CHANGES IN WATER LEVEL REGIMES IN KARST-DENUDATION REGIONS, INFLUENCED BY MINING ACTIVITY, IN THE VARIOUS LIMESTONE AND DOLOMITE RESERVOIRS

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Both in Hungary and on a world scale, a vast amount of data has been accumulated from observations made in connection with deep-mining activity, and this information has contributed to a better understanding of the internal hydraulic regimes of karsts. Although concrete experience is always restricted to local phenomena, if the data on a sufficient number of cases are systematized, the general regularities can be formulated. In Hungary, comprehensive experimental information on karst water levels has primarily been acquired in the regions of the Transdanubian coal-mines and certain deep bauxite mines. If this information is compared with the data on the long-term water yields of karst springs and with the curves depicting the changes in time of the productivity and capacity of artificial wells for the utilization of karst water, accurate correlations may be obtained concerning the nature and magnitude of the horizontal and vertical communication conditions in the deep rock strata in which karst water is stored.

Above all, it has been demonstrated that, for compact, uniform-structured limestones, in a practical sense it is not possible to speak of interstice porosity of matrix type, and even crystalline rocks hardly possess such a porosity. This is probably connected with the diagenetizing compaction of the lime mud and, for crystalline rocks, with the metamorphizing compression inducing recrystallization, generally at high layer pressure and temperature.

Attention must also be paid to mining experience from strata below the most compact limestones, virtually without interstice porosity, are able to store water under pressure. It is stated by KASSAI, for instance, that „In the Esztergom coalfield, the limestone below the water danger level is everywhere much wetter than the mine moisture level. Water drips even from apparently completely compact limestone, and the more so, the deeper we are beneath the water danger level, i.e. the greater the hydrostatic pressure."

This latter observation, which apparently contradicts the results of petrologic tissue examinations, is undoubtedly objective and correct. It is still not satisfactorily decided what proportion of the water stored in the rock in the mining example involves the rock porosity itself, and what proportion the microcracks consealed in the limestone; this latter must also be taken into account, almost from the final stage of the process of diagenesis in most limestones. Similarly to the rocks of the reservoir levels at Nagylengyel, the limestones and dolomites (primarily Triassis) studied in the Esztergom coal-mining region have practically no water-permeabillity capacity resulting from porosity of a matrix nature.

The question of rock porosity can in any event not be treated schematically. The development of a relative freedom from porosity is to a certain extent a question connected with the geological age. It can be demonstrated that the limestones are in general the more compact, the older they are in a geological sense. A considerable intrastructural interstice volume may be encountered in young (from the end of the Tertiary and from the Quaternary) limestones. For example, the matrix porosity of Sarmatian limestone in Central Europe is generally 1–7%, whereas that of younger freshwater limestones (tufaceous limestones, meadow limestones, etc.) may exceed even 10–20%. Naturally, this porosity level makes a significant contribution to the liquid-accepting capacity or the water-permeability capacity of the limestone, i.e. these limestones also possess structural permeability.

The development of the cracks and breaks (in general the lithoclase network) is primarily a consequence of the compact, dense structure of the older limestones. The compactness means that the limestone behaves as a very inflexible and brittle substance to forces acting on it, and it cannot respond to them with even the slightest deformation.

Severely crumpled limestones too are to be observed in certain surface mines (e.g. in the Mecsek Hills); these could accommodate to the tectonic forces only by breaking into thousands of pieces, and accordingly such strata are always more or less friable. If they display a continuous consistency, they are the result of a secondary, postgenetic cementation process.

The limestone in the Earth's crust is always subjected to physical forces (mountain-forming and layer pressures, tectonic forces) which lead to the development of a strong degree of microcracking. The less recrystallized the structure of a limestone, the greater the possible extent of cracking. In other words, this means that the brittleness of the rock is decreased somewhat by the secondary recrystallization. We refer here to the excellent translation of calcite crystals.

Having studied the structural rupturing of several hundred limestones of different geological ages and from different sites of occurrence, we have found the interesting correlation that the quantity of the micro-lithoclases of limestones is a function, among others, of the geological age. We have found the largest number of structural cracks (10–36 per unit surface) in Palaeozoic sedimentary limestone formations, less (6–20 per unit surface) in limestones from the Mesozoic, and the least (1–8 per unit surface) in those from the Tertiary. At the same time, tufaceous limestones from the Quaternary (Pleistocene and Holocene) do not contain such structural hairline cracks, or only very rarely. This is otherwise to be expected, if it is borne in mind that the younger rocks were clearly affected by fewer tectonic and other forces.

However, it is also noteworthy that the structural cracks in limestones from the Carboniferous and earlier are often strongly cemented together by calcite deposits. Our results coincide in all respects with those of similar studies carried out by Dedinszky at Nagylengyel.

It is a very important fact that *the structural cracks that have developed in the limestone are themselves not sufficient* to convert the rock into a formation permeable to water. *The interstices and hairline cracks* (generally attributable to crust pressures) in the geologically older rocks (which can a priori be regarded as cracked) *play practically no role in the flow of the karst waters under layer conditions*; the diagenetic and tectogenetic interstices in the rock compressed by the layer pressure are so narrow that the possibility for liquid to move in them is prevented by the surface adhesion of the walls of the interstices, which is more effective by several orders of magnitude. Consequently, one of the petrological characteristics of limestone and dolomite formations to be found a depth of several hundred, or even 1000–2000 m can be stated with high reliability to be their impermeability.

The situation changes radically, however, if these rock formations come into a hydrological environment which, in certain rock levels and regional ranges, involves the chemical and physical conditions of *directed corrosional or erosional attack.*

By directed hydrological attack, we understand that the rock formation is subject to a lime-aggressive hydrodynamic pressure excess from some preferred direction, and that this is so much greater than the hydrostatic pressure that it is able to overcome the adhesional forces in the widest interstices in the rock and to induce the flow of water in these interstices. If the solutions flowing through the system of interstices are aggressive as concerns carbonate rocks, these interstices simultaneously begin to be broadened out by corrosion. This naturally reacts in a reversible way on the adhesion forces: the wider the interstices in the water-conducting system, the lower the resistance it exerts against the flow of water. In the very first stage of directed hydrological attack, therefore, this process will give rise to *a state of selective karstic further development of the primary interstice network in the rock*. This is manifested in the fact that there will be certain interstice communication systems in the interior of the rock formation; as a result of the corrosion (and possibly of later alluvial erosion), these will be broadened out rapidly and grow into an internal network of channels. At the same time, an enormous number of the initial interstices in the rock will be preserved, i.e. they do not join the movement of fluid, the minewater reserves remain as water stagnating due to its adhesional binding, and therefore inactive water.

From this moment on, the whole of the karst formation is to be regarded as a permeable formation, in spite of the fact that some detail of the rock formation or the rock specimen itself behaves perfectly impermeably in various laboratory permeability tests. *Carbonate rocks therefore have the basic fluid-permeability characteristic that the movement and storage of fluid occur not in the matrix, and not in the hairline cracks or in the possible stylolites, but virtually exclusively in certain concrete (karstically broadened out) interstice systems, in the interior of blocks of rock that can otherwise be considered to be homogeneous and water-impermeable masses.*

The above findings harmonize in all respects with the mining experience. Very long mine galleries can frequently be driven into the karstic rock formations in the deep levels below the karst water level, without an appreciable flow of water being observed. However, if the gallery happens to intercept a karstically broadened interstice system, this may lead to the influx of amounts of water that are catastrophic as concerns the future operation of the entire mine, whereas even half a metre previously there was no sign of water. The experience acquired from the rescue and pumping operations following such mine floodings confirm that the corrosionally (or erosionally) broadened out passages in the karsts possess extremely long open hydrological communications.

Mining activity at levels below the karst water level, and even considerably deeper (eocene programme), has demonstrated that in the interior of most karst blocks there are *markedly karst water dangerous* and *markedly danger-free levels or seams*; this clearly indicates that the degree of cavity formation within a block or group of blocks consisting of limestone or dolomite is extremely heterogeneous both horizontally and vertically. This is connented with the fact that the karst processes are generally only two-dimensional in the three-dimensional mass of rock, i.e. *they relate to some plane*, but even within this plane they are usually *linear*.

It can readily be seen that those channels which developed in definite levels in response to the karstification effects in the interior of the karst blocks communicate sensitively with one another hydrologically. The liquids in them are in motion in a flow system, or are in a static state. The experience from extensive measurements proves that the more intensive the movement of fluid within some network of karst channels, the closer is the base of the karst, which can generally be defined to a good approximation by the surface level of the karst water.

In contrast, under the undisturbed conditions in the deep karst, the karst water undergoes no, or scarcely any movement, these movements at most generally involving the slow translocation of mass, to an extent depending on the thermodinamic convection. However, if the duct system storing water in the interior of the karst is tapped off somewhere, a forced flow of water immediately begins, from the water-capture (replacement or inflow) points towards the depression centre produced by the drilling, mining operations or other means. The more active the water flow in some karst network, the greater the rate of further broadening (by corrosion or alluvial erosion) of the caverns ensuring the supply of the water; for the corrosion (erosion) to persist, it is necessary for a continuioius supply of water masses capable of work to flow to this region.

