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CARBONATE SPELEOGENESIS: AN INCEPTION HORIZON HYPOTHESIS

SPELEOGENEZA V KARBONATNIH KAMNINAH: HIPOTEZA ZAČETNIH HORIZONTOV

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David Lowe in John Gunn: Spelogeneza v karbonatnih kamninah: hipoteza začetnih horizontov

Procesi, ki oblikujejo kraške prevodnike in jame v karbonatnih kamninah so sorazmeno dobro poznani, manj pa je bilo poskusov razložiti najzgodnejšo, začetno fazo speleogeneze. Temeljno vprašanje je: "Zakaj in kako karbonati doživijo prehod iz kamnine brez kanalov v prevotljeno gmoto?" Podrobna proučitev kemizma raztapljanja in mehanike tekočin, spoznanje o vlogi sindiagenetskih procesov in temeljita razširitev spelogenetske časovne lestvice so omogočili oblikovanje učinkovtite hipoteze začetnih horizontov, ki nudi nove odgovore na mnoga vprašanja spelogeneze in z njo povezanih dogajanj.

Ključne besede: apnenec, jame prevodniki, hipoteze o začetnih horizontih.

Abstract UDC 551.44:552.54

David Lowe and John Gunn: Carbonate speleogenesis: An inception horizon hypothesis

Processes whereby conduits, and ultimately caves, develop in carbonate rocks are relatively well understood but there have been few attempts to explain the earliest, inception, stage, of speleogenesis. The fundamental questions are: "Why and how do carbonates undergo the transition from *rock without conduits* to *rock with conduits*?". Re-examination of dissolution chemistry and flow mechanisms, recognition of the role of syngenetic processes, and a radical expansion of potential speleogenetic timescales have allowed the development of a versatile *Inception Horizon Hypothesis*, which provides alternative answers to many of the questions of speleogenesis and related subjects.

Key words: limestone, speleogenesis conduits caves, inception horizon hypothesis.

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1. INTRODUCTION: CONDUITS AND CAVES IN CARBONATE ROCKS

The terms conduit and cave are commonly used interchangeably, although strictly a conduit is a void greater than 100mm in diameter and a cave is a void large enough to permit human access. In this paper we follow these strict definitions and ask, "Why and how do carbonates undergo the transition from *rock without conduits* to *rock with conduits*?". These questions are significant because flow is generally laminar in aquifers without conduits and hence transfer of pollutants is slow, with significant decay and dilution. Conduit flow is usually turbulent, allowing transport of suspended sediment and rapid pollutant transfer with little or no decay or dilution.

As commonly used, the term speleogenesis includes the origin of caves (Lowe & Waltham 1995), but many classical cave formation papers have addressed only the question of processes responsible for developing conduits into caves (eg Davis 1930; Swinnerton 1932; Gardner 1935; Warwick 1953; Davies 1960; Ford 1965; Palmer 1975, 1991). These processes are moderately well known, but still far from fully understood. In contrast, little has been written about the earliest development phase, which we term inception.

Karstification occurs continuously in young carbonate sequences with a relatively high porosity and permeability, particularly on carbonate platforms. Well developed cave systems are described in Pleistocene limestones on Tonga (Lowe & Gunn 1986) and the Bahamian archipelago (Mylroie & Carew 1990). Some such caves, and by inference smaller conduits, may survive ongoing diagenesis and later tectonism and play an important role in subsequent speleogenesis (Lowe & Gunn 1986 & in preparation; Lowe 1989). In considering speleogenesis it is commonly assumed that older, better indurated, carbonates are characterised by a low primary permeability and an absence of integrated conduits. Our aims in this paper are to consider factors influencing conduit inception in such carbonate sequences and to outline a synthesis of conduit inception and later speleogenesis that provides a working model of cavern origin mechanisms. Particularly important is the potential role of *non-karstic* processes in speleogenesis (Lowe 1992a; Lowe & Gunn 1995). Those karst processes *(sensu stricto)* and related landform evolution, including cave development, involving carbonate rocks (loosely termed limestones) are generally assumed to reflect the effects of carbonic acid upon calcium carbonate. The importance of carbonic acid to ongoing cave development cannot be disputed, but its role in speleo-inception is less clear (Lowe & Gunn 1995).

2. DEFINITION OF INCEPTION AND INCEPTION HORIZONS

The term inception, used here to describe the earliest phase of speleogenesis in carbonate sequences, is only partially synonymous with *initiation*. Use of

Simplified view of the life cycle of conduits/caves within a single "tier" of a typical carbonate succession, indicating:

① Terminology in common and informal use;
② Part of the terminology developed by Worthington (1991);
③ Terminology used by Lowe (1992a).

Elapsed **TIME**, increasing from left to right, is not to scale.

NO CONDUITS	⇒ CONDUIT GROWTH ⇒		TURBULENT THRESHOLD	⇒ CAVE ⇒ GROWTH	OVERALL DECAY OF CAVES	NO CAVES
①	INITIATION			various phases of DEVELOPMENT	abandonment and eventual removal	①
②	INITIATION PHASE	*LAMINAR FLOW NOTHEPHREATIC PHASE*		SYNGENETIC AND PARAGENETIC CONDUIT GROWTH PHASES	STAGNATION AND DESTRUCTION PHASES	②
③	INCEPTION	GESTATION		DEVELOPMENT	ABANDONMENT and DESTRUCTION	③
true point of "cave" **origin**	Period of transitional change		Turbulent flow begins	Major growth phases	can be complex and multiphase	Host rock removed

Fig. 1: Simplified view of some different terminology schemes covering phases of cave development in carbonate rock sequences.

the latter term by some earlier workers assumed speleogenetic processes to be active before the establishment of local hydraulic gradients, viable underground drainage systems and conduit flow, without considering their nature, mechanism, guidance and duration. The inception concept allows closure of an obvious but unexplained interregnum during early speleogenesis, inherent in some descriptions of *initiation*. If the inception concept is accepted, the terminology of workers whose *initiation* did include primitive processes is necessarily superseded, though not invalidated. If terminology to cover the phase between inception and the start of turbulent flow is also defined, the misleading term *initiation* can be ignored in future discussions of speleogenesis. We suggest the term *gestation* to describe growth during the laminar flow phase between the conception [inception] and birth [break-out] of a conduit system (Fig. 1).

The term inception horizon (Lowe 1992a) describes: **Any lithostratigraphically controlled element of a carbonate sequence that passively or actively**

favours localized inception of dissolutional activity, by virtue of physical, lithological or chemical deviation from the predominant carbonate facies within the sequence. There is commonly a link between inception horizons and boundaries between lithostratigraphical divisions or depositional cycles *(sensu lato)*. The variety of physical, lithological and chemical boundary signatures necessitates a flexible definition. Although discussion in this paper is limited to cave development in carbonate rock sequences, similar arguments can be applied to void inception in more soluble rock types (such as evaporites) and in less soluble rocks such as sandstones.

Many authors (eg Gardner 1935; Ford & Ewers 1978) have noted that not all bedding planes in a carbonate sequence support speleogenesis. The general understanding was summed-up by Ford (1976: p.29): *"In speleogenetic studies it is common to speak of 'favourable' or 'unfavourable' beds: these are simply reflections of greater porosity and permeability, impurities, pyrite inclusions and so on. Much more study is required before the nature of the favourability can be fully understood."*. Thus, the importance of favourable horizons in supporting speleogenesis is recognised and acknowledged, but effort to link them into a cave inception and development hypothesis has been limited.

3. THE NATURE OF INCEPTION HORIZONS

Commonly held views that bedding planes and/or *impermeable horizons* exercise stratigraphical *control* are inadequate to explain all elements of speleogenesis, but there is no doubt that many such horizons, and others, influence localization of cave inception, and continue to guide later speleogenesis. Inception elements formed along these horizons during the early life of carbonate successions may escape subsequent tectonic obliteration and influence later cave development in folded and faulted sequences (Lowe & Gunn 1986; Šušteršič 1997). At least four broad and overlapping categories of inception horizon can be identified (Lowe 1992a).

Aquifuge, aquiclude, aquitard and aquifer horizons.

