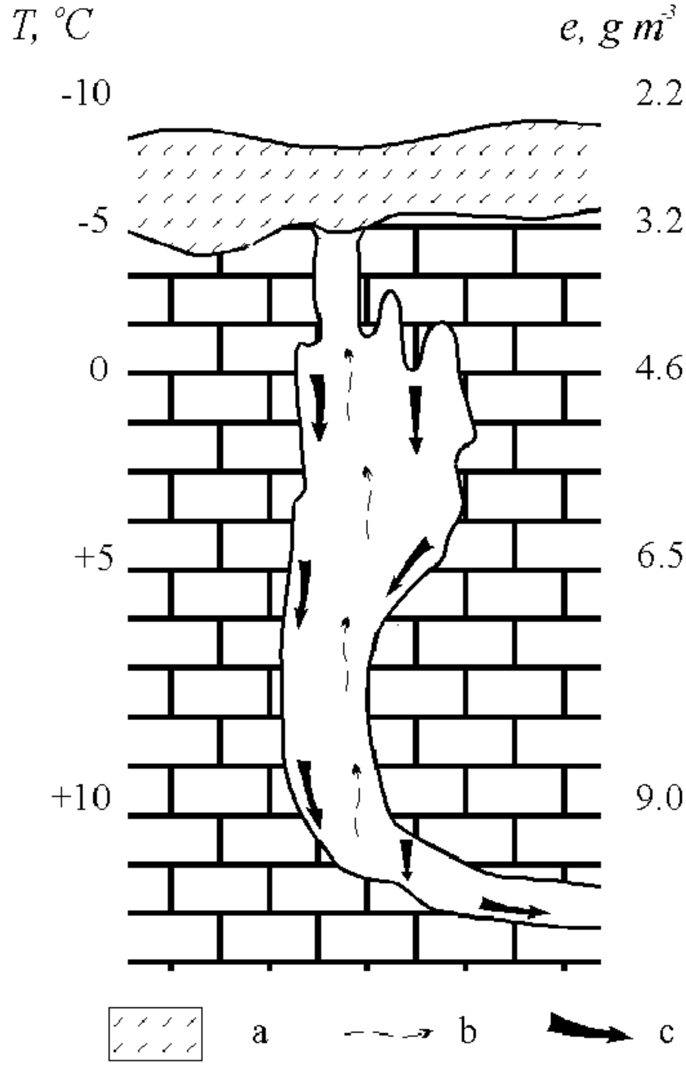

Figure 6. The pattern of air and moisture circulation characteristic of cold-season condensation setting. a - snow; b - movement of water in form of vapor; c - movement of water under the influence of gravity; T - the temperature of the cave air; e - absolute humidity.