The further karstification of the walls of the water-bearing karst channel network is a regular characteristic of all extensive limestone or dolomite karsts: the more extensive some surface or merely subsurface (buried) karst zone, the greater the possibilities of surface and subsurface flow to and from it, this inducing in it flow systems in different directions. The very valuable results of water-labelling experiments in the karst regions of the Totes Gebirge in Austria and Frankenalb in West Germany have been reported by Maurin, Zöttl and Apel. These clearly reflect not only the directions and the surprisingly large distances (several times 10 km) of the deep flows, but also their unexpectedly high velocities.

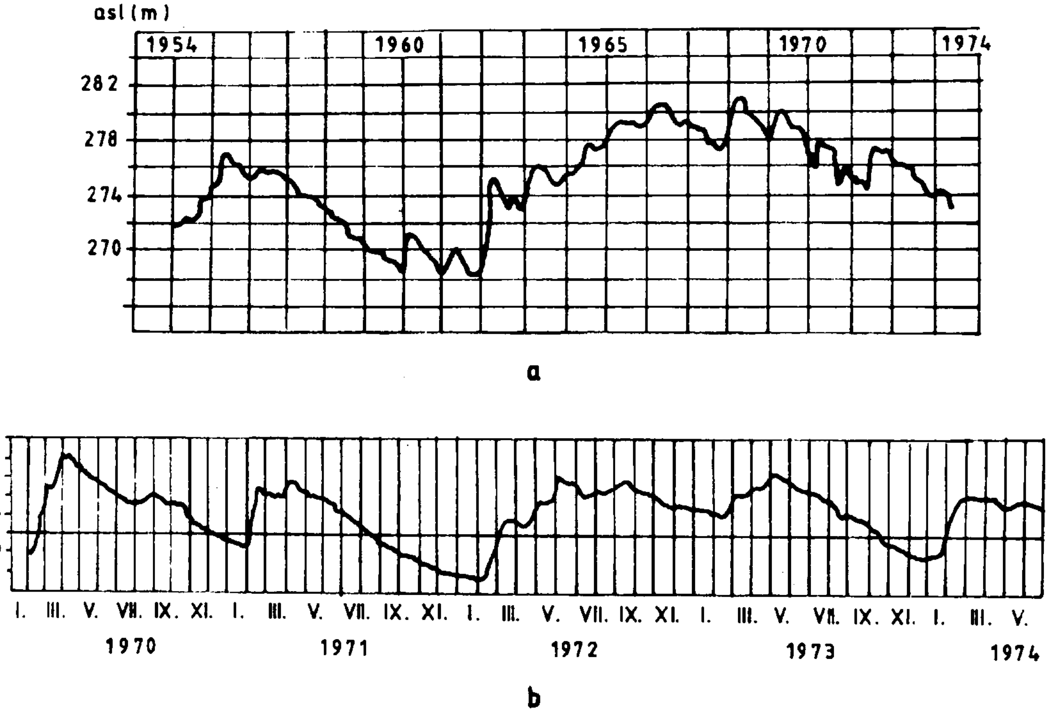

Fig. I. Fluctuation of karst water level in the Bakony Hills (after Böcker).
a. long-term fluctuation in observation well no.1;
b. seasonal fluctuation in observation well no.7.

It should further be noted that flows are also present in the cavity networks below the karst water level in those cases when neither absorption nor tapping-off foci can be confirmed. In such cases, the carst water level fluctuations reflecting the degree of precipitation generally follow the long-term and short-term changes in the climate. In the karstic passages filled with liquid, these fluctuations naturally induce equilibrating flows in a horizontal plane area. Figure 1 depicts the long-period and short-period karst water level fluctuations as a function of the precipitation in an area of the Bakony Hills (Fig.1.)

The deep-mining experience from Dorog, Tatabánya, etc. clearly documents that *vertical fluid communications* too exist between the leached horizons that have developed in a well-separated way, above and below one another, formed in the karsts in the different periods. In the view of most research workers, these communications are produced along the breakplanes and other tectonically strongly transverse tracts, generally postgenetically compared to the karst-formation stages.

A part is also played in the karstic cavity formation by the tectonic planes in the stages before the karstic activity periods; however, this role is primarily expressed in the *preformation* of the developing passages, i.e. in the circumstance that the main directions and axes of the caverns undergoing leaching-out correspond to or coincide with the strike directions of the tectonic lineaments.

This interdependence is so correlative in most karsts that it may be utilized to determine the relative age of the groups of phenomena. If the corrosional (or erosional) karst cavern systems have axis directions coinciding with the tectonic directions (the passages were tectonically preformed), the tectonic activity of necessity also displayed activity phases in geological times earlier than the karstification. However, if the direction of the karst passages is independent of and different from the tectonic directions, this definitely points to neotectonism younger than the karst.

Of course, this does not exclude the possibility that a tectonic break plane produces rock movements in several phases (both before and after karstification). In this case, however, the cavern systems in tectonically determined situations undergo damage, being changed into a chaotic rock labyrinth filled with rock debris or possibly with founder breccia.

Abundant examples of all three types of basic situation are provided by the caves and by the caverns exposed by the mining activity in the deep karsts of the Transdanubian Central Hills. Numerous sections of the Ördöglyuk Cave at Solymár are almost completely independent of the tectonic planes of the rock formation. A similar phenomenon was observed during the mapping of the hydrothermal cavities in the Sátorpuszta Cave near Dorog. Accordingly, these cave passages had presumably already developed in the interior of the rock mass when the breaks determining the present tectonic picture had not yet occurred. In contrast, the Ferenchegy Cave in the Buda Hills is clearly tectonically preformed; it is a cave passage exhibiting a truly grid-like horizontal plan, which convincingly demonstrates the tectonic preformation in the corrosional cavity-development phase. The frequently confused heaps of rock blocks in the Mátyáshegy Cave, however, clearly indicate that the leaching-out period was not only preceded by prekarstic tectonism, but was also followed by one or more periods involving neotectonic crust activity.

After this, it is perhaps unnecessary to give further justification as to how important it may be to know precisely not only the exact sites of the breaks, but also their activity periods, in the hydrocarbon-bearing deep karst at Nagylengyel. Only in the knowledge of these correlations can an attempt be made to adopt some standpoint as concerns the assessment of the extent and nature of the vertical hydrological communications between the deep-lying leached-out horizons (with a determining role in the hydrocarbon bearing).

Without going into a detailed study here of the concrete situation at Nagylengyel, one should recall the increasingly well-known correlation expressed in the subsidence of the karst water level throughout Transdanubia, and in the drying-up of the water supply of certain groups of cold and even hot springs (see Figs. 1 and 2 and Table I), following the ever larger utilization of water from the Transdanubian deep-karst caverns.

Unfortunately, the signs indicate that the deep-karst leaching-out horizons in

Table 1.
Water utilization from the karst water system of the Trasdanubian Central Hills

Water utilization			1957	1978
manner	reason	site	Q,m^3/min	Q,m^3/min
Artificial	Mining	Csordakút	–	5
		Dorog	63.2	6
		Tatabánya	44.2	136
		Kincsesbánya	13.6	74
		Várpalota	2.7	15
		Balinka	3.2	15
		Dudar	1.6	2
		Ajka	18.2	16
		Nyirád	4.0	307
		Total	150.4	576
	Total water supply		114.4	100
Total artificial tapping			265.1	676
Natural	Springs	Héviz	34.8	26.1
		Tapolcafő	55.7	0
		Tata	27.0	0
		Budapest hot springs	59.1	32.3
		Balaton uplands	111.6	20.4
		Total	288.2	78.8

Transdanubia possess hydrological correlative systems that are well-elaborated and defined not only horizontally, but also vertically. In the various Transdanubian regions and in the most varied depths of these karsts, the hydrological communications between the karst water passages are very similar to those between the blood vessels in the human body. It is highly possible that the deep karsts at Nagylengyel also belong in this large regional system of wide-ranging connections, independently of whether water or oil is currently stored in their passages. At any event, the likelihood of such possibilities is further increased by the drying-up of the Tapolca Lake Cave and by the considerable decreases in the yield and the temperature of the Héviz Lake (see Table 2 and Figs. 3 and 4).