These rock properties may appear dissimilar. However, in the inception horizon context, allocation of such terms to beds within a carbonate sequence or (in the case of the term aquifer) to the whole sequence, should be viewed with suspicion. The terms identify overlapping segments of a continuum, and beds may exhibit more than one such property during different stages of speleogenesis. For example, prior to and during inception, the entire carbonate mass, rather than being an aquifer, may be essentially impermeable, and beds that will later be aquicludes can provide the earliest viable water routes (Lowe, 1992a; Klimchouk In Press). Some clayrocks, particularly shales, may possess sufficient linked primary porosity, relative to that of enclosing carbonates, to allow pore fluid bleeding through or from these supposed aquicludes (eg. Neuzil 1986, 1994). Adjacent crystalline carbonates may initially exhibit relatively lower primary porosity and associated permeability. Values included in Table 1 illustrate the range of porosity, primary permeability and secondary permeability in a selection of rock types. The overlap between porosity and, particularly, permeability values for some carbonates, sandstones and shales is significant.

Clay beds *(sensu lato)* in a carbonate succession act as barriers to significant water movement on a local basis, but mere presence of clay does not necessarily localise speleo-inception above it. Water movement conditions before conduit flow begins are totally unlike those affecting later development. Primitive seepage is driven largely by mechanisms unrelated to hydraulic gradients (eg. Davies 1960; Davis 1966; Pye & Miller 1990), though normal hydraulic flow becomes increasingly important later. Early oscillatory or directional water movement is as likely (or more likely) in sandstones and some shales, with linked primary porosity, as in crystalline carbonates (Table 1). Any related acid generation or physical dissolution effects can be localised against adjacent carbonates, the earliest dissolution affecting the contact zones.

Some carbonates in potential inception situations are permeable due to linked primary porosity. Syngenetic dissolution in the littoral (freshwater/saltwater interface) environment has attracted much recent research (eg Back & others 1986; Bottrell & others 1990; Mylroie & Carew 1990; Whitaker & Smart 1990) and is not re-examined here. Discussion of these important processes in the inception horizon context is presented by Lowe (1992a: Chapter 3). Oolites and similar rocks may exhibit primary porosity and permeability, though diagenesis and secondary processes can obscure original rock properties. Some coarse shell beds, reef limestones and pseudobreccias exhibit an apparently primary porosity and permeability that is actually imposed by post-depositional dissolution. It is debatable whether these are primary inception horizons or a secondary manifestation of speleo-inception *(sensu lato)*.

Of great potential relevance to speleo-inception is the apparent interchangeability of aquifers, aquitards and aquicludes (but not true aquifuges) with respect to time (Lowe 1992a: p.161). A viable aquifer before inception, because of (albeit minimal) permeability related to linked primary porosity, may almost instantaneously invert to aquiclude status when linked dissolutional voids form at its boundaries. Open-textured sandstone provides an ideal inception aquifer (*sensu* Gardner 1935), but cannot compete as a drainage route with dissolutional conduits that develop at its boundaries. After the onset of speleogenesis the sandstone still transmits water, but its permeability is orders of magnitude less than that provided by conduits (Table 1). Pre-speleogenesis bleeding through cemented sandstone, shale or clayrock with poorly linked porosity is less than seepage in open-textured sandstone and the

Table 1: Selected values of porosity, primary permeability and secondary permeability for various rock types and open caverns (compiled from published sources including Smith, D.I. et al, 1976, and various British Geological Survey publications). Where a range of source information was consulted, a range of values is quoted, to illustrate potential variation even within a single named rock unit. The values quoted are not claimed to be definitive, either for specific lithologies or for a particular named unit.

Rock type	Porosity %	Primary Permeability mm/day	Secondary Permeability mm/day
Basalt	7.7	0.014	-
Typical clay	30 - 60	0.01 - 2.5	-
London Clay (Tertiary)	37 - 59	0.026	-
Gault Clay (Cretaceous)	31 - 48	0.00017	-
Lower Oxford Clay (Jurassic)	30 - 54	0.043	-
Typical quartzite	0.5	0.0019	-
Typical sandstone	10 - 30	500	-
Sherwood Sandstone (Triassic)	0 - 30	0.86 - 3340	-
Fell Sandstone (Carboniferous)	9.8	150	-
Chatsworth Grit (Carboniferous)	14.6	170	-
Mudstone/shale	2 - 25	0.000086 - 0.86	-
Sandy or silty shale	3 - 30	86	-
Recent coral limestone	20.0 - 45.0	1,000,000	-
Oolite	1.0 - 10.0	10 - 1,000	1,500
Chalk	14.0 - 40.0	10 - 1,000	60,000
Massive limestone	0.1 ~ 1.0	1 - 10	8 - 60,000
Marble	0.1 ~ 0.4	1	20,000
Caverns	-	-	10^8 -10^9

contrast between pre- and post-inception permeabilities is more pronounced. Commonly, non-carbonates are labelled aquicludes or aquitards, whilst greater thicknesses of initially low-porosity, effectively impermeable, carbonate are assumed to be aquifers. In reality, many carbonate rocks exhibit aquifer properties only because of the presence of voids achieved due to dissolution, which in this context is inseparable from speleogenesis. Development of conduits in indurated carbonate rock increases nominal permeability more than 10 million times (Smith & others 1976: p.184) (Table 1).

Trans-bedding contrasts *(sensu lato)*

These inception horizons are difficult to describe and to justify. Instinctive expectation is that well-marked bedding planes provide, by their mere presence, potential inception foci, as deduced by Gardner (1935) and reiterated by many later authors. If so, it might be expected that more bedding plane guided passage would exist in most carbonate successions, where generally only a proportion of available bedding plane fissures are affected by dissolution (eg Ford and Ewers 1978). It is unprovable whether most supposedly *open* bedding plane fissures existed before dissolution/speleogenesis, but assuming such existence, it is unlikely that this alone can provide conditions suitable for inception under most circumstances. Trans-bedding contrasts include real and incipient partings. The former, deduced to exist as voids before speleogenesis, are relatively rare. The latter, emphasised by dissolution along a plane of lithological contrast, are relatively common. Many bedding planes reflect hiatus during sedimentation, but a smaller number of *master bedding planes* (Schwarzacher 1958) represent substantial temporal breaks between cycles of deposition. The British Dinantian cycles approximate to defined Regional Stages, and facies changes between them commonly define lithostratigraphical boundaries. Detailed re-examination (Mundy *in* Arthurton & others 1988) after Schwarzacher's work, confirmed complex cyclicity, with some major breaks marked by karstified surfaces and terrigenous deposits (Fig. 2).

Other major bedding planes are simply breaks, representing time gaps, separating beds that may differ greatly in chemistry/purity and crystallinity. Such contrasts are less easily identified than breaks with karstic surfaces and/or terrigenous deposits, yet they are particularly important in sequences that lack other, more favourable, inception horizons. Ideal development shows a sharp contrast between fine-grained, lime-mudstone, deposits below and coarsely crystalline carbonates above. Sweeting & Sweeting (1969: p.209) noted: "*A study of the landforms suggests that sparry limestones are more impermeable than the biomicrites...*", but Rauch (1972) argued that an increase in crystal size, and especially in sparry cement content, leads to increased dissolutional development. Contrasts between micritic and sparry rocks can signify change from regressive to transgressive depositional conditions. As deposited, the lower beds

WATER DEPTH	DOMINANT LITHOLOGY	THICKNESS AND PERMEABILITY	INCEPTION ROLE
	first bed of overlying cycle		
at or above sea-level	coal, seatearth, volcanic fallout and other terrigenous deposits	relatively thin; some beds with significant primary permeability	generation/transfer of sulphuric acid from *in situ* pyrite (etc)
shallow water ⇑	calcite mudstone, with dolomite and evaporite minerals such as gypsum	thin; initially impermeable; possible horizon of syngenetic **(palaeo) karstification**	Sulphuric acid from evaporite; dolomite/clay mineral reactions; aqueous dissolution
⇑ these rocks make up most of the cycle	mainly oolitic limestone	*relatively thin, with potential primary permeability*	upper surface is favoured location of early dissolution
⇑	pale, thicker-bedded bioclastic limestone	thick **[major part of cycle]**; initially impermeable	early dissolution restricted to tectonic or lithogenetic fissures
⇑	dark, thinner-bedded bioclastic limestone	relatively thin; initially impermeable	as above
⇑	calcareous mudstone	thin; very low primary permeability	as above; possibly some sulphuric acid from pyrite oxidation
deep water	non-calcareous mudstone	thin; very low primary permeability	sulphuric acid formed from pyrite
	last bed of underlying cycle		

Fig. 2: Schematic view (not to scale) of the rocks comprising a single idealised major carbonate depositional cycle [shown within a thick border] and the thick, relatively pure rocks [shaded] that comprise the majority of the cycle. Most inception activity takes place within the thinner and less pure beds [unshaded] The beds at the bottom of the cycle are deposited in deep water, and those above in progressively shallower water.

commonly include minerals that can generate strong acid, or be dissolved physically, producing solutions of salts, such as gypsum or epsomite, that will attack sparry beds above more readily than the source micrite below (cf. Gillott 1978).