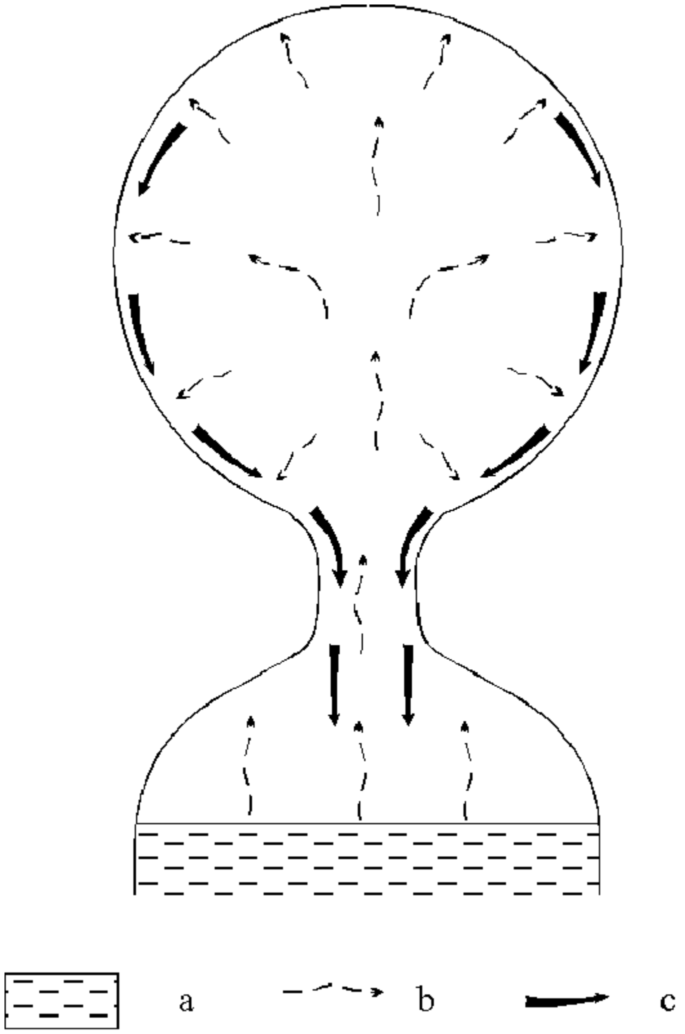

Figure 7. Condensation in a hydrothermal cave: a - thermal lake; b - movement of water vapor; c - movement of water as a liquid under the influence of gravity (after Szunyogh, 1982).

The winter condensation could be the mechanism, which prevents the large-scale removal of the moisture from karst massifs by evaporation during cold seasons. The surface area of open cave entrances through which such removal can take place is negligible relative to the total surface area of karst massifs.

Existence of winter condensation was confirmed by targeted observations in karst massifs of the Western Caucasus (Dublyansky et al., 1985). On some of them, the snow cover lies during 3-5 months and its thickness reaches 6-12 m (e.g., Bzib massif). There exists only insignificant runoff in caves; it is well correlated with the changes of negative air temperatures on the surface. Detailed microclimatic surveys have shown that this runoff cannot be accounted for by melting of snow at its base due to geothermal flux. The karst massifs are deeply cooled fragments of the Earth's crust, where the "normal" geothermal gradient begins to control the rock temperatures only at great depths.

Winter condensation was also determined in the Pinego-Kuloy karst region, Northern Russia, where Malkov and Frantz (1981) reported formation of condensate drops during 11 days, when outside air temperature varied from -7º to -42ºC.

Hydrothermal condensation. A special case of condensation in caves is hydrothermal condensation occurring above the surface of underground thermal waters during the partial dewatering stage of hydrothermal caves (Fig. 7). Such a mechanism is believed to be responsible for the carving of peculiar spherical niches known in caves of Hungary (Müller, 1974), Italy (Cigna & Forti, 1986), and elsewhere. Theoretical consideration (Szunyogh, 1982; 1990, Dublyansky, 1987) as well as laboratory experimentations (Dreibrodt, 1994, pers. comm.) have shown that condensation in such a system is a naturally attenuating process: it slows down due to the low rate of heat transfer through the bedrock. In natural settings, however, hydrothermal condensation may become a powerful influence in karst formation if cooling of the bedrock occurs due to even minor ventilation. The latter is quite probable, as such caves develop not far from the topographic surface within the zone of aeration. A prominent example of such convection-condensation-corrosion is known in Grotta Giusti, Italy. The cave contains a lake of thermal water having a temperature of 32-34ºC, while the temperature of the rock in the upper level of the cave is 20ºC. The rate of condensation in this cave was estimated to be 8,640 l day^{-1}, and the estimated amount of bedrock $CaCO_3$ dissolved was 630 g day^{-1} (Cigna & Forti, 1986).

Study of condensation on the local level reveals many interesting problems, which require special detailed studies. Examples of such particular problems are: formation of condensation moisture in "mixing fogs", condensation in narrow passages due to increase of velocity of the air flow (accompanied by decrease of the pressure and temperature), influence of cave ice on condensation (sublimation), evaporation from the surface of inflowing water and further re-distribution of the moisture in the cave, and many others.