It is quite understandable, therefore, that a correct conception of the characteristics of the karst that has subsided in the depths so as to be at present inaccessible for direct empirical observation and for geological and karst-morphological survey, can be formed only if the features generally valid for the models of other karsts that

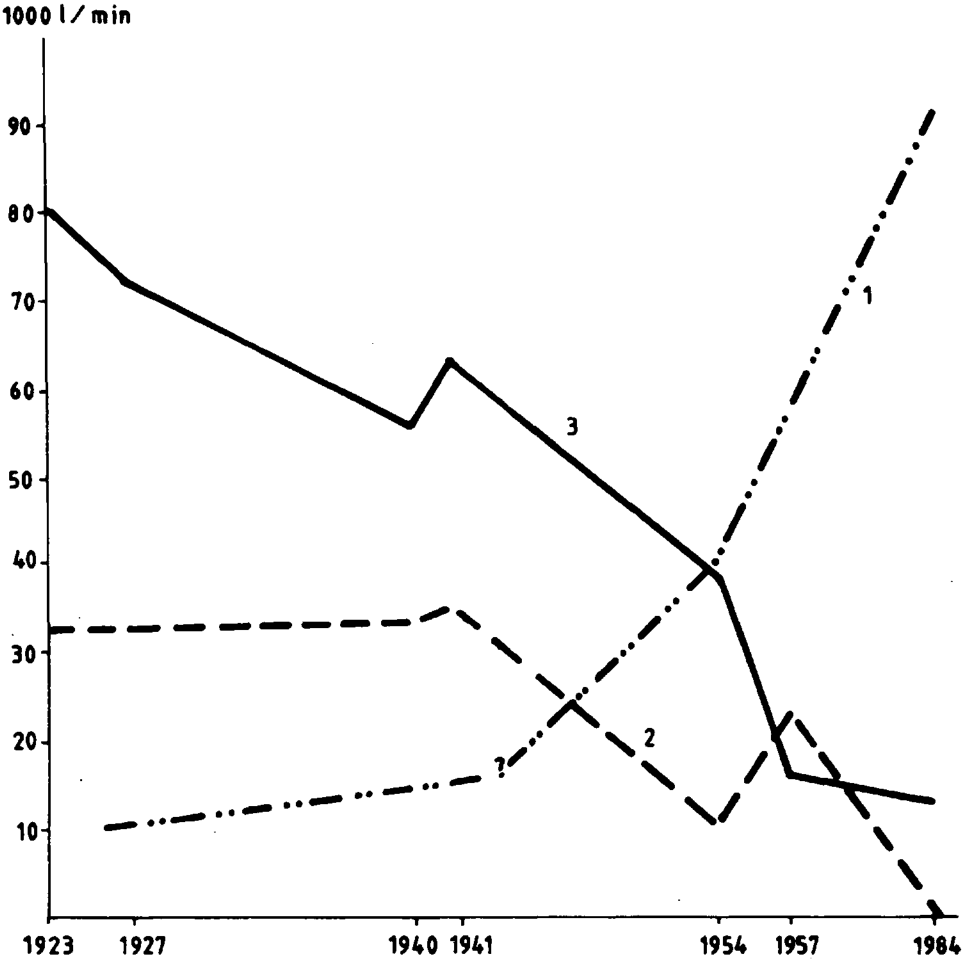

Fig. 2. Even in 1964, there were unmistakable signs of a fall in the Transdanubian karst water level as a consequence of the karst water utilization exceeding the seepage due to the precipitation. The Figure shows the correlations of the karst water utilization by the precipitation. The Figure shows the correlations of the karst water utilization by the coal-mines at Tatabánya and the changes in water yield of the springs at Tata, about 19 km away, in the period 1923–1964 (based on the 1968 compilation by Wagenhoffer, with the yield data of Csörnyei, Lenkei, Horusitzky, Kessler and Papp).

1 = measured or estimated quantity of karst water pumped out of the Tatabánya workings;
2 = water yield of the Tükör Spring at Tata;
3 = water yield of Fényes Springs at Tata.

Table 2.
Water utilization and water level fall in the bauxite area at Nyirád

Year	Average water utilization m^3/min	Fall in water level mB.l*	Water utilized (m^3) / Bauxite mined (t)
1960	10.2	173	32
1965	76.4	164	451
1970	212.7	129	268
1971	208.8	123	254
1972	245.5	113	241
1973	272.2	105	224
1974	286.9	97	168
1975	278.1	94	136
1976	259.6	92	142
1977	290.0	87	164
1978	304.7	81	182
1979	301.6	77	179
1980	300.4	72	172
1981	296.7	68	181
1982	276.0	65	209
1983	270.5	62	217

*mB.l = height in metres above Baltic Sea level

may be studied on the surface too are correlated to the deep-situated masses of karstic rock.

The principle that holds most generally for karsts is corrosional attack, i.e. the circumstance that water of precipitation (or sometimes other) origin produces cavities of various sizes in the different parts of the carbonate layer formation by leaching out the rock. The dissolution occurs in all cases on those surfaces where the aggressive water is in direct contact with the rock. The dissolution is therefore always a surface (two-dimensional) phenomenon, independently of whether this surface is the free surface of some rock layer, or the surface of some rock tube, rock crack, or even a capillary-sized micro-interstice. However, the karstic dissolution (corrosion) does not penetrate into the pore spaces in the rock, and it does not develop the matrix of the rock therefore.

The second axiom is that any water (solution) is capable of dissolving the carbonatic rock only up to the limit of its dissolving ability (corrosional capacity). Thus, if a solution is saturated up to the level of its dissolving ability, it can no longer dissolve up carbonatic rock. Accordingly, when water first penetrates into a narrow rock crack, stylolite or rock capillary, this water dissolves up rock until it is saturated. However, if the crack, stylolite or capillary is so narrow that the water is retained in it by forces of adhesion (it becomes mine moisture), it can not carry out further dissolution, i.e. the corrosion comes to an end, and the water in the interstice ramains for a very long time in a state of static and chemical rest.

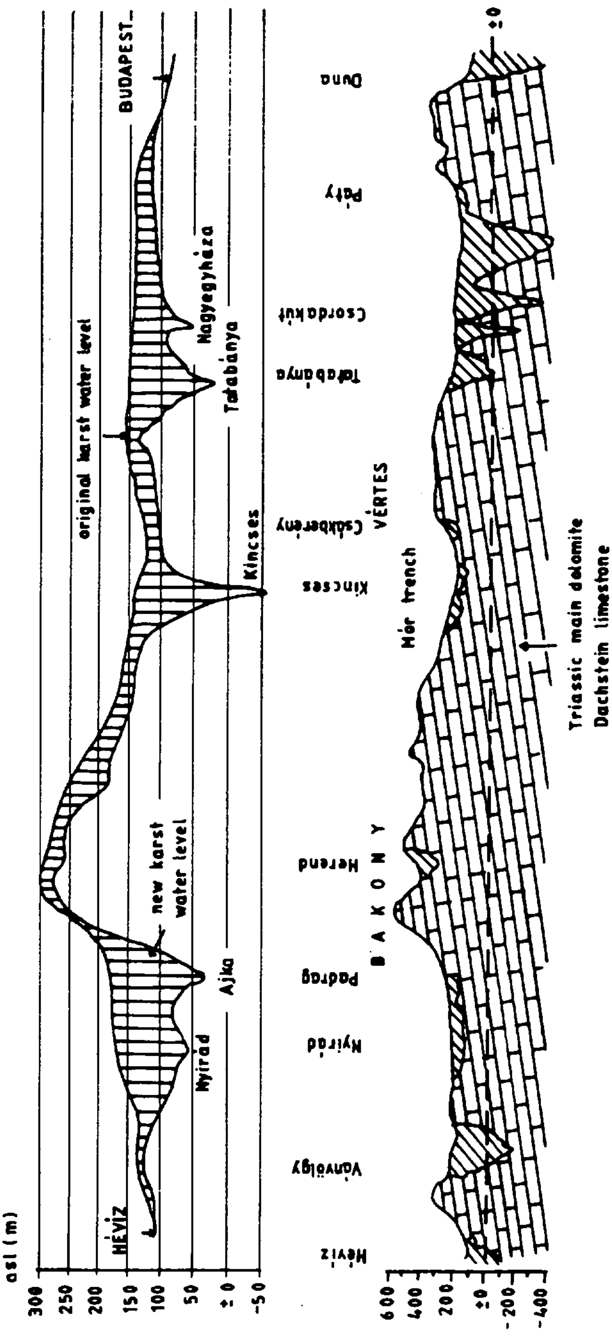

Fig. 3. Longitudinal (strike direction) hydrogeological section of the main karst water system of the Transdanubian Central Hills.