Acid-generating horizons

Howard (1964) demonstrated theoretically that early speleogenesis depends upon acid generated in the rock mass, rather than externally derived carbonic acid. He stated that even if minute voids exist at depth and even if a mechanism exists to drive fluid motion through them, surface-derived groundwater would be non-aggressive due to saturation with calcium carbonate. This view was less revolutionary than ideas of sulphuric acid dissolution presented by Durov (1956). Howard stressed the need for locally generated acid during early speleogenesis, followed by gradual domination by carbonic acid. Durov suggested that sulphuric acid is of relatively great importance throughout speleogenesis, though carbonic acid is also involved. Only a difference of degree separates the interpretations. Strong acid is essential to speleo-inception in some situations, and acid generation continues throughout the life of the cave, but quantitatively its relative importance commonly diminishes as caves develop. Meteoric carbon dioxide and carbon dioxide produced as a reaction by-product enter the system and mixture dissolution (eg Bögli 1964) begins to operate, swamping groundwater with bicarbonate and masking background sulphate levels. Possible explanations of high sulphate levels in limestone springs have been discussed by Worthington and Ford (1995).

Chemical and microbial processes that generate sulphuric acid, reviewed by Lowe (1992a: chapter 7) and Lowe & Gunn (1995), depend upon sulphides or sulphates occurring in the rock, though sulphur-bearing organic material (eg hydrocarbons) may be important locally. Reactions can be simple and direct, such as sulphide oxidation to sulphuric acid, or via several steps, such as reduction of sulphate to sulphide followed by oxidation to sulphur and thence to sulphuric acid. Bacterial and/or chemical oxidation of organic or inorganic sulphur also occur. Horizons that can supply raw material for oxidation and reduction reactions include:

a) Evaporitic sulphates
b) Regressive (lagoonal or near-sabkha) carbonates with evaporite inclusions
c) Regressive, dark carbonates with organic content
d) Carbonates with sulphide inclusions
e) Coals and associated pyritic seat-rocks
f) Proximal volcanic and (possibly) high-level intrusive rocks containing sulphides
g) Distal volcanic rocks: fine sulphide-rich air-borne fallout onto the carbonate surface or into the sea over the carbonate (clay *wayboards*, palaeosols and some shales).

These horizons include carbonate as well as non-carbonate lithologies, but acid-producing material is generally concentrated at or near the levels of hiatuses between depositional cycles (Fig. 2). Increased salinity, locally subaerial conditions and long periods of air-fall, contributed relatively small, but vitally important, quantities of sulphate, sulphide and organic-rich material against a background of decreased overall carbonate deposition. Only at or near cycle boundaries was carbonate deposition sufficiently limited to allow relative domination of acid-forming and/or readily soluble impurities.

Physically soluble horizons

The physical solubility of calcium carbonate and dolomite in pure water is relatively insignificant. Other minerals within carbonate successions are more soluble. Polyhalite, kieserite (or epsomite), carnallite, silvite (together termed *bittern salts*) and halite precipitate during total evaporation of a stagnant sea-water body (Scoffin 1987), but are the last minerals to crystallize, due to their high solubilities. Earlier, first calcium carbonate and then calcium sulphate are precipitated. Bittern salts are commonly absent and the halite sequence depleted (Scoffin 1987: p.100), However, precipitation of lime-mudstone (approximately synonymous with porcellanous limestone, chinastone, calcilutite or - in some contexts - micrite) and gypsum/anhydrite is common. Ideally the least soluble mineral precipitates first, followed by the next most soluble, but some concurrent deposition occurs, and the resultant lime-mudstone can contain calcium sulphate inclusions.

Survival of calcium sulphate in carbonate sequences, particularly those re-exposed to surface or near-surface weathering, is uncommon, except in arid areas. Calcium sulphate within lime-mudstone is less prone to removal by surface effects, though some may be lost due to *karstification* during ongoing regression. Surviving calcium sulphate may dissolve later, due to speleogenesis or speleogenesis-like processes, if within zones of groundwater movement. The argument is chicken and egg, as it cannot clearly be demonstrated whether water movement initiates dissolution or whether voids created by dissolution encourage water movement. In either case a potential link between calcium sulphate and speleogenesis is suggested.

Much sulphate in young carbonate sequences probably re-dissolves in groundwater, causing major or minor matrix readjustment. Early re-dissolution may trigger formation of carbonate pseudobreccias, just as a more easily demonstrated evaporite removal at depth formed breccias in English Triassic mudstones (Elliott 1961; Firman & Dickson 1968). Pseudobreccias present potential hydraulic pathways during subsequent speleogenesis. Only in deeply buried sequences, where groundwater motion is relatively slight (though, in context, potentially increasing), are significant sulphate levels preserved, as beds or inclusions within a carbonate matrix (cf. Dunham 1973). As surface modification effectively lifts gypsiferous rock into zones of more active groundwater movement, the amount of sulphate preserved decreases (cf. Krothe & Libra 1983). Theoretically, sulphate loss is complemented by void creation, probably only partially realised due to redistribution of carbonate matrix and insoluble residues. The potential porosity increase may be vital in the speleogenetic context.

Sulphates may have two other speleo-inception roles. Gillott (1978) showed that dissolved calcium sulphate, epsomite and halite accelerate aqueous (rather than acid) dissolution of calcium carbonate. The potential that such processes are involved in speleo-inception cannot be ignored. Finally, sulphates can be converted to sulphuric acid by chemical and bacterial means, as discussed above. Thus, soluble minerals within carbonate successions can influence inception in at least three ways. As calcium sulphate commonly occurs as distinct beds or concentrations of inclusions within specific but relatively limited thicknesses of rock, it is valid to deduce that such zones act as inception horizons. Whether it is also valid to include horizons that have lost sulphate (eg pseudobreccias) and gained porosity, among such horizons is merely a philosophical conundrum. Realistically, speleogenesis is well advanced (but potentially quiescent following gypsum removal) by the time the new rock fabric is created.

Other potential inception horizon functions

This discussion mainly concerns cave development in well-indurated carbonate sequences, of limited permeability before speleo-inception. A major exception is that of syngenetic or penecontemporaneous development in young (eg aeolian or reef) limestones (Lowe 1992a: Chapter 3). Other carbonate sequences that are permeable due to linked primary porosity are common within the geological column. Such rocks are not found consistently at specific chronostratigraphical levels, but reflect local depositional facies and subsequent diagenesis. The Upper Cretaceous Chalk of south-eastern England is not identical to rocks of the same name and age in northern England and differs from carbonates of the same age beneath much of France. Variation also occurs within some Jurassic carbonate formations and less widespread Permian carbonates of northern England. The potential relevance of the Inception Horizon Hypothesis to cave development in Chalk and other porous rocks, and the probable nature of the inception foci within these sequences are discussed by Lowe (1992b).

4. APPLICATION OF THE INCEPTION HORIZON HYPOTHESIS TO CARBONATE SPELEOGENESIS

The Inception Horizon Hypothesis includes many diverse elements. Not all are implicated in cave development in every cavernous sequence nor in the same sequence in different settings. This section outlines application of the hypothesis to indurated carbonate successions. Important processes of littoral zone dissolution and the question of palaeokarsts are reviewed elsewhere (Lowe 1992a).