STUDY OF CONDENSATION ON THE OBJECT LEVEL

These studies deal with the separate parts of caves (e.g., isolated rooms, near-entrance zones, etc.), condensation devices of different design, as well as special tasks (e.g., studies of mineral formation, development of measures to preserve ancient graffiti and paintings, etc.).

Being studied at the object level, condensation appears to be quite a heterogenous process, and the pattern of condensation/evaporation within individual caves can be extremely complex. In some caves, the seasonal pattern of condensation and evaporation discussed above, can be interrupted by relatively short (from days to weeks) reversals (e.g., evaporation in summer due to passage of frontal systems and change of air circulation pattern).

Table 3
The output of different types of condensation setups constructed on the surface.

Author	Years	Location	Altitude m asl	Characteristics of the setup Volume m^3	Type of infilling	Yield l day-1 per each m^3 of infilling
Golovkinsky, N.A. and Peddakas, I.K	1864-1905	Crimea, Southern Coast	300	0.04-0.14	clay, sand	0.028
Zibold, F.I.	1912	Eastern Crimea	190	1117.0	pebble	0.320
Khudiaev I.E.	1931	Crimea, Southern Coast	480	0.03	gravel	0.980
Beliavsky, A.Y.	1940	Kiev	100	0.01	sand, loess	2.324
Tugarinov, V.V.	1951	Moscow area	280	300.0	gravel	0.620
Reiniuk, I.G.	1951-1965	Kolima Region	200	from 0.007	sand	0.022
				to 0.016	gravel	0.370
Protasov, V.A.	1955	Crimea, Southern Coast	400	0.25	gravel	0.018
Klimochkin, V.V.	1958-1970	Siberia and Kola Peninsula	?	0.01-0.05	sand	0.050
					pebble	0.060
					gravel	0.100
Dublyansky, V.N.	1960	Western Crimea	1100	900.0	gravel	0.016
Pribluda, V.D.	1963-1976	Western Crimea	900	22.0	gravel, cobbles	0.012
Mean						0.386
C_v						1.71

Condensation typically occurs on the surface of the cave bedrock, sediments (in the latter case it could be accompanied by different kinds of sorption), or water bodies. Besides, it can occur in the cave air itself, as warm, relatively moist surface air enters, cools and condensation fog eventually forms. This process can be classed as formation of aerosols (the fog particles must grow greater than ~5 µm in size to become visible). Though this process can occur through homogenous nucleation, more often it occurs heterogeneously (condensation of moisture on solid aerosol particles, which serve as condensation nuclei). If the water condensed on aerosol particles, its further migration inside cave will be governed by aerosol mechanics, rather than by gas dynamics.

Dripping and splashing water (from waterfalls, flowstone, etc.) can evaporate into cave air and be transported to other cave locations and condense. Splashing produces relatively large (~10 µm) hydroaerosol particles, which increases the specific surface of the liquid and fosters evaporation. Also, water for condensation/evaporation processes can be introduced as surface water flowing into a cave. The pattern of condensation/evaporation processes can be influenced by the airflow structure of the cave (see, e.g., data on the air flow directions inferred from the orientation of cave popcorn in Carlsbad Cavern; Queen, 1981).

Even though the data concerning condensation on the object level are abundant, these data are mostly descriptive, and studies presenting numeric estimations of condensation are quite scarce. Some examples are given below.

Studying archeology of the medieval cave towns in the Crimea, Firsov (1990) has noticed intensive condensation occurring in some crypts in summer. He estimated that a crypt carved in massive limestone and having the volume of 5.5 m^3 generates 0.25 l m^{-2} day^{-1} of condensate. Prokofiev (1964) was first to perform the direct measurements of the amount of condensate forming in different rooms of Vorontsovskaya Cave in the Western Caucasus. He used original traps for condensed (and partly infiltrated) water. The traps yielded up to 1300 g m^{-3} of water at an air exchange rate of $161.3 \cdot 10^6$ m^3 day^{-1}. Similar observations were carried out in a number of caves in Europe and Asia.