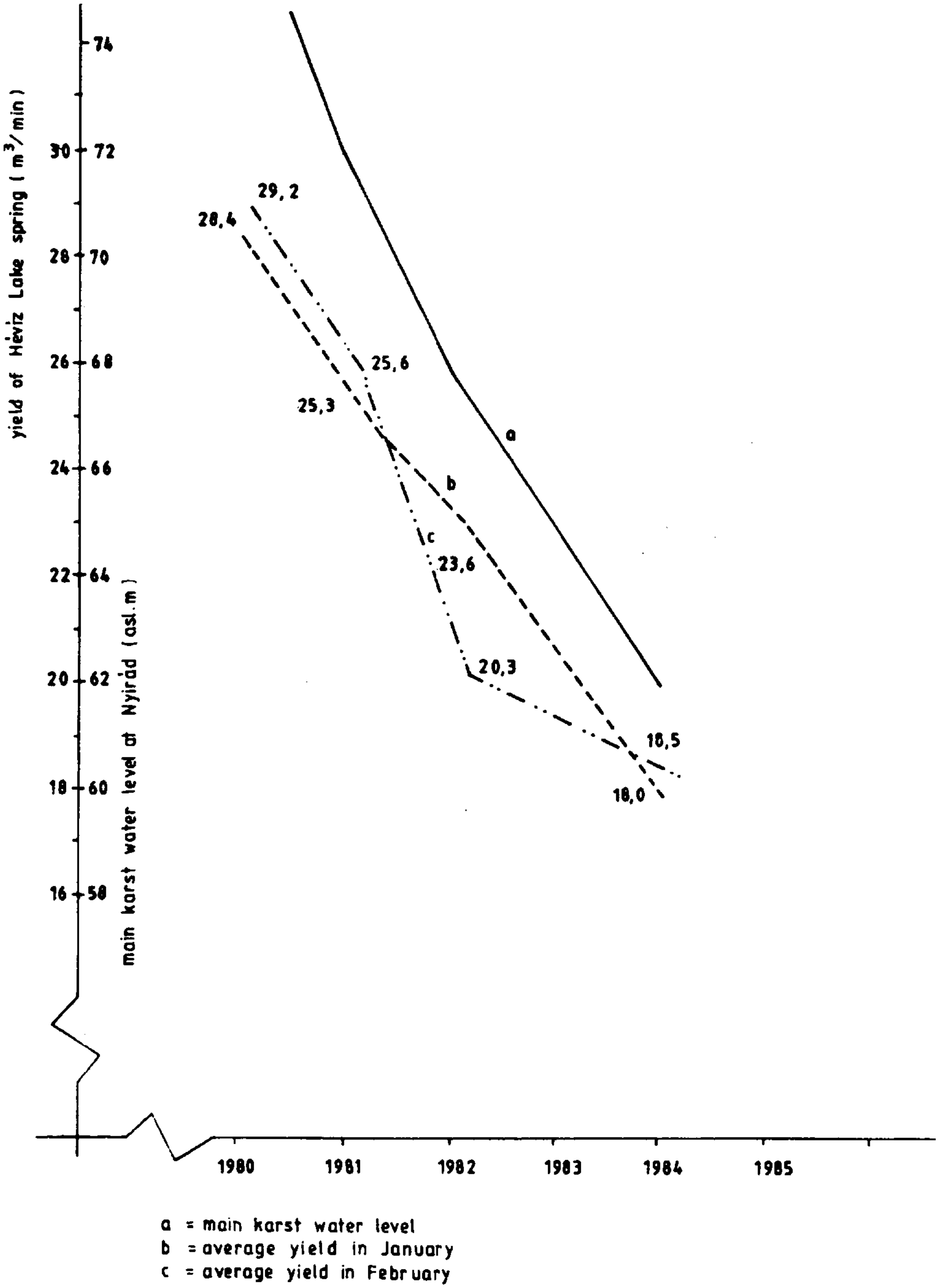

Fig. 4. Average yields of the Hévíz Lake spring in January and in February, and variation of the main karst water level at Nyirád, in the period 1980–1984.

On the free rock surface, and in those rock interstice systems which are in hydraulic communication with one another and which are already sufficiently wide for the total quantity of solution entering them not to be bound there by adhesion, the water moves on further under the influence of gravity, so that it is constantly being replaced by new water molecules. With this we have reached the third criterion for the efficiency of karstic corrosion: *the motion of the water, and the degree to which the conditions of its exchange are ensured.* This exchange of the water means that the saturated solution on the rock surface is removed and flows further, being replaced by unsaturated and aggressive solution. The karstification, i.e. the corrosional destruction of the rock, is therefore restricted everywhere to the external rock surfaces and to the subsurface faces in constant contact with *moving* water, and accordingly, in contrast with chemical wearing-away, it does not affect the rock structure.

Thus, it is obvious that a limestone surface wich rises to be higher than the local erosion base will primarily undergo dissolution and karstification on the *uppermost surface* that is most exposed to the precipitation. The extent and the dynamics of karst corrosion are not impeded by the fact that a soil layer of various thickness (not impermeable to the precipitation) might cover the karstic rock. Indeed, in such cases the soilwaters coming into contact with the limestone generally acquire a considerable quantity of excess carbonic acid while in the soil, and consequently they are even more active in dissolving the carbonatic rocks than in the case of karsts with bare surfaces. With the passing of time, the karst process on the surface engraves various karst forms, lapies, dolines, etc. into the rock. However, moisture originating from the precipitation also permeates into the network of interstices in the rock, and proceeds increasingly more deeply under gravitational control. The only exceptions to this are those narrow capillaries and cracks in which the adhesional forces impede such motion of the water.

Naturally, the solutions setting out towards the depths in the wider cracks in the rock can still dissolve up the wall-material of the cracks in the vicinity of the surface; by this means, they enlarge and extend the cracks in the rock through corrosion. The karstification will therefore have the result that, whereas the limestone roof is destroyed in an areal manner, in the interior of the rock there will be a broadening-out of certain vertical interstices, channels and flues which absorb all of the water from the surface; thus, in a hydrological sense, the karst surface will dry out and become a „lithogenetic desert".

Nevertheless, the vertical amplitude of the actual corrosional karst zone in the middle-hill karsts of the temperate belt (including the Mediterranean) rarely exceeds 20–25 m, for by the time the water passes deeper than this in the karst, the solution is saturated, it loses the limestone-dissolving capacity it originally had at the surface. All this is readily understandable, if attention is paid to the fairly short reaction times required for the hydrogencarbonatic dissolution of limestones, the extent of the limestone surface in contact with unit mass of water, and the slowness of the permeation due to gravity.

Extensive investigations in Hungary and abroad show that the depth of the karstified zone produced by this rock dissolution is even less (10–15 m) in the tropical karsts; this can be explained in terms of the shorter reaction time required for the warmer solutions to attain saturation. The aggressive solutions can often pass down to essentially greater depths in the limestone karsts of the subpolar regions and the high mountains in cold climates; hence, the upper leaching-out horizon is thicker there. It is natural that this too is governed by the reaction time for the solution to become saturated: the colder the solution, the longer the reaction time of hydrocarbonatic corrosion.

Of course, in most temperate belt karst (the Nagylengyel karsts too presumably belonged in this category) the difference in height of the uppermost level of the karst compared to the level of the erosion base is substantially in excess of 20–25 m. In such cases, a neutral horizon appears in the profile of the karst, in this horizon the karst waters seeping down in the primary or tectonically formed network of interstices in the rock no longer carrying out dissolution; instead, the interstices are used as routes for the seepage, to an extent permitted by the forces of adhesion and gravity. From the aspect of the karst process, this neutral horizon is an inactive rock sphere (seepage zone); it is the thicker, the higher the uppermost surface of the karst relative to the karst water surface and to the local karst erosion base determining this.

However, the karst water progressing vertically downwards under the action of gravity will sooner or later be stopped by a karst water saturation zone, the level of which is controlled by the local erosion base, or by a karst water saturation sphere supported by some water-impermeable layer. The descending karst water now mixes with the karst „layer water".

The subsequent direction of motion of the water molecules under the karst water level is no longer determined directly by gravity, but by the hydraulic laws relating to solutions under hydrostatic pressure and by the laws of hydrodynamics and depression valid for systems of interstices connected in a network.

While the water molecules and the gaseous species accompanying them trickle down in the seepage zone and have not yet reached the water saturation level, they are not affected by a hydrostatic pressure that would disturb the carbon dioxide — lime solution equilibrium that develops in the uppermost 20–25 m zone of the rock. The situation changes immediately, however, when the water passes below the karst water level; here, the water and gaseous species are under a higher hydrostatic pressure, for the intercommunicating interstices in the rock are totally filled with water. In this profile horizon of the karsts, the water is still in motion. If it were not, there would be no place for the new water constantly arriving from the surface. However, the direction of movement here is no longer determined by gravity, but by the deepest possible outflow point (spring mouth). The direction is generally a lateral one.

This zone of the karst, characterized by the lateral movement of water and by complete filling with water, is known as the *lens belt*, for it bulges both upwards and downwards in the karst mass, in the shape of a lens. The thickness of this lens is the least in the vicinity of the outflow possibility, and it increases on progressing from here into the interior of the karst block.

The karst water arriving from above again becomes capable of dissolution in the lens; the amount of rock it can dissolve will depend on the increase in pressure, and on the absorption and activation of the carbon dioxide present in the gas bubbles carried along with the permeating solution. Between the limits of the lens, the tension is the greatest in the vicinity of the lower limiting plane of the lens, and accordingly the efficiency of secondary dissolution will be the highest here. To all this must be included the secondary dissolution enhancement occurring as a consequence of *mixing corrosion*: in the interior of the lens zone, the mixing takes place of karst waters with differing hardnesses, seeping down in a fairly isolated way in different vertical interstice systems. Although the karst block continues in a downward direction, the water filling all the interstices and passages does not perform karstification below the lens zone, for the conditions of water motion and water exchange are absent; thus, the karst profile horizons deeper than the lower limit of the lens zone are to be regarded as *inactive dead karst.*

On the basis of the above discussion, it is apparent that fundamentally *two hollowing-out rock spheres develop* in the karstically denuding rock masses: one in the uppermost limestone layer (with a thickness of 20–25 m), and another deeper down, at the level of the local erosion base the karst-activity period. Experience shows that this lower (lens zone) leaching-out horizon has a profile thickness of approximately 20–30 m, or, more distant from the outflow sites, at most 40–50 m.

The *extent of hollowing-out* in the upper leaching-out horizon relating to the limestone roof is generally much greater than that of the lens zone horizon. Additionally, there are also fundamental differences between the caverns of the two karst horizons in the *direction* of the dissolution cavities. The majority of the karst passages in the upper roof zone have vertical axes, and the drain passages that develop close to one another communicate only rarely in the lateral direction with the neighbouring or more distant similar karst cavities. In contrast, most of the cavities in the lens zone are in well-developed lateral contact with one another. Naturally, this does not mean that these karst cavities communicate with the other caverns of the karst merely in the plane of the leaching-out horizon.