Speleo-inception in indurated carbonate successions is probably driven by mechanisms other than simple hydraulic/gravitational flow, such as capillarity, earth tides (Davis 1966) or ionic diffusion (Pye & Miller 1990). These promote directional or oscillatory water transfer in or adjacent to the carbonate, generally within buried sequences, across great distances. Water transfer may begin along incipient or real structural or stratigraphical partings (Davis 1966) and/or palaeokarstic voids within the carbonates. Alternatively progressive transmission may be from and into adjacent porous rocks (Palmer 1975; Klimchouk In Press) or via fractures penetrating adjacent non-porous rocks. As water moves in the rock mass, enlargement of proto-routes begins due to physical and chemical changes including dissolution of sulphates, oxidation and reduction reactions involving sulphates, sulphides and native sulphur (with or without microbial mediation) and dissolution of carbonate by strong acids produced *in situ* (eg Durov 1956; Howard 1964; Worthington 1991)). Carbon dioxide produced by some of these reactions enables further dissolution (eg. Ball & Jones 1990).

These processes begin deep below the water-table and are unrelated to surface topography and local hydraulic gradients. Inputs of solvent water to the initially low permeability carbonate mass are diffuse or concentrated along fissures, and derived from relative aquifers above or below. Output from the carbonate is from its boundaries (or across/via faults) into adjacent, more permeable, beds. In suitable structural situations concentrated movement against gravity will occur due to artesian pressure (see also Klimchouk In Press). As buried dissolution continues, the full lateral extent of inception horizons may be incipiently affected. Some areas will, however, be more favourable to water movement and/or dissolution, due to structural effects, local chemical incentives or the presence of open or loosely-filled palaeokarstic voids. Entire susceptible beds can be removed or modified, resulting in the formation of regionally extensive features that will have the superficial appearance of stylolites, or the widespread development of pseudobreccias. Simultaneous inception at several horizons may be linked by dissolutionally widened fractures.

Inception probably proceeds infinitesimally slowly, despite the potency of the dissolutional mechanisms. Initial slowness is indicative of relatively weak driving mechanisms, inevitable supersaturation of the migrating fluids and an original lack of a continuously linked set of proto-routes. If primitive water movement follows the junction between impermeable carbonate rock and an adjacent porous aquifer, considerable time may pass before activity extends beyond the contact zone and opens fracture planes sufficiently to reach inception horizons within the carbonate. Eventually, discrete zones of enhanced seepage propagate and transition from seepage to laminar flow occurs as the indeterminate threshold between inception and gestation is crossed. During gestation, laminar flow concentrates along preferred zones within inception horizons and their linking fractures. Seepage persists in peripheral parts of the inception horizons and effectively parallel, sub-parallel or dendritic sets of small tubes develop, each with ill-defined tributary seepage zones. Locally, single tubes become dominant in areas determined by structural factors and capture drainage from other inception/gestation seeps and flows within their area of influence. These *victor tubes* transmit water by laminar flow until they achieve a diameter of 5-10mm, at which (breakthrough) point turbulent flow becomes dominant and the potential growth rate of the tubes increases (eg. White & Longyear 1962; Dreybrodt 1990).

Throughout these processes the overall water motion need not be downwards or downdip, but lies along a regional hydraulic gradient (Fig. 3). Structural and hydrological settings in which all early movement within the carbonates is topographically and geologically upward are readily imagined and by no means contrived.

These processes and developments, and later stages discussed below, can affect undeformed, sub-horizontal, successions, gently tilted homoclinal sequences, or rocks that have suffered greater deformation. The potential for features conceived and enlarged in undeformed sequences to survive subsequent gentle or severe tectonism is important. Features that survive, intact or fragmented, continue to influence ongoing speleogenesis in their new structural setting (eg. Lowe & Gunn 1986; Šušteršič 1997).

Inception, gestation and later growth proceed in buried rocks, whether or not they suffer deformation, but eventually the incipient system will be intersected by the land surface. Such breaching disrupts the regional hydraulic regime. Depending on structural, stratigraphical and topographical considerations, input sinks, gravitational risings or artesian springs may develop, related to local hydraulic gradients (Fig. 3). Elements of the original, regional hydraulic gradient will continue to affect water movements above or below the newly exposed input/output area. Resurgences created by downcutting are generally associated with the highest inception horizon in the succession. Passages updip of such risings are drained and modified by vadose downcutting. Passages directly behind artesian risings remain flooded whilst more remote passages, confined at higher topographical levels, are drained.

Pre-existing conduits at lower stratigraphical levels than newly created risings remain in the phreatic zone, but if incipient fracture links exist, some underflow (cf. Worthington 1991; Klimchouk In Press) from deeper conduits can target on and rise towards the spring rather than following original routes along the regional hydraulic gradient. As surface topography cuts deeper, lower inception horizons are intercepted. Risings on higher horizons are abandoned to all but local percolation and/or flood water from the land surface or subsurface back-up. Thus, tiered cave systems are drained sequentially; dissolution continues at one or more lower levels, whilst vadose modification (accompanied by seepage from underdeveloped local feeders), abandonment and eventual erosional removal dominate above. Ultimately the lowest inception horizon in the succession, which need not be at the base of the carbonates, is unroofed. As surface downcutting extends below its level, drainage and vadose incision generally occur and in suitable geological settings an accessible canyon is cut back from the rising, with its floor entrenching underlying rocks. Rarely

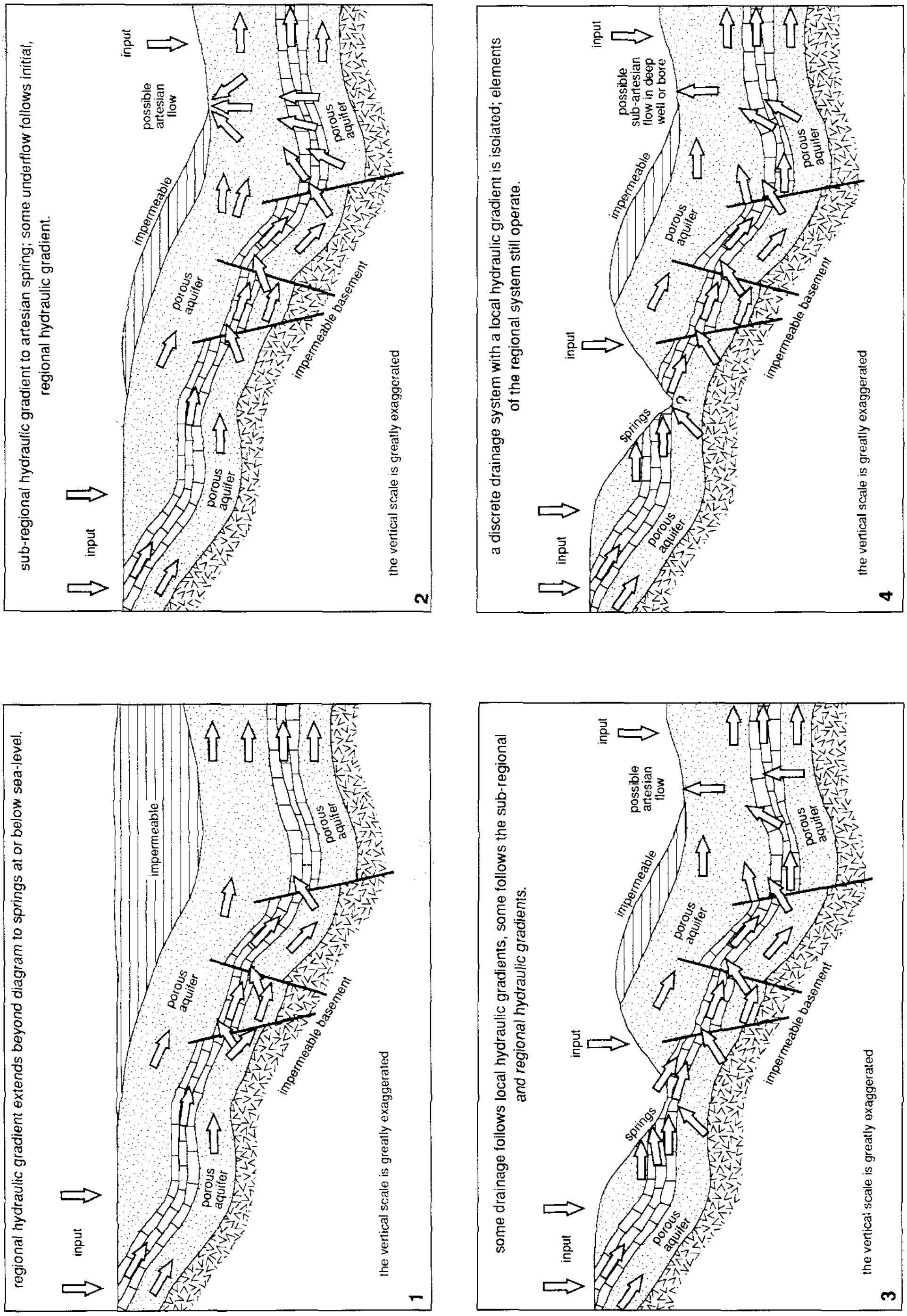
regional hydraulic gradient extends beyond diagram to springs at or below sea-level.
input
impermeable
porous aquifer
impermeable basement
the vertical scale is greatly exaggerated
1
sub-regional hydraulic gradient to artesian spring; some underflow follows initial, regional hydraulic gradient.
possible artesian flow
2
some drainage follows local hydraulic gradients, some follows the sub-regional and regional hydraulic gradients.
springs
3
a discrete drainage system with a local hydraulic gradient is isolated; elements of the regional system still operate.
possible sub-artesian flow in deep well or bore
4