Condensation was also studied by means of lysimeters and condensers with differing designs (metallic cones, cylinders, boxes, casing tubes, polyethylene canisters, etc.), varying sizes (from 0.01 to 1120 m^3) and various types of filling material (sand, gravel, pebbles, limestone boulders). They were installed or constructed at altitudes ranging from 190 to 1100 m in the Crimea, Caucasus, Central Russia, Kola Peninsula, and Southern and Eastern Siberia. The yield of water in these experiments varied from 0.01 to 2.3 l day^{-1} from each cubic meter of the filling material (Table 3). Attempts to use these values directly to calculate condensation in adjacent karst massifs have failed (Glukhov, 1963; Klimochkin, 1973).

THE ROLE OF CONDENSATION IN KARST

There are several aspects of condensation in karst: (1) increase of the amount of water moving through the rock; (2) increase in the total volume of karst porosity; (3) formation and destruction of cave deposits; (4) alteration of cave microclimate. The data on these processes are scarce and often con-

Table 4
Chemistry of condensation waters.

Parameters	Moisture condensed on clean surface	Stationary drops on the ceiling	Trails and films on the walls	Source
Carbonate Karst				
Number of samples	7	55	66	DUBLYANSKY, 1977;
Mean TDS mg l-1	106	22.0	140.0	DUBLYANSKY et al., 1985;
Mean TDS CV	0.58	1.15	0.25	HOMZA, RAJMAN, & RODA, 1970
Hydrochemical type	HCO_3-Ca(Mg)	HCO_3-Ca	SO_4-HCO_3-Ca	KLIMOCHKIN, 1973;
Chemical denudation				NEMERIUK & PALTSEV, 1969;
µm×year-1				MAIS & PAVUZA, 1994;
calculated at 10ºC	-	-	2-19	MUCKE & VOLKER, 1978;
actual	-	-	0.5-4.0	PROKOFIEV, 1964
Carbonate Hydrothermal Karst				
Chemical denudation				SZUNYOGH, 1990
µm×year-1 (*)				
at 60ºC	-	-	200-50	
at 20ºC	-	-	30-4	
Sulfate Karst				
Number of samples	-	5	44	DUBLYANSKY et al., 1984;
Mean TDS mg l^{-1}	-	2000	2100	MALKOV & FRANTZ, 1981;
Mean TDS C_V	-	-	0.27	MUCKE & VOLKER, 1978
Hydrochemical type	-	SO_4-Ca	SO_4-Ca	
Chemical denudation				
µm×year-1				
calculated at 10ºC	-	-	92-730	
actual	-	-	90-121	
Rock Salt Karst				
Number of samples	-	-	17	BELTIUKOV, 1989;
Mean TDS mg l^{-1}	-	80000	322000	EREMENKO & KOLPASHNIKOV 1974
Mean TDS C_V	-	-	0.8	
Hydrochemical type	-	Cl-Na(K)	Cl-Na(K)	
Chemical denudation				
µm×year-1	-	-	21,000	

All samples are composite (many drops are mixed). They were typically collected at the end of a long period of nil precipitation or when the massif was covered by snow. (*) Growth of a spherical niche slows down with increase of its diameter; TDS - total dissolved solids

troversial.

INCREASE OF THE AMOUNT OF WATER AVAILABLE FOR SPELEOGENESIS

Our data suggest that the share of condensation in the water balance does not normally exceed 9% of the annual sum of precipitation (Table 2). However, condensation occurs during the warm season, when there is not much of precipitation. It plays, thus, an important role in the dry-season discharge of karst springs and rivers. Winter condensation does not increase the total amount of underground water, but prevents moisture from escaping the subsurface and creates specific local patterns of water circulation. These general conclusions need to be checked and numerically assessed by regional- and local-level studies.

DESTRUCTIVE PROCESSES

Many workers believe that condensed waters initially have exceptionally high aggressiveness with respect to bedrock limestone (Trombe, 1952; Gvozdetsky, 1954; Bernaskoni, 1966; Andrieux, 1970; Gergedava, 1970; Pasquini, 1973; Ginet, 1977; Mucke & Völker, 1978). The data on the composition of condensate from different karst massifs of Eurasia are compiled in Table 4.