Of course, the upper and the lower karst leaching-out horizons differ from each other characteristically only where karstic rock mass was raised up sufficiently from its topographical environment in the course of the destruction phase. However, where the karst roof remained close to the karst water level during the denudation (e.g. the relative elevation of the limestone terrain was only of the magnitude of 40–60 m), the two genetically characteristic karst horizons merge with each other.

Otherwise, the broadened-out cavity systems of the two corrosional karst horizons are not hydrologically separated from each other even if there is an appreciable height difference between the two levels. Nevertheless, the connection between the two levels is then rather loose, for it is generally manifested via rock interstices, cracks and capillaries that were not broadened into wider passages by the karst corrosion.

It is a frequent phenomenon in the karsts that the denudation processes recur in a number of phases. It is also a very common finding that the lens zones develop at different levels during the different karst activity phases, and thus one karstic block may possess 2–3, or even more lower leaching-out horizons. These levels may be parallel with one another, but if the tectonisms between the karst phases resulted in level tiltings, the cavern levels may also intersect one another at various angles.

So far, the cavern-forming role of karstification has been studied only in the simplified hydrological situation where the corrosion of the karst is brought about exclusively by the external water seeping in from the karst surface. However, there is another very striking karst-forming and cavity-developing process too, which, even if not in all karsts, in very many may play the deciding role in the formation of the passage systems. This factor is an *exogenous* (i.e. originating outside the karst) water flow (a stream or river) which works in the shaping of the surface by means of alluvial erosion, giving rise to linear valley deepening (or broadening). This category includes essentially all living water moving in a bed that obtains its water replacement from non-karstic catchment areas. If such normal flowing water comes into contact with some karst at a terrain point that is higher than the local erosion base (karst water level) of the karst, then the interstice system in the karst will sooner or later tap off the bed of the water flow, and the water will pour into the karst.

The alluvium, capable of erosional bed-gouging work is naturally washed into the subsurface bed by the running water, and in this way the valley deepening (or broadening) process is essentially transferred into the interior of the karst. The subsurface stream carries out very effective work in the soft limestone with its generally hard and highly abrasive alluvium (mainly quartz rains, sand and gravel), and within a very short time it washes out very spacious transition caves in the karst block at a level conforming to the erosion base of the karst.

Karsts in which erosional caves have been washed out by inundations of water originating outside the karst are known as *B-type karsts* (exogenic or allogenic karsts), while karsts not containing erosional cavities are *A-type* (endogenic or autogenic) systems. A-type karstification is therefore in effect the manifestation of a classical karst process: the process of corrosional destruction (and partially the cavernization) of rock soluble in carbonic acid solution. In contrast, B-type karst denudation is essentially a non-karstic surface-forming customary geographical process: the characteristic appearance of normal erosional river valley deepening in the depth of the karst. The occurence of the process in some karst is totally coincidental; it is predominantly a function of the environmental topographical connections, and is not a necessary step in the process of regular development of all karsts.

B-type karst cavities differ in numerous respects from the corrosional karst caverns of A type. The most important principles are as follows:

1. The A-type karst cavity networks do not have well-defined bottom and roof levels, i.e. the corrosional passages and channels join together corrosional caverns and chambers developed at different heights; that is, certain parts of the cavity system are situated at different base heights. In contrast, the B-type caves extend practically in one plane. They always slope from the direction of the former swallow-hole in the direction of the former spring, and there are no long sections where the opposite fall is observed.

2. The horizontal plan of A-type cavern systems is reminiscent of a network of capricious labyrinths, whereas that of the B-type karst cavities presents a picture of a network of running water: there are wide main channels, with less wide side-arms running into them.

3. In the interior of A-type karst cavities there is no alluvial sediment originating from outside the karst. B-type caverns and caves always contain minor or major amounts of such karst-foreign sediments (sand, gravel, stone rubble).

4. The direction of A-type karst caverns is sensitively determined from the rock interstices, faults and other a priori lithoclases created in the tectonic phases preceding the karstic periods. The B-type cavities and caverns do not follow these tectonic or atectonic preforming interstices strictly; during their development, a major role is always played in their genetics by the hydrodynamic, hydraulic bed-developing work of the flowing waters, the fluid mechanical laws of which are exerted with a stronger effect than the tectonic preformation. This is the reason why B-type cave sections are also to be found in completely homogeneous, interstice-free and tectonically intact rock blocks, while such blocks are unfavourable for A-type cavity formation.

5. From a hydrodynamic aspect, there is a particularly important difference between the two cavity types. The A-type caverns are in hydrological communication with rock interstices capable of leading off a practically unlimited amount of water. However, the B-type karst caverns possess such communications to a much lower extent; there are frequently cave passages of various lengths in them where there are no such communications at all.

The international literature does not appear to contain experimental data relating to the determination of the degree of permeability of the rock walls in karstic cavities of the different types. Most publications merely draw conclusions from measurements of the extents of cracking and cavity formation in rock sections, and from mine moisture levels, determined by the drying of various carbonatic rocks. Studies are also sometimes made of the conductivities of specimens under directed liquid pressure.

In Hungary too, we know of only one experiment (VITUKI, 1958) in which a large quantity of water was pumped onto the limestone surface above a cave cavity (the Feketeterem of the Baradla Cave at Aggtelek). This was done to investigate the time needed for this water to pass through the given rock interstice system and to reach the cave chamber about 80 m below the flooded surface.

This experiment provided only statistically evaluable results, which could scarcely be utilized to define seepage rates. Such a large dispersion in time was observed in the 80 m rock formation in the course of the experiment (seepage times ranging from 90 minutes to one month) that it was impossible to assess the behaviour of the rock strata under the permanent fluid load. No references can be found in the karst hydrological, petrographical or even mineral oil geological literature to control studies under in loco nascendi conditions, i.e. where the stratigraphic conditions have not been disturbed, to seek possible permeability differences between the rock walls of A-type and B-type karst cavities, in response to the pressure of a liquid column directed over a long period of time. Accordingly, in 1983–84 I planned and carried out a series of experiments designed to clarify this question.

For control of the permeability of cave walls under liquid pressure, glass tubes about 2 cm in diameter and 130 cm were used. These were suitable for holding 100–120 cm liquid columns, and for the periodic exact measurement of any changes in level of the liquid columns in them. These measuring tubes were employed to study both A-type and B-type caves in Hungary, in accordance with the following principles:

1. At the site of the examination, the rock surface was carefully cleaned of all surface deposits on it that were foreign to the rock (sand, travertine, rock debris, etc.). For every measurement point, a circular area about 10–12 cm in diameter was cleaned with a wire brush, with water, and in the event of necessity with a knife-blade or chisel too. In some cases, chips were hammered off the rock surface in order to obtain a totally sterile surface.

2. Where it appeared necessary,the cleaned rock surface was dried with a cloth soaking up moisture.

3. One end of the measuring tube was supported on the rock to be examined (at the centre of the cleaned surface). A suitable set of stands was then used to fix the tube in place in as vertical a position as possible.

4. The lower end of the fixed glass tube was next carefully sealed hermetically to the rock surface, none of the glue being allowed inside the end of the tube. Several layers of adhesive were used: the rim of the tube was first stuck down with a layer of plasticine about 0.5 cm thick, followed by a hermetic coat of epoxy resin, as illustrated in Fig. 5.

5. After a bonding time of 24 hours, a layer of thick clay and small stones was added, primarily to eliminate mechanical stresses during the experiment.

6. The glass tube was next filled with liquid (a fairly concentrated fluorescein solution which could readily be observed under the light conditions in the cave), and the changes in the height of the liquid column were read off at definite intervals. Any evaporation loss of the fluorescein solution in the control vessel (this proved to be a negligible correction factor in most measurements) was subtracted from the fall in the solution level, and the changes in level of the liquid column were plotted in a diagram. The first reading was taken 30 sec after the column was filled, the second 5 minutes later, and the third after 60 minutes. In experiments where a fall in level was not observed after 60 minutes, a new reading was made after 24 hours. If this too was negative (a change in level of less than 1 mm), the experiment was regarded as finished. When there was a change in the initial column height, however, the experiment was continued, with reading at appropriate intervals, until all of the solution had run out.In some cases, the experiment was repeated with high-viscosity, sediment-free paints. Characteristic diagrams from the observed data are presented in Figs. 6–9.