Fig. 3: Schematic view of the stages in the establishment of local hydraulic gradients in a carbonate rock unit and adjacent porous aquifers confined by impermeable rocks: (1) all underground drainage follows extended routes along regional hydraulic gradients under artesian or deep phreatic conditions; (2) confinement may be broken by erosion allowing establishment of upward movement under artesian conditions; (3) deeper surface erosion intersects the carbonate aquifer to establish the earliest local hydraulic gradient, but some drainage still follows the regional hydraulic gradient; (4) elements of the carbonate bad are isolated from the regional situation and have only local hydraulic gradients, but surviving parts of the regional drainage system continue to function.

there may be minimal inception-type development at the lower limit of the soluble rock, yet unless true inception conditions obtain at that level it is unlikely to capture the complete flow of the higher resurgence before a significant canyon forms above.

Throughout post-gestational (post-breakthrough) cave growth, stagnation and erosional removal, disused, underused or incipient fragments of original inception networks are preserved at higher levels. If low level routes are blocked by clastic debris, by back-up of surface or underground floodwaters or, exceptionally, by glacial ice, higher segments may be re-invaded temporarily or permanently. After early failure or abandonment, parts of higher, relict, systems might have been adopted by local percolation water or flow from isolated sinks. Such drainage could utilize and enlarge pre-existing inception horizon guided sections of the proto-system down gradient from open links to lower horizons. Thus, flood water can back up to invade and utilize significant conduits that did not exist when the higher tier was first abandoned. This explanation differs from earlier views of flood water overflows, such as that of Palmer (1975).

The Inception Horizon Hypothesis encapsulates the essence of many processes and relationships that contribute to an overall picture of speleo-inception and ongoing speleogenesis. Emphasis is placed on elements falling outside, or considered only locally within, most current models, and on elements relating to non-karstic dissolution, particularly where this is localized in the carbonate mass by the presence of inception horizons. The importance of carbonic acid dissolution to development, particularly at relatively shallow depth, is not belittled, but the vital importance of other processes to inception in young or mature indurated rocks, is emphasised. The role of bedding-related factors, together termed inception horizons, is stressed in the context of sequential tier and resurgence development, but fracture-guided links also carry drainage between inception horizons, capture drainage at the surface and deliver resurgent water back to the surface. In the remainder of this paper the Inception Horizon Hypothesis is used to provide possible explanations of the origins of various components of a typical cave system.

5. EXPLANATION OF UNDERGROUND FEATURES BY THE INCEPTION HORIZON HYPOTHESIS

Features commonly viewed as inherent parts of a typical carbonate cave system may be explained readily by the Inception Horizon Hypothesis, on the basis that not all parts of a carbonate sequence are equally prone to speleogenesis. The following considerations depart from some traditional views.

Vertical or sub-vertical shafts

The term shaft is used here to describe generally vertical or sub-vertical elements of cave systems, termed pitches or pits by explorers in Britain or the USA respectively. Other definitions that include considerations of supposed origins or observed morphology exist, but their sophistication is unnecessary for this discussion. As used here the term disregards elements of fissure-guided passages requiring vertical descent during exploration but reflecting the morphology of the fissure rather than the geological guidance of the cave skeleton. Inception horizon theory predicts that in undeformed terrains proto-shafts are conceived in the flooded (broadly artesian or phreatic) zones as (sub-) vertical links between (sub-) horizontal inception horizons. If bedding dip is closer to vertical, inception horizons guide shaft-like features, linked by sub-horizontal, structurally-guided elements. In the former situation, initial groundwater movement follows guiding fissures, notably joints and high-angle faults, probably driven initially by processes such as *groundwater pumping* (Davis 1966) and later by artesian pressure. Aggressive groundwater moves between inception horizons via the fissures, and dissolution occurs on a wide front. As gestation progresses in the inception horizons, flow from and into discrete conduits localises groundwater movement within the fissures, causing local widening. Drainage from an inception horizon might move vertically upwards, vertically downwards or in any lateral sense towards another favourable horizon. As the flooded dissolutional conduits grow and normal hydraulic laws begin to operate, all inception links will enlarge initially, but combinations with favourable hydraulic gradient will enlarge preferentially, eventually gathering most of the drainage.

Following uplift and drainage, when vadose gravitational flow replaces artesian and phreatic hydraulic flow, only vertically or obliquely downward linking-routes are followed by free drainage. Vadose flow along a relict dissolutional conduit will plunge down vertical links, or cascade along downward oblique links, opening shafts or descending, fissure-guided passages. (Sub-) vertical shaft lips are cut back and down by headward erosion as vadose trenches form in conduit floors. Cursory examination of passage morphology may fail to reveal that both passage and shaft originated under flooded conditions. At the shaft foot the vadose stream normally abandons the guiding

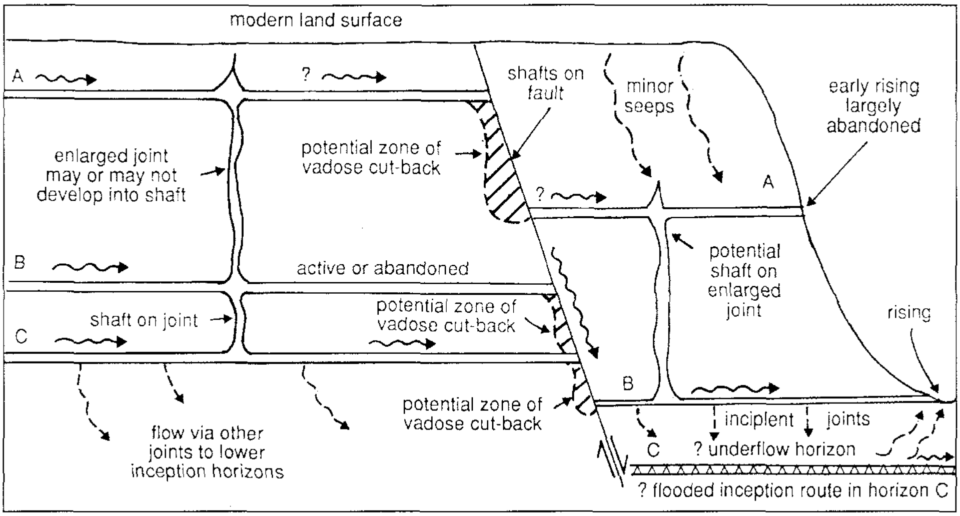

Fig. 4: Schematic representations of the role of joint- or fault-guided links in the formation of vertical and sub-vertical shafts. In this figure and in figures 5 and 6 the simplest possible two-dimensional view is presented. In reality, at any of the points where drainage diverges from bedding-guided routes, conduit development might propagate up, down or laterally along a guiding fracture to generate a three-dimensional system.

fissure for a conduit in a topographically lower inception horizon. More rarely, if only an immature conduit exists, flow below the shaft continues within the guiding fissure towards another inception horizon. This situation is commonly accompanied by ponding of water (cf sumps, below).