Analyses were mostly performed on composite samples (up to 10,000 individual drops) collected from cave walls, which means these waters had the ability to dissolve the bedrock. Condensate has quite variable mineralizations (TDS; C_v up to 1.15), differing in karsts in different lithologies. Condensate water collected after a certain travel (30 to 100 m; flow as films and trails along walls) has higher mineralizations and lower coefficients of variation C_v (0.25 to 0.60). This suggests intensive corrosion of the bedrock.

The data on samples collected on a clean cool surface (ice-filled containers or refrigerators) are scarce. In some cases the measured TDS are low (e.g., 8.27-8.31 mg l^{-1} in Ochtinskaya Aragonite cave in Slovakia; Homza, Rajman, & Roda, 1970). In other cases, surprisingly high values of TDS were obtained (e.g., 130-170 mg l^{-1} in Hermanshöle in Lower Austria; Mais & Pavuza, 1994). Tarhule-Lips (pers. comm.) has found that the air moisture sampled in several caves of the Cayman Braker islands (Caribbean sea) can be slightly undersaturated to slightly supersaturated relative to bedrock limestone. This problem warrants further rigorous study.

Numeric estimation of the share of condensation in the water balance has been done only for one karst massif (Alek, Western Caucasus; Dublyansky et al., 1985). The total chemical runoff due to condensation in the warm period was calculated to be 41.2 tons (16.2 m^3) of limestone, which accounts for only 3.7% of the gross value of karst denudation. Condensation corrosion is most intensive in July (19%) and August (16%). At present, data are insufficient to estimate the speleogenetic role of winter condensation.

Many forms of cave macro-, meso-, and micromorphologies are attributable to condensation-corrosion. These are: spherical chambers 1 to 3 m in diameter in hydrothermal caves (Szunyogh, 1982; 1990); cupolas and ceiling bells (Andrieux, 1970; Mucke & Völker, 1978); solutionally widened fissures, niches, cells, vertical gutters, rills, edge patches, drop dents, indentations, etc. on cave walls (Bernaskoni, 1966; Eraso, 1969; Mais, 1973; Cigna & Forti, 1986; Davis & Mosch, 1988; Beltiukov, 1989; Jameson, 1989; 1995) (Fig. 8). Condensation corrosion often cuts through not only the bedrock, but also cave infilling (calcite, gypsum, salt, and ores) and speleothems (Hill & Forti, 1986).

Condensation may be particularly important in hydrothermal karst. During the stage of partial dewatering, when there is a free water surface in air-filled caves, thermal water may evaporate, move to the upper (cooler) parts of the cave due to convection, and condense on the cave walls (Fig. 7). The air