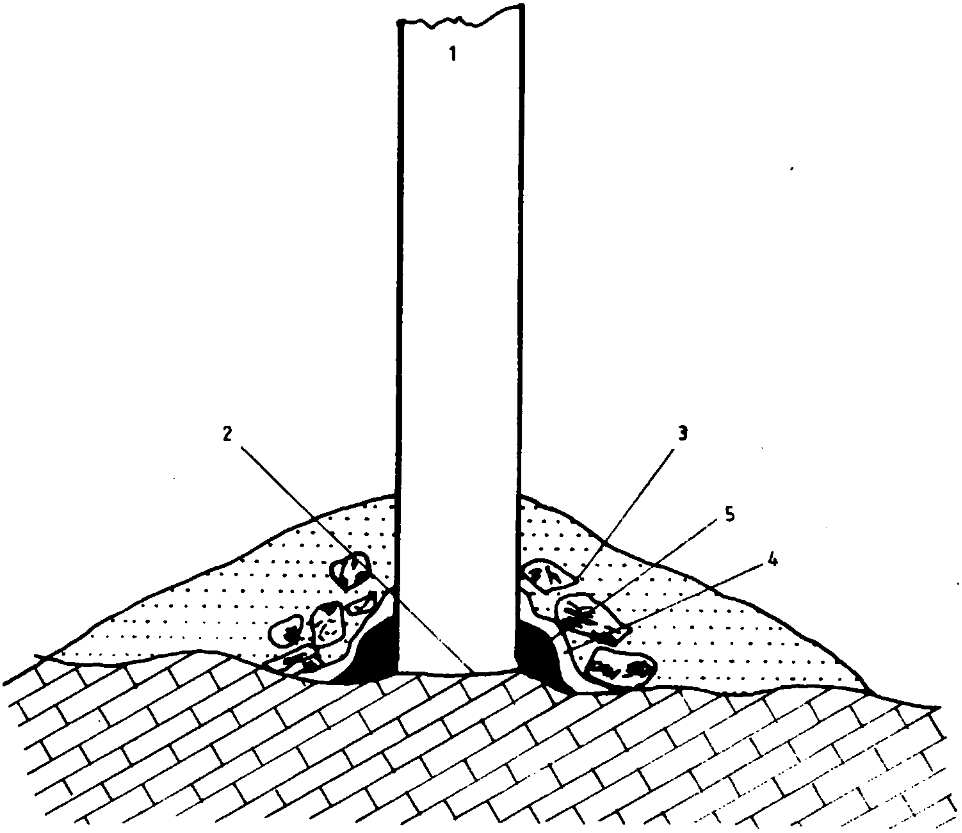

Fig. 5. Principle of hermetic sealing of measuring tube used for experimental control of permeability of cave walls under liquid pressure.
1 = 2 cm diameter glass tube;
2 = cleaned rock surface to be examined;
3 = outer stone and clay covering;
4 = epoxy resin coat;
5 = inner plasticine adhesion ring.

In the vast majority (94%) of the cases, the permeability measurements in B-type cavities revealed apermeability. Accordingly, the question arose of whether the reason for this might be the small height of the liquid column applied (120 cm water column = 0.012 MPa). This uncertainty led us to construct an experimental apparatus with which a number of sites in the B-type cavities of the Aggtelek dripstone cave were examined under a water column 4.5 m high. The essence of this apparatus was a tall stand, with a high-pressure, large cross-section (about 10 cm diameter), flexible, corrugated metal tube fixed on it.This was attached to the examined surface as described above, and the fall of the liquid column in it was controlled by means of a small float. *Even with a column pressure of 0.045 MPa,*

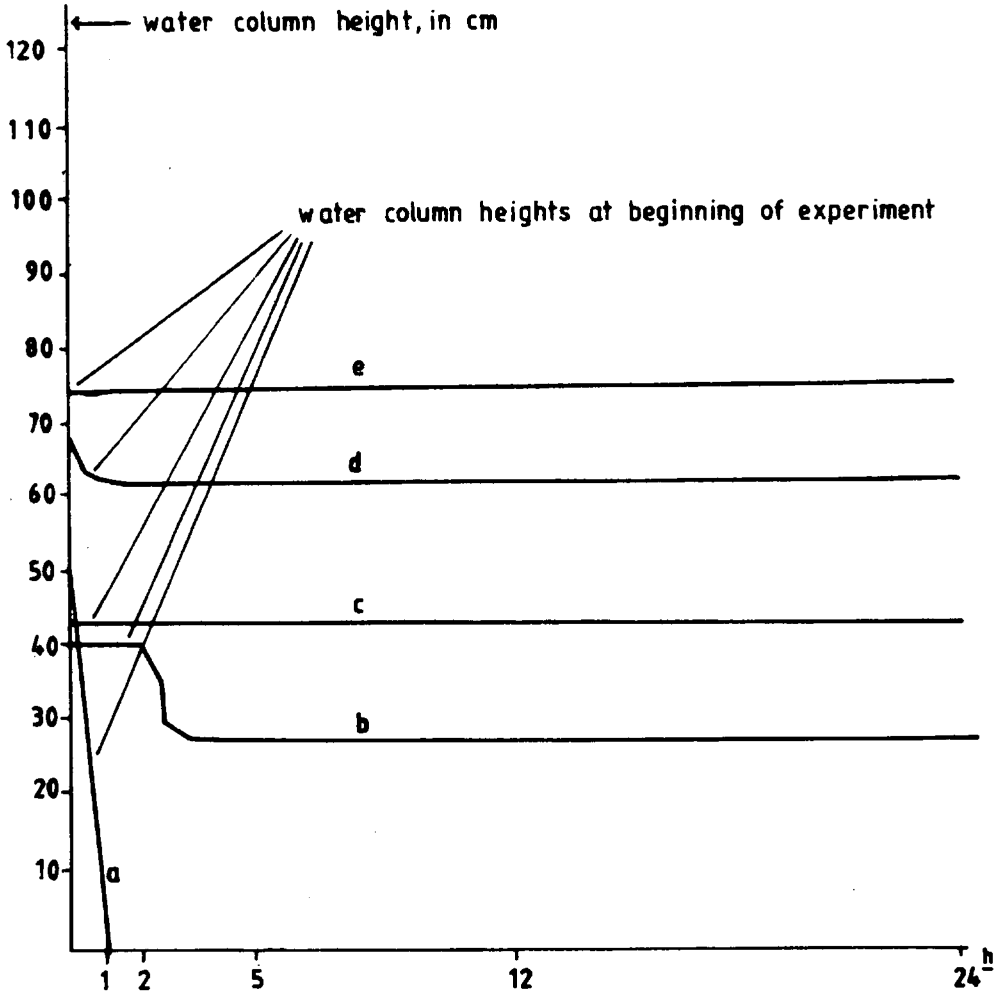

Fig. 6. Percentage frequency of result curves from in loco solution permeability tests involving 0.012 MPa column loading in certain A-type karst cavities (Mátyáshegy Cave, Pilisvörösvár dolomite caves, Remete Cave) and in tectonically stressed rock regions (based on 36 observation series).

1 = 7 cases (19.5%) of unlimited absorption capacity;

2 = 2 cases (5.5%) of initially unlimited absorption capacity, later becoming increasingly more limited;

3 = 3 cases (8.3%) of moderate absorption capacity, displaying a weakening trend;

4 = 4 cases (11.1%) of disappearing absorption capacity;

5 = 17 cases (47.2%) of a total absence of absorption capacity.

An additional 3 cases (8.3%) were atypical (not interpretable).

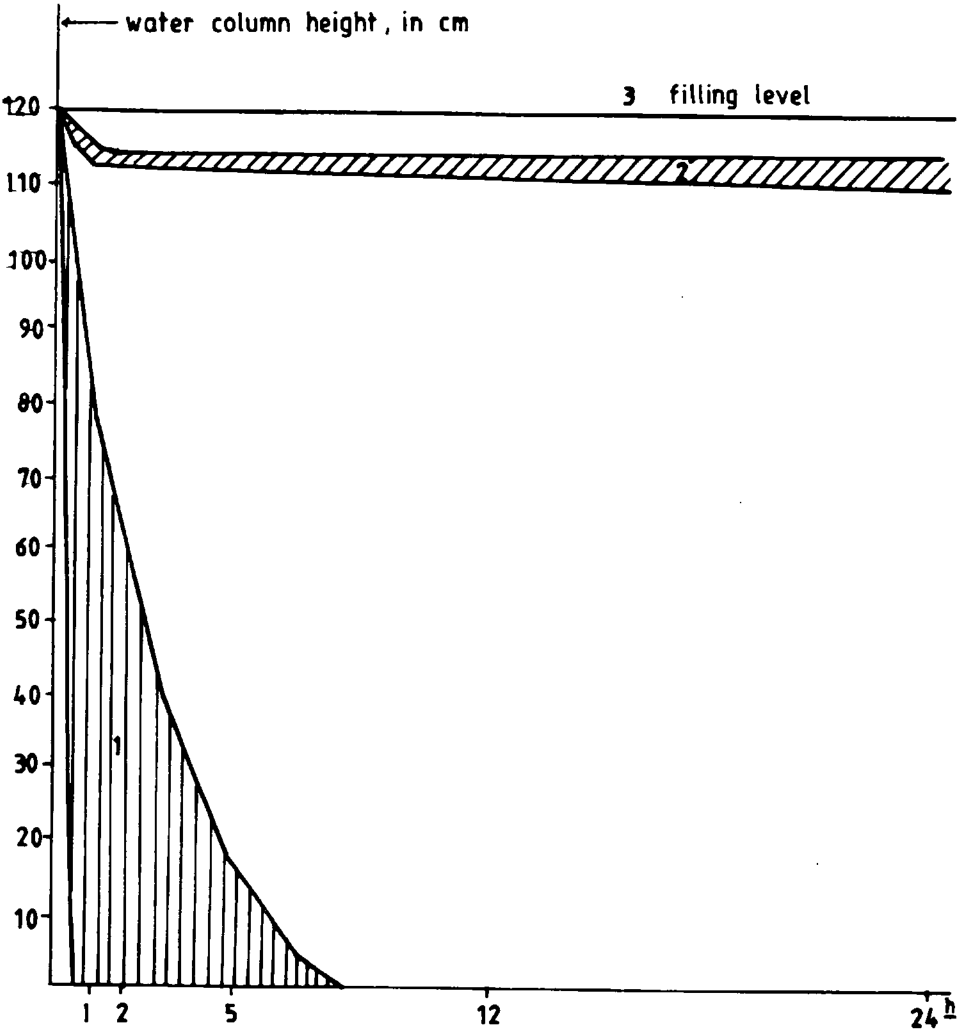

Fig. 7. Percentage frequency of result curves from in loco solution permeability tests involving 0.012 MPa column loading in certain B-type karst cavities (Baradla Cave, Béke Cave, Kecskelyuk Cave) (based on 84 observations).