Shaft-forming fissure links are of two broad kinds, both potentially present in (sub-) horizontal and dipping situations. One develops along joint planes where seepage through the effectively saturated rock mass targets upon stratigraphically lower or stratigraphically higher inception horizons. Concurrently a route could pursue the original horizon across the fissure (cf abandoned high level passages, below). In the other, guided by fault planes, water travels upwards, downwards or laterally to reach a favourable target in stratigraphically higher or lower inception horizons, or the same horizon at another topographical level. Possible combinations are shown in a highly schematic, two-dimensional form, in Fig. 4. In the situations illustrated, fissure links may extend great distances in the third dimension.

Upward shafts (avens) and related features

The term aven is used in Britain to describe (sub-) vertical upward extensions from cave passages or chambers. Some avens have no negotiable

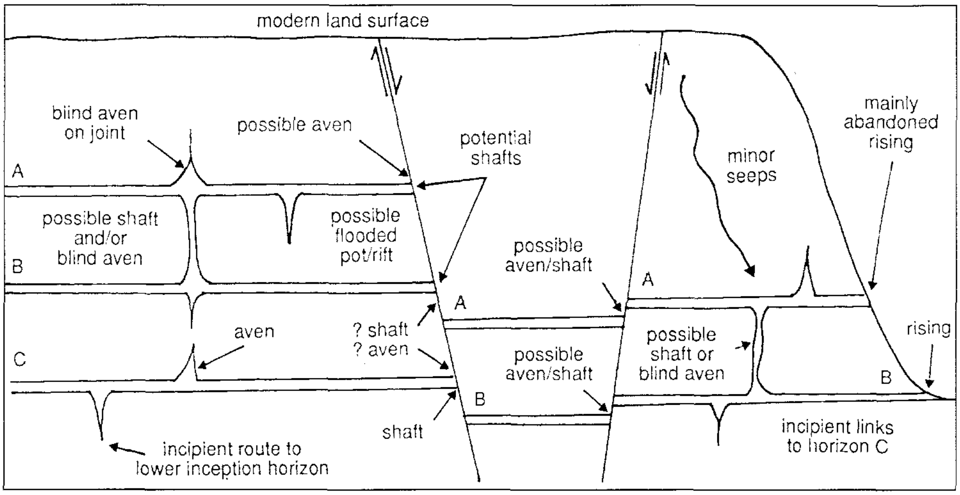

Fig. 5: Schematic representation of the formation of 'avens' [see explanation of Figure 4]

upward connection, others provide links to higher passages. In this context avens do not include generally-local dissolutional features that are not fracture-guided. The previous section provides a basis for examination of aven formation in the inception horizon context. If dissolutional links can form in any direction under artesian/phreatic conditions, when vadose conditions are established any pre-existing upward ramifications must become disused as drains from any lower horizon that was involved in their inception. Vadose streams occupying inception horizon conduits plunge down vertical shafts, cascade along oblique fissures or continue along the original inception level, but incipient or active upward routes are disregarded by that particular flow. However, upward development from one horizon could be downward development from a higher one. Three broad possibilities remain. There may exist blind upward ramifications that failed to establish a viable link to a remote target horizon. Secondly, an aven in the roof of one inception conduit may rise to join a higher abandoned inception conduit. Thirdly, an aven in a passage roof may be an active inlet shaft from a passage conceived along a higher inception level. These three categories, each expandable to fit many actual underground situations, are shown in a highly diagrammatic form in Fig. 5.

Abandoned high levels and passage continuations

Fig. 6 illustrates links that have formed where an inception horizon meets a joint and development continued along the inception horizon as well as along the joint. Such onward development probably pre-dated significant disso-

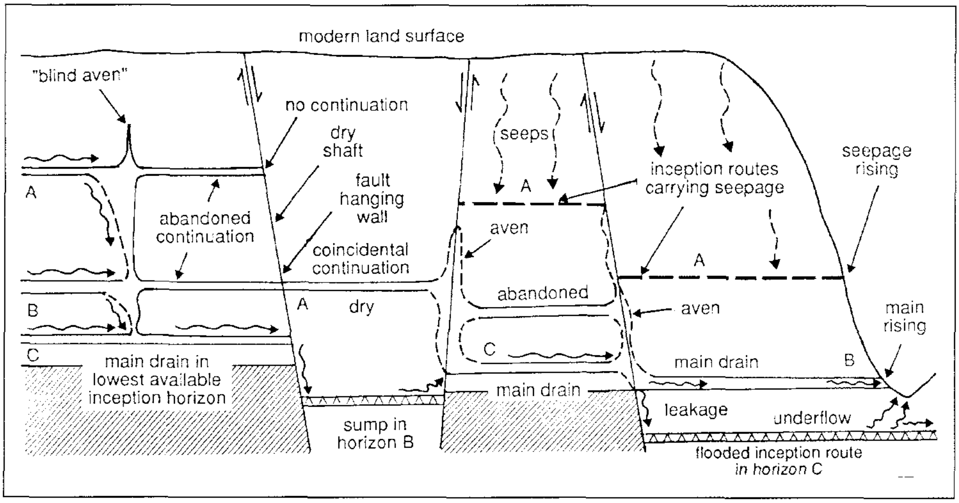

Fig. 6: Schematic representation of the formation of 'abandoned high level passages', 'avens', 'shafts' and 'sumps' [see also figures 4 and 5]

lution along the fissure. If, after uplift, vadose flow continued across any incipient links on the joint plane, the latter would become water-logged sites of continued dissolution. If dissolution along the joint link eventually broke through, the inception horizon would progressively be abandoned, as the lower, more favourable route enlarged. A parallel situation could be enforced at the time of vadose establishment, if a downward route along a suitable joint was already sufficiently open to permit capture of the flow (as discussed above). The observation that not all phreatic conduits continue across fissure-guided shafts is simply explained. No continuation will occur (except where inception horizons are coincidentally juxtaposed) across a fault-guided shaft.

Flooded passage sections

Negotiable cave passages may commonly appear to terminate where water meets the roof, forming features that have been termed sumps, syphons or (water) traps. Some are of limited horizontal extent and comprise water-filled conduits that re-connect to open passage beyond the flooded section. They may be passable or impassable to human explorers. Others may extend deep into the flooded zone with no readily accessible links back to unflooded conduits. Fig. 6 provides a two-dimensional schematic view of possible situations where links may form vertically or laterally along guiding fissures between inception horizons during inception. There will be situations where, after uplift, vadose drainage in an invaded inception conduit will find no advantageous onward route vertically or laterally downwards. This situation will normally be encountered in the context of fault-guided rather than joint-guided links. In order that drainage from the invaded inception horizon may progress down the hydraulic gradient it must transfer to another, more suitable horizon. Initially, connections between the two horizons are flooded and may extend great distances laterally, though water levels are effectively identical at both ends. The simplest situation involves a short, flooded, downdip tube and a "phreatic" lift up the fault plane, but more complex links ramify laterally in three dimensions and may include several fault-guided links and sections guided by downfaulted inception horizons and other fissures.

General views of multi-level speleogenesis

A question that reappears throughout the history of publication on speleogenesis concerns the origin of multi-level or *tiered* caves. Awareness of the problem may be implicit, as in the case of early discussions by authors such as Davis (1930) and Gardner (1935) or explicit, as in the work of Swinnerton (1932). None of these achieved a fully workable hypothesis of multi-level speleogenesis, though Gardner's ideas included a view close to that in the Inception Horizon Hypothesis. The major conceptual problem in understanding the genesis of multi-level caves is that of providing a model applicable in folded as well as unfolded terrains. Superficially, it seems that Swinnerton (1932) addressed this more closely than did Davis (1930) or Gardner (1935). This is illusory; the supposed sub-horizontal situation within most of W.M. Davis's examples and the folded situation discussed by Swinnerton are points near the ends of a continuum, wherein Gardner's dipping sequence occupies a more central position. Not all earlier discussions of multi-level caves were misdirected, but many suffered from trying to link passage levels to a development chronology, the common assumption being that the highest passage in a multi-level system formed first and the lowest formed last. This view is modified in the Inception Horizon Hypothesis, which suggests that, potentially, all levels were conceived under artesian and/or phreatic conditions at approximately the same time. Bridging the gulf between this concept and earlier ideas is recognition that after artesian/phreatic inception at two (or many) levels in a carbonate block, development may be greatest in the highest incipient passage and least in the lowest. Downward decrease of development potential reflects more favourable hydraulic conditions near the water-table (shallow phreatic zone). However, the orderly sequence may be locally inverted if a lower inception horizon is significantly more favourable than those above, or if significant artesian activity continues at depth without affecting shallower passage development.