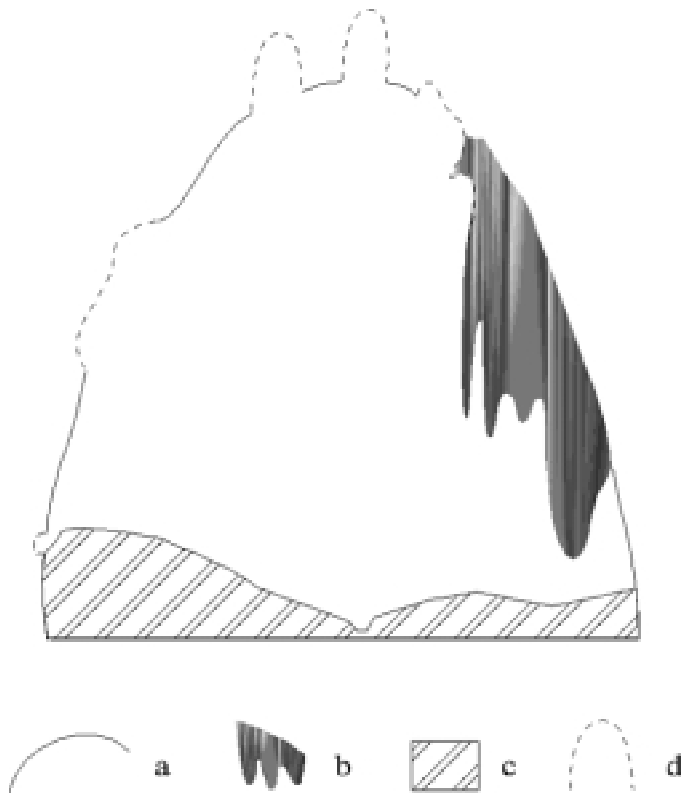

Figure 8. Destructive action of condensed waters. a - primary karst cavity; b - speleothems; c - cave sediments; d - morphologies caused by condensation corrosion (cupolas, niches, facets, grooves, pits, etc.).

mass above the surface of a thermal lake is thermodynamically unstable, because the warmer (less dense) air lies below the cooler (denser) air. Thus, air convection readily develops. Aggressiveness of the condensate is controlled by the content of CO_2 in the cave air and by the thickness and flow pattern of the films of condensate.

Another situation, particular to hydrothermal caves, is corrosion due to the presence of H_2S in the cave air. Worthington and Ford (1995) have shown that a high content of sulfate is characteristic of the thermal waters which contributes to dissolution of hypogene caves. During the stage of partial dewatering, the hydrogen sulfide in thermal waters escapes into the cave air. Some of it redissolves in films or droplets of condensate, where it is oxidized by dissolved oxygen. Produced sulfuric acid attacks limestone converting it to gypsum, forming fragile gypsum crust on the cave walls and ceiling. Such a mechanism, termed "replacement-solution", was suggested by Egemeier (1981). It is important to note that replacement-solution must be coupled with condensation (gypsum crust does not form on dry cave walls). Many caves of fossil hydrothermal karst exhibit morphological features which can best be explained by the discussed mechanism. Examples of such caves are known in Hungary (the Buda Hills), Kirghizstan (the Tyuya-Muyun), Algeria (the Bibans), and elsewhere. The process of replacement-solution is still active in caves of the Pryor mountains, Wyoming (Egemeier, 1981) and Grotta Grande del Vento, Italy (Cigna & Forti, 1986).

ACCUMULATIVE PROCESSES

Condensation coupled with evaporation and aerosol mass-transfer may play a significant role in the formation of a variety of speleothems. Hypotheses for a condensation origin of stalactites (though incorrect) were advanced by H. Jacob, E. de Clave, and J. Beumont in the seventeenth century (Shaw, 1992). Holland et al., (1964) included a group of condensation-related speleothems in their classification of cave formations. Cser and Mauha (1968) suggested an aerosol origin for one type of helictites and supported this hypothesis by means of an elegant experiment (fragments of calcite crystals were set in a plastic frame; 90 volts DC were applied to the base of the frame and the latter was exposed to the cave atmosphere; appreciable growth of crystals was observed after a several-month exposure). Many examples of speleothems supposedly related to condensation are given by Hill and Forti (1986). They suggest a condensation-related origin (along with other possible modes of formation) for a number of subaerial speleothems, such as: coatings and crusts (p. 29); coralloids (popcorn, coral, grape, or knobstone shapes; p. 33); rims (p. 54); ice frost crystals (p. 83); moonmilk (p. 116); as well as to clay vermiculations (p. 161). These speleothems are composed of calcite, gypsum, halite, carnallite, nitrates, and some other minerals. The list of specific formations of cave ice attributed to condensation is even larger (Mavliudov, 1989). More and more often, scientists resort to aerosol-condensation theory to explain the origin of some peculiar gypsum and carbonate speleothems (Calaforra & Forti, 1994; Turchinov, 1994; Klimchuk, Nasedkin, & Cunningham, 1995; Dublyansky & Pashenko, 1997).