1 = 5 cases (6.0%) of unlimited absorption capacity;
2 = 11 cases (13.1%) of disappearing absorption capacity;
3 = 66 cases (78.6%) of a total absence of absorption capacity.
An additional 2 cases (2.4%) were atypical (not interpretable).

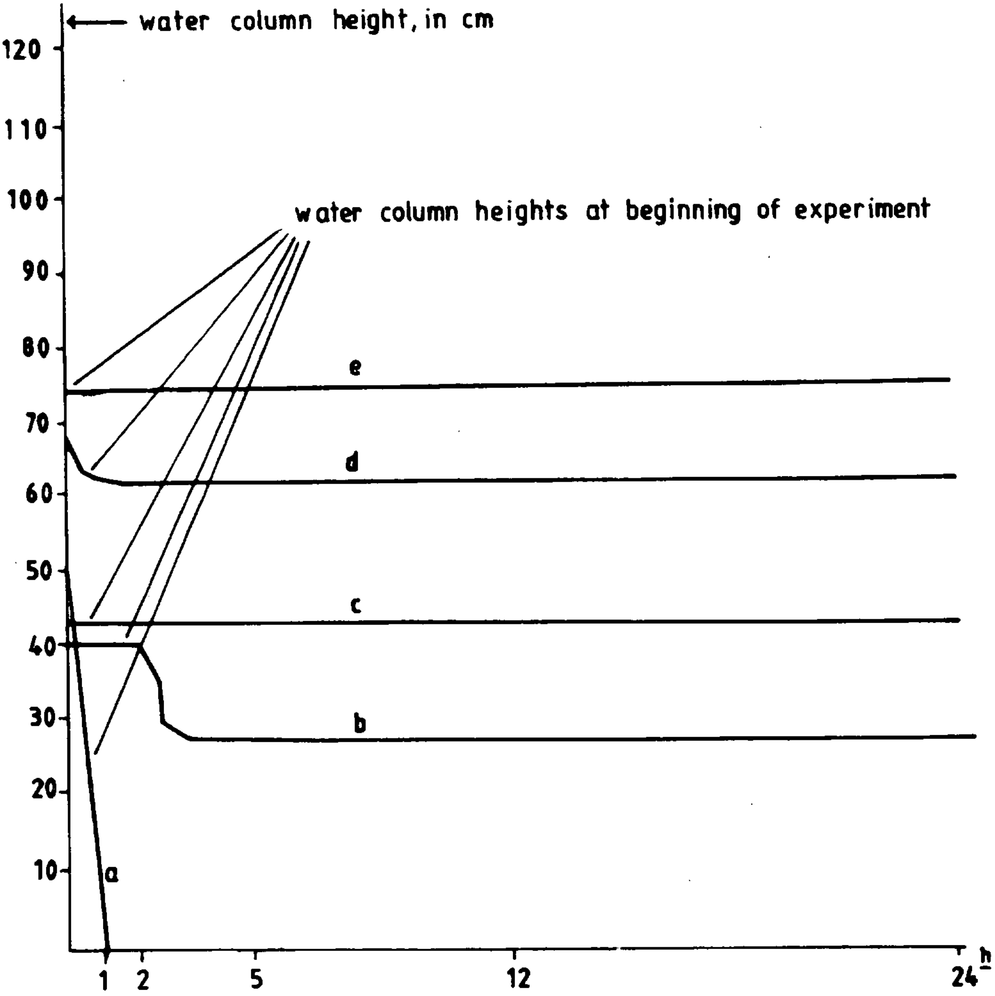

Fig. 8. Some type curves from in loco solution permeability tests with an inclined tube in B-type karst cavities.

a = unlimited absorption capacity;
b = following a brief absorption phase, complete minutes was observed after 130 minutes of column loading;
c = total absence of absorption capacity;
d = disappearing initial absorption capacity;
e = total absence of absorption capacity.

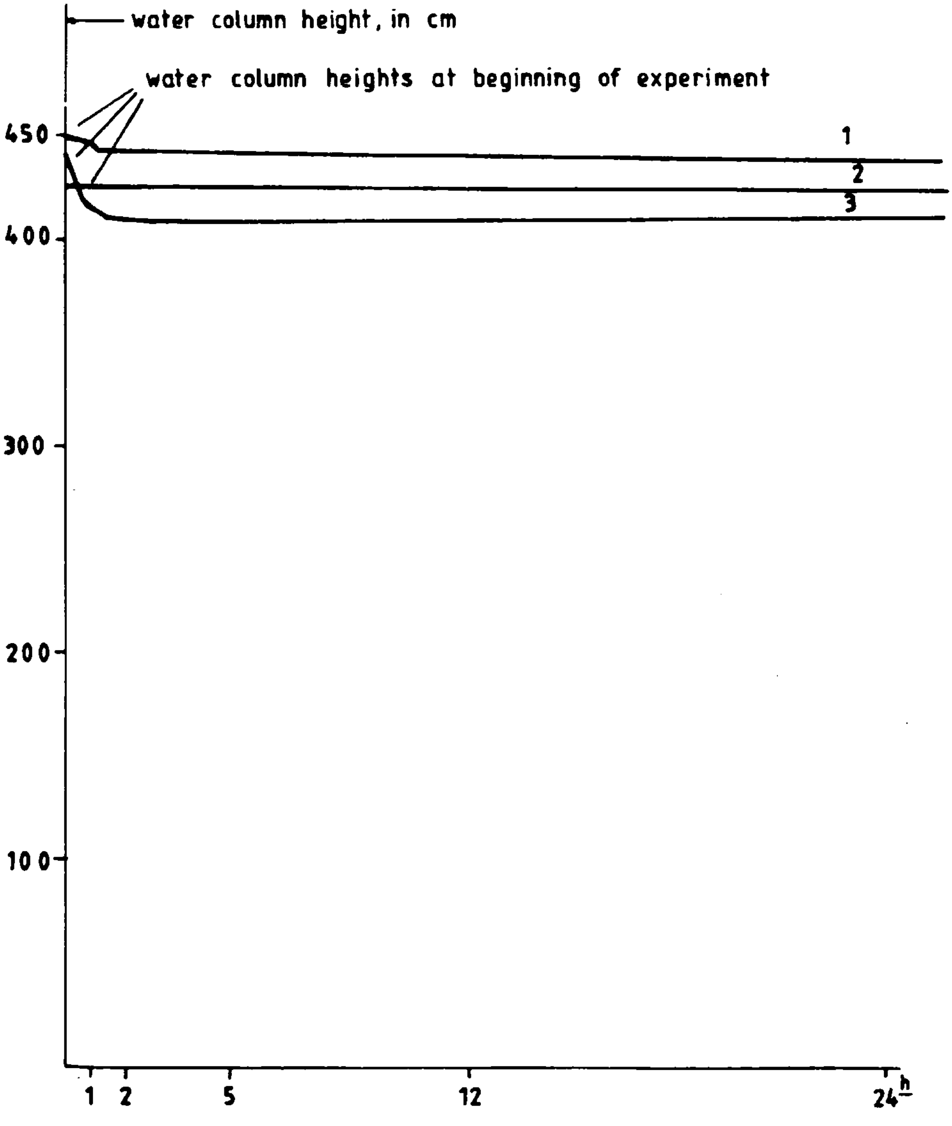

Fig. 9. Result curves of in loco rock-permeability tests (at 3 measurement sites) with a water column load of 0.045 MPa in a B-type karst cavity (Baradla Cave). (In each case there is a disappearing absorption capacity or a total impermeability.).

however, the permeability behaviour did not differ significantly from that typically observed in the control studies with glass tubes.

The results of the experimental series may be summarized in essence as follows:

1. From the aspect of liquid conduction, the rock formations of the A-type cave cavities proved well permeable at one-third of the examined sites, whereas 94% of the tests in the B-type caves pointed to a complete absence of permeability. It follows from this that the fluid-retaining capacity of B-type cave cavities is about 5–6 times more favourable than that of A-type cavities.

2. In the case of the rocks comprising the wall of A-type caverns, the liquid moves along the layer planes of the rock and in the karstic capillaries. In the B-type caverns, however, the vast majority of the layer planes and the rock interstices do not mean a pathway for the flow of liquid.