As surface topography and hence regional and local hydraulic gradients alter with time, the level of the water-table drops, eventually falling below the highest and (generally) best developed phreatic conduit system. Drainage may be wholly or partly diverted from its original route to resurge at a spring manufactured by a surface valley intersecting the conduit. Part or all of the drainage might, however, divert to the next lower inception level, via fracture-guided routes, immediately or in due time. In some cases vadose conditions will take over for the up-gradient part of the original system as deduced by Gardner (1935) but, in complex structural situations, parts of the system will remain flooded. Even after transition of part of the underground drainage network to the vadose zone, a deeper flow component remains in lower inception horizons (and within the truncated down-gradient extension of the first). These will in turn be intercepted by the surface topography and the higher passages will be progressively abandoned by all but local seepages.

6. CONCLUSIONS

Much of this paper has involved description and lateral re-examination of elements that lie within the currently accepted concepts of speleogenesis or have contributed to them. Early ideas that were subsequently abandoned now appear to remain potentially valid to the overview of speleogenesis. Parts of the current view may be re-evaluated and concepts viewed as universal appear potentially less widely applicable, whilst concepts previously accepted as of only local significance are seen to be potentially of widespread importance.

The hypothesis discussed here does not replace existing cave development models, but expands upon them. In so doing, it provides a linking string, or strings, that allow concatenation of aspects previously seen as separate and specialized. In attempting to justify this linkage, some pre-existing relationships are questioned and new explanations are developed, but much of the background structure of speleogenetic dogma remains intact. If the qualitative hypothesis presented provides an acceptable working model and stimulates empirical studies that confirm its validity, much of the extant chemical and mathematical dataset about which current theories pivot may have to be more closely reconsidered.

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SPELEOGENEZA V KARBONATNIH KAMNINAH: HIPOTEZA ZAČETNIH HORIZONTOV

Povzetek

1. UVOD: KRAŠKE VOTLINE V KARBONATNIH KAMNINAH

V članku razpravljava, zakaj in kako nastanejo v kamnini, kjer prej ni bilo povezanih votlin, kraški kanali[1]. Osvetliti želiva dejavnike, ki vodijo k nastanku prevodnika in nadalnji speleogenzi ter podati delovni model mehanizmov, ki porajajo kraške votline.

Izraz speleogeneza, kakor ga običajno pojmujemo, naj bi pomenil **nastanek** jam (Lowe & Waltham 1995), vendar se mnoga klasična dela s tega področja posvečajo izključno vprašanju nadalnjega **razvoja** obstoječega prevodnika v jamo (n.pr. Davis 1939; Swinnerton 1932; Gardner 1935; Warwick 1953; Davies 1960; Ford 1965; Palmer 1975, 1991). Čeprav sodelujočih procesov še ne razumemo do zadnjih podrobnosti, lahko vendarle ugotovljamo, jih poznamo vsaj v precejšnji meri. Nasprotno pa je bilo o najbolj zgodnji razvojni fazi, ki jo imenujeva začetje[2], doslej napisanega le malo.

V speleogeteskih razpravah se zdi predpostavka, da imajo starejše, bolj sprijete karbonatne kamnine nizko primarno poroznost in da zveznih prevodnikov takorekoč ni, bolj ali manj samoumevna. Posebej na karbonatnih platformah poteka zakrasevanje v mladih karbonatnih skladovnicah s sorazmerno visoko poroznostjo in prevodnostjo skupaj z diagenezo. Dobro razviti jamski sistemi so znani s pleistocenskih apnencev otočij Tonga (Lowe & Gunn 1986) in Bahamov (Mylroie & Carew 1990). Nekaj takšnih jam, in po logiki stvari, tudi manjših prevodnikov, se ohrani skozi diagenezo in morebitno tektonsko preoblikovanje ter igra pomebno vlogo pri nadalnji spelogenezi (Lowe & Gunn 1986, v pripravi; Lowe 1989).

Za speleogenezo se nama zdi vloga *nekraških procesov* (Lowe 1982a, Lowe & Gunn 1985) posebnega pomena. Kraške procese (*v ožjem smislu*) na karbonatnih kamninah in razvoj geomorfnih oblik, ki iz tega sledijo (in kamor spada tudi razvoj jam), imamo običajno za izid delovanja ogljikove kisline na kalcijev karbonat. O pomenu ogljikove kisline za kasnejši razvoj jam pač ni potrebno razpravljati, manj pa je jasna njena vloga pri samem nastanku jam (Lowe & Gunn 1986).

2. DEFINICIJA ZAČETJA IN ZAČETNIH HORIZOTOV

Izraz *začetje*, kot ga uporabljava v tem besedilu, pomeni najbolj zgodnjo fazo v spelogenezi karbonatne sekvence in je je le delno soznačen izrazu *iniciacija*. Pojem začetja zapolnjuje neogibno vrzel v razumevanju speleogeneze, ki ostaja doslej večinoma odprta. Če privzamemo misel o začetju in definiramo izraze, ki naj pokrijejo fazo med začetjem in pričetkom turbulentnega toka, lahko ohlapni pojem *iniciacija* v nadalnji razpravi o speleogenezi opustimo. Pač pa predlagava izraz *snovanje*, s katerim opišemo rast kanala v času laminarnega toka med začetjem in prebojem.

Izraz *začetni horizont* (Lowe 1982a) opisuje: **katerikoli element karbonatne sekvence, ki ga odrejajo litostratigrafska svojstva kamnine in ki, kot posledica fizikalnih, litoloških ali kemijskih razlik v prevladujočem karbonatnem faciesu znotraj skladovnice, pasivno ali aktivno proži raztapljanje**. Začetni horizonti se do neke mere skladajo z mejami med litostratigrafskimi členi oz. sedimentacijskimi cikli (*v širšem smislu*).

3. SVOJSTVA ZAČETNIH HORIZONTOV

Splošno razširjeno mnenje, da lezike in/ali nepropustni vložki po stratigrafski plati uokvirjajo spelogenezo, ne pojasni vseh njenih tančin; nedvomno pa ti elementi odrejajo mesto začetja v prostoru in usmerjajo nadalnji razvoj jame. Elementi začetja, ki se oblikujejo vzdolž teh horizontov v zgodnjih obdobjih nsatajanja karbonatne kamnine, lahko prestanejo tektonsko preoblikovanjo kamninske gmote in vplivajo na kasnejši razvoj jam v nagubanih ali razlomljenih kamninah (Lowe & Gunn 1986, Šušteršič 1997).

Horizonti z značajem akvifuga[3], akvikluda[3], akvitarda[3] oz. akviferja[3]

Na pogled so si naštete hidrogeološke kategorije zelo različne. V okviru razmišljanj o začetnih horizontih pa so le izseki kontinua, ki se med seboj lahko prekrivajo in v različnih fazah speleogeneze znotraj posamezne skladovnice tudi menjajo svoje vloge. Nekateri glinovci, še posebej skrilavi, morejo v primerjavi s sosednjimi karbonati izkazovati zadovoljivo zvezno primarno poroznost in dopuščajo mezenje skozi ali iz domnevnega akvikluda (Neuzil 1986, 1994). Tabela 1 (izvirno besedilo) kaže iznos poroznosti in primarne ter sekundarne prepustnosti nekaterih kamnin. Pomembno je prekrivanje iznosov poroznosti in še posebej prepustnosti med posameznimi karbonati, peščenjaki in glinastimi skrilavci.

V krajevnem merilu pomenijo glinaste plasti (*v šišem smislu*) v karbonatni skladovnici zaporo obilnejšemu prenikanju, vendar njihova navzočnost še ne potisne začetja više, proč od njih. Pogoji pronicanja vode so namreč pred vzpostavitvijo kanalskega toka popolnoma drugačni kot pozneje. V tem času je izmenično (ali usmerjeno) pronicanje vode bolj verjetno v peščenjakih kot v karbonatih. Če se pridružijo še nastajanje kislin, ali fizikalno raztapljanje, lahko uspešno načne sosednjo karbonatno kamnino.