CAVE MICROCLIMATE

The pattern of condensation in caves is controlled by cave microclimate. There exists, also, a feedback. Condensation of water is accompanied by significant yield of heat (585 kcal kg^{-1}). This affects cave microclimate; specifically it changes the fields of temperature and humidity (Andrieux, 1970; Molerio, 1981; Racovitca & Viemann, 1984). One of the prominent examples of such an impact is the short-periodic (seconds to tens of seconds) auto-oscillations of air movement, overprinting the more long-periodic "cave breathing" of barometric nature (Finnie & Curl, 1963; Dublyansky, 1977). Such auto-oscillations were reported from Krasnaya Cave in the Crimea (Dublyansky & Sotskova, 1989).

CONCLUSION

The problem of condensation in karst is a quite complex one. The data about condensation in the karstosphere are scattered in publications of karst researchers, physicists, chemists, meteorologists, hydrogeologists, mining geologists, soil scientists, geographers, glaciologists, biospeleologists, archeologists, construction engineers, etc. These specialists consider particular aspects of condensation and use research methods specific to their sciences. There is no consensus in the literature on the role of condensation in formation of karst waters, as well as on its role in formation of caves.

The problem of karst condensation can be studied with either a hydrogeologic or speleogenetic approach. Each line of approach is very different and the two approaches are seldom combined. The hydrogeological aspect of condensation deals with the role of condensation at the scale of a karst massif. Examples of typical problems are: (1) the share of condensation in water balance; (2) the role of condensation water in karst denudation; (3) the chemistry of condensed water; (4) patterns of moisture and condensate migration within karst massifs during different seasons; etc. Such a large-scale approach makes it necessary to generalize many characteristics, such as the fissuration of rock, or the coefficients of air-exchange at the scale of the karst massif, which necessarily decreases the preciseness of the results. In the framework of the hydrogeological approach, atmospheric moisture is considered to be a major source of water involved in condensation (and thus, karst) processes.

The speleogenetic approach deals with the role of condensation in the development of individual caves, the carving of smaller solutional forms, and the creation of speleothems. The smaller scale makes it necessary to perform more precise measurements of pertinent parameters (temperature of air and condensate; humidity, chemistry of condensate, etc.). These parameters can be used in laboratory- and theoretical modeling of cave-forming processes. The ultimate purpose of these studies is to explore the possible role of condensation in the creation of specific cave morphologies and speleothems, and to find the mechanism(s) involved in these processes.

When using the speleogenetic approach, one should consider more than just the moisture brought into the cave with the outside air. In caves containing water (lakes, streams, etc.), the water may evaporate from water surfaces, migrate, and then condense in different parts of the cave (Hill, 1987). Condensation of moisture from cave air and from evaporation of standing waters is also possible due to change of thermodynamic characteristics inside a cave (Dublyansky & Lomaev, 1980; Badino, 1995).

One important problem which has not been studied adequately yet is the relationship of condensation and cave aerosols. The moisture in the cave air may exist as more than just a form of vapor; it may also exist as all-water aerosol particles (hydroaerosols; Gádoros & Cser, 1986), as well as shells on solid aerosol particles (Pashenko et al., 1993; 1996). The laws of gas dynamics and aerosol mechanics are different, thus the migration of water in these two forms must have different patterns. Elevated contents of radon, typical of the cave air, foster the radiochemical reactions between hydroaerosol particles and gaseous components of the cave atmosphere. For instance, radiochemical processes may convert H_2S of the cave air (even in very small amounts) into H_2SO_4, which dissolves in water of hydroaerosols and drastically increases aggressiveness of the latter. It is becoming apparent that aerosols can play a significant role in mass transfer of moisture and speleothemic material inside caves, and can be particularly important in the formation of speleothems (Dublyansky & Pashenko, 1997).

Although awareness of the importance of these processes is growing, neither condensation nor cave aerosols have been adequately (quantitatively) studied to date. The future studies should develop a comprehensive theory of gas and aerosol mass transfer in caves, involving evaporation, convection, aerosol and gas mass transfer, and condensation. This problem is an interdisciplinary one; it warrants coupled efforts of hydrogeologists, meteorologists, physicists, and karst researchers.

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