3. It must be considered, therefore, that corrosional cavity formation (A-type leaching-out and lens zone) in the process of karstic maturation of the rock is regularly accompanied by the high permeability of the rock mass enclosing the cavity, i.e. by the openness of hydrological communication between the caves. In these caves, the liquid permeability of the rock walls delineating the cavity is always considerably larger than the permeability (degree of crack formation) that usually develops in limestones purely in response to the brittle deformational effects of tectonims. For this reason, the A-type karst caverns can not be considered lastingly suitable for the isolated retention of liquid phases, even in the event of siphon or domed cavity morphology. In contrast, caves developing with genetics independent of the hydrological maturation of the rock (with B-type karst erosion) are generally permeable only to such a level and in those sites where the rock is influenced by effective forces of brittle deformation (tectonic and diagenetic lithoclases, etc.).

4. The circumstance that 6% of the experiments conducted in the B-type cavity systems documented an unlimited swallow capacity, together with the water-conducting openness of some of the tectonic interstices, presumably means that this type of cavity too may possess interstices ensuring seepage communications towards the upper leaching-out karst horizon. The process of dripstone formation in the B-type caves is a clear indication of this.

References

Ajtai, Z.: A karsztvíz védekezés aktív formájának eredményei hazánkban. (Results of an active form of karst water defence in Hungary. (Báki Közleményei, 1963, VIII, 1, pp. 11–24.

Albel, F.: Újabb elgondolások a karsztvízkérdéssel kapcsolatban. (New considerations in connection with the karst water question.) Hidr. Közlöny, XXX, 406–413, 1950

Alliquander, Ö.: Hidromechanizáció a fluidumbányászatban. (Hydromechanization in fluid mining.) Földtani Kutatás, 1982, 2, pp. 77–90

A NYIRÁDI BAUXITBÁNYÁSZAT fejlesztése és hatása a Hévízi tóforrásra. (Development and effect of bauxite mining at Nyirád on the lake spring at Hévíz.) Industrial Ministry study, Budapest, 1984, p. 45. Manuscript.

Barkai, Z.: Új eljárás repedezett mészkő és dolomit tárolók effektiv porozitásának meghatározására karotázs módszerekkel. (New procedure for the determination of the effective porosity of cracked limestone and dolomite reservoirs with electrical survey methods.) (Lecture Extract.) Magyar Geofizika, VI, 1965, 3–4, pp. 47–48.

BÖCKER, T.: A karsztosodás, a tektonika és a karsztvíz kérdéséről a bauxitbányászatban. (The question of karstification, tectonics and karst water in bauxite mining.) Bány. és Koh. Lapok, 36, 2, 1963, pp. 99–102.

BURGER, A. — DUBERTRET, L.: Karszterületek hidrogeológiája. (Hydrogeology of karst regions.) MKBT publication, Budapest, 1982.

CHRAMUSEV, A. C.: Hidrogeologicheskaya klassifikatsiya treshchinovatikh gornikh porod. Sovietskaya Geologiya, 1941, 1.

DARÁNYI, F.: A Bakony-hegység karszthidrológiai kérdései a bányászati tapasztalatok alapján. (Questions of karst hydrology in the Bakony Hills on the basis of mining experience.) Hidr. Közl., XLVI, 2, 1966, pp. 11–219.

DEDINSZKY, J.: A nagylengyeli kőolajtároló kőzetek repedezettségi-üreségi vizsgálata. (Study of cracking and cavity formation in mineral oil-bearing rocks at Nagylengyel.) Földt. Közlöny, XCVIII, 1, 1968.

DEDINSZKY, J.: Magyarországi repedezett szénhidrogéntárolók, nyitott kőzetrések előfordulásának lehetősége a mélyben. (Possibility of the deep occurrence of cracked hydrocarbon reservoirs and open rock interstices in Hungary.) Manuscript, Gellénháza, 1970, pp. 1–10.

DOLESCHALL, S. et al.: Nagylengyel típusú repedezett mészkőtárolók működési mechanizmusának vizsgálata. (Study of mechanism of operation of cracked limestone reservoirs of Nagylengyel type.) Bányászati Lapok, 1967, 4.

DUDKO, A. — ÓDÓR L.: A betemetődési mélység és a kompakciós víz mennyiségének becslése a térfogatsúly-értékek segítségével (Dunántúli-Középhegység). (Estimation of burial depth and the quantity of compaction water by means of gravimetric density values (Transdanubian Central Hills)). Annual Report of MÁFI for 1978. Budapest, 1980, pp. 291–299.

FARKAS, S.: A halimbai és nyirádi bauxitterület vízföldtani helyzete. (Hydrogeological situation of the bauxite area at Halimba and Nyirád.) Földt. Közl., 1979, 3–4, pp. 548-561.

FRANKE, H.: Mischungskorrosion an Haarissen. Die Höhle, 16, 1965, 3, Wien.

GÁNTI, T.: A barlangok keletkezésének kémiai vonatkozásai. (Chemical aspects of the formation of caves.) Hidr. Közl., 1957, 3.

HOPPE, W.: A szilárd kőzetek vízvezetőképességének megállapítására vonatkozó módszerek és tapasztalatok. (Methods and experience relating to the establishment of the water conductivity of solid rocks.) Hidr. Közl., 42, 1, 1962, pp. 51–54.

KASSAI, F.: Paleogén szénbányászatunk, a karsztvíz és a védekezés módjai. (Palaeogenic coal mining in Hungary, karst water and the means of defence.) Hidr. Közl. 1984. 1–4.

KASSAI, F.: A karsztvíznívó jelentősége és ezzel kapcsolatos problémák. (The significance of the karst water level and problems connected with this.) MTA Müsz. Tud. Oszt. Közl., I, 1953.

KÁLMÁN, M.: Karsztvízbetörések leküzdésére Tatabányán végzett kísérletek. (Experiments performed at Tatabánya to overcome karst water inundations.) Bány. és Koh. Lapok, LXXXIII, 1950, pp. 394–402.

LAPTYEV, F. F.: Agressivnoye deystvie vodi na karbonatniye porodi, gipsi i betoni. Leningrad-Moscow, 1939.

LÁNG, S.: Karsztvízforgalom és karsztvízháztartás a Dunántúlon. (Karst water turnover in Transdanubia.) Földr. Közl., XXIII, (XC IX), 3–4, 1975, pp. 305–324.

MAGARA, K.: Compaction and fluid migration. Elsevier, 1978, Amsterdam–Oxford–New York, p. 357.

MAUCHA, L.: A karsztvíz árapály-jelenségének kimutatása (Demonstration of tide phenomenon of karst water.) Bány. Kut. Int. Közl., 11, 1-2, 1967, pp. 87–94.

MÁELGI, F.: Jelentés a rétegnyomásváltozás és a földkéreg dilatáció közötti kapcsolat vizsgálatáról. (Report on a study of the connection between the variation in layer pressure and the dilatation of the Earth's crust.) Manuscript, Kőolaj- és Földgázbányászati V., Nagykanizsa, 1980–1982.

MÜLLER, P.: A karbonátos kőzetek, mint víztárolók. Karsztvizek. Karbonátos kőzetek kutatása, vizsgálata és gazdasági jelentősége. (Carbonatic rocks as water reservoirs. Karst waters. Research, investigation and economic significance of carbonatic rocks.) Budapest, 1964, pp. 359–366.

NAGY, P.: Az aktív vízszintsüllyesztés módszerei és eredményei a Fejér megyei bauxitbányáknál. (Methods and results of active depression of water levels in the bauxite mines in Fejér County.) Földt. Közl., 1979, 3–4, pp. 562-567.

ROGLIC, J.: Karstprozess und fluviatile Erosion. Rep. of the Comm. on Karst Phenomena, XVIII-th Int. Georg. Congr., Rio de Janeiro, 1956.

ROGLIC, J.: Das Verhaltniss der Flusserosion zum Karstprozess. Zeitsch. f. Geomorph., IV, 2. Göttingen, 1960.

SÁRVÁRY, I.: A karsztvízszint változása a Dunántúli Középhegységben 1960–67-ig. (Change in karst water level in the Transdanubian Central Hills between 1960 and 1967.) Hidr. Tájékoztató, 1968, June, pp. 52–54.

SCHMIDT, E. R.: Karsztvízjáratok kialakulásának geomechanikája. (Geomechanics of development of karst water passages.) MTA Közl., VIII, 1, 1953.

SCHMIDT, E. R.: A geomechanikai szemlélet szerepe a karsztvízkutatásban és a karsztvíz elleni védekezésben. (Role of the geomechanical approach in karst water research and in the defence against karst water.) Bányászati Lapok, 1954.

VNIGRI, A.: A porózus és repedezett térfogat morfológiai-genetikai tulajdonságai. (Morphologic-genetic properties of the porous and cracked volume.) Leningrad, 1969. (pp. 66–77 of the book „Methods of investigation of cracked reservoirs".)

WILLEMS, T. — VIGH, F.: A hazai karsztvízföldtani viszonyok és a mélyművelés kölcsönhatásai. (Karst hydrogeological conditions in Hungary and the interactions of deep mining.) Bány. Kut. Int. Közl., IX, 2, 1964, pp. 7–27.

ZOJER, H. — ZÖTTL, J.: Die Bedeutung von Isotopenmessungen im Rahmen kombinierter Karstwasseruntersuchungen. Österreichische Wasserwirtschaft, 26, 3–4, 1974, pp. 62-70.

ZÖTTL, J.: Karsthidrologie. Springer Verlag, Wien-New York, 1974.