Nekateri karbonati so prepustni zaradi svoje primarne poroznosti. Sindiagenetsko raztapljanje na stiku sladke in slane vode je bilo v zadnjem času deležno velike pozornosti (Back & al. 1986; Bottrell & al. 1990; Mylroie & Carew 1990; Whitaker & P.L. Smart 1990). Podobno so že od vsega začetka lahko visoko porozne nekatere oolitne karbonatne kamnine. Peščenjaki z odprtimi razpokami so lahko idealen začetni akvifer (v smislu Gardnerja 1935), seveda pa ne moreje tekmovati z razvitim kraškim prevodnikom.

Dejansko zadobijo mnoge karbonatne kamnine lastnosti akviferja šele, ko raztapljanje povzroči nastanek votlin, kar je v smislu naše razprave neločljivo povezano s speleogenezo. Tedaj v trdnih karbonatih dotedanja prepustnost zraste več kot 10 milijonkrat (Smith & al. 1976: str. 184; Tabela 1).

Medplastovne razlike (*v širšem smislu*)

Medplastovne razlike se kažejo vzdolž obstoječih ali nakazanih presledkov med skladi. Za prve menimo, da se pojavljajo kot praznine že pred speleogenezo in so sorazmeno redke. Naprotno pa so slednji, ki jih raztapljanje v ploskvi litološkega kontrasta še poudari, sorazmerno pogosti. Mnoge lezike odsevajo vrzel v času sedimentacije, toda manjše število med njimi, po Schwarzacherju (1958) *vodilne lezike*, pomenijo pomebne časovne presledke med posameznimi cikli odlaganja.

Preostale odprte lezike so presledki, ki odsevajo časovne vrzeli in lahko ločijo plasti, ki se rezko razlikujejo po čistosti kamnine (kemizmu) in stopnji prekristaljenja. Običajno se v spodnjem skladu odlagajo minerali, ki ob oksidaciji spoščajo močne kisline ali pa se topijo fizikalno. Minerali kot sadra, epsomit ipd. razkrajajo sparite v zgornji plasti učinkoviteje kot mikrite, iz katerih izvirajo (Gillott 1978). Takšne kontraste je teže zaznati kot paleokraška površja ali sedimente kopenske faze, a so posebnega pomena kadar manjka drugih, začetju prikladnejših horizontov.

Horizonti ki sproščajo kisline

Howard (1964) je teoretično pokazal, da bolj kot na od zunaj dotekli ogljikovi kislini, zgodnja speleogeneza temelji na kislini, ki nastaja znotraj same kamninske gmote. Menil je, da bi tudi v primeru, ko na primerni globini drobne votlinice že obstojajo in ko mehanizmov, ki potiskajo tekočino skoznje ne manjka, voda ne bila agresivna, saj se prehitro zasiti s kalcijevim karbonatom. Še bolj prekucuška je bila misel Durova (1956), ki je predložil, da se prvo raztapljanje odvije s pomočjo žveplene kisline. Pristopa se razlikujeta edino v poudarkih. Vsekakor je v nekaterih okoliščinah navzočnost močne kisline za začetje bistvena. Taka kislina se seveda sprošča ves čas spelogeneze in se njen učinek absolutno ne zmanjša, vendar po pomenu reakcija ogljikove kisline kmalu popolnoma prevlada.

Kemični in biogeni procesi, ki sproščajo žvepleno kislino, koreninijo v sulfidih ali sulfatih, ki se pojavljajo v kamnini. Včasih je pomembna tudi navzočnost organske snovi, bogate z žveplom (ogljikovodiki). Reakcije so lahko preproste in neposredne, ali pa postopne. Horizonti, ki lahko prispevajo reaktante za oksidacijo ali redukcijo so predvsem:

a) sulfatni evaporiti
b) regresivni (lagunarni ali sebkini) karbonati z vložki evaporitov
c) regresivni, temni karbonati z organsko primesjo
d) karbonati z vključenimi sulfidi
e) premogi in druge s piritom bogate kamnine
f) predornine oz. plitve globočnine z minerali, ki vsebujejo žveplo
g) piroklastiti, bogati z drobno razpršenimi sulfidi, ki so se usedli na kopne ali podmorske krbonatne površine.

Fizikalno topni horizonti

Fizikalna topnost kalcijevega karbonata in dolomita v čisti vodi je sorazmeno nizka, so pa bolj topni drugi minerali, navzoči v karbonatnih skladovnicah. V času hlapenja vodnega telesa se odlagajo polihalit, kieserit, epsomit, karnalit, silvin in halit (Scoffin 1987), a zaradi svoje visoke topnosti kristalijo poslednji. Večino haloidov in sulfatov v mladih karbonatih verjetno ponovno raztopi podtalnica. Teoretično to pomeni nastajanje votlinic, ki jih le delno zapolnijo netopne primesi oz. karbonat iz osnove. Dovolj zgodnje raztapljanje lahko sproži nastajanje karbonatnih psevdobreč, kar bi s stališča speleogeneze zopet pomenilo pomembno povečanje poroznosti.

Gillott (1978) je pokazal, da raztopljeni kalcijev sulfat, epsomit in halit pospešujejo neposredno raztapljanje kalcijevega karbonata. Možnosti, ki jih ta proces odpira začetju pač ne gre spregledati. Končno nekateri biogeni ali kemični dejavniki sulfate spremenijo v sulfide, s posledicami, o katerih smo govorili nekoliko prej.

Druge možnosti pojavljanja začetnih horizontov

V naši razpravi se oziramo predvsem na nastanek jam v dobro sprijetih karbonatnih skladovnicah, katerih prepustnost je bila pred začetjem omejena. Pomebna izjema je razvoj v najmlajših, subrecentnih eolskih ali grebenskih apnencih (Lowe 1982a). Teh kamnin še ne moremo šteti v določen stratigrafski nivo, ampak odsevajo, geološko gledano, trenutne pogoje odlaganja in takojšnje diageneze. Možno vlogo krede (kamnine) in drugih poroznih kamnin je obdelal Lowe (1982a).

4. APLIKACIJA HIPOTEZE ZAČETNIH HORIZONTOV NA SPELOGENEZO KARBONATOV

Hipoteza začetnih horizontov vključuje raznorodne dejavnike. V razvoj posameznega zaporedja kanalov niso vpleteni vsi, niti ni verjetno, da bi bili v enakih kamninskih skladovnicah navzoči vedno isti. Začetje v karbonatnih kamninah verjetno poganjajo drugačni mehanizmi kot preprost tekočinski tok na osnovi hidravličnih zakonov, ki ga poganja težnost. Verjetno gre za kapilarnost, plimovanje zemeljske skorje (Davis 1966) ali ionsko difuzijo (Pye & Miller 1990). Medtem ko se voda premika skozi kamninsko gmoto, se večajo njene prvotne poti, naj bo to zaradi fizikalnih ali kemijskih dejavnikov. Opraviti imamo predvsem z raztapljanjem sulfatov, z oksidacijo ali redukcijo sulfatov, sulfidov ali samorodnega žvepla (s pomočjo delovanje mikrobov ali pa ne) ter z raztapljanjem karbonatov s pomočjo močnih kislin, ki nastajjo na kraju samem (Durov 1956; Howard 1964; Worthington 1991).

Našteti procesi se odvijajo globoko pod gladino podtalnice in se ne ozirajo na oblikovanost površja in hidravlični gradient. Voda, ki vstopa v karbonatno gmoto prihaja z višje ali nižje ležečega vodonosnika in je potuje razpršena po nezveznostih v kamnini. Napredujoče raztapljanje postopoma zajame celoten začetni hoziront. Posamezni predeli so premikanju vode in/ali raztapljanju prikladnejši, naj bo to zaradi strukturnih učinkov, krajevnih sprememb v kemijskih lastnostih kamnine ali navzočnosti slabo zapolnjenih/odprtih paleokraških votlin. Tako lahko izginejo celotne plasti, nagnjene k tovrstnemu razkroju in učinki dobijo regionalne razsežnosti.

Začetje se verjetno prične neznansko počasi, ne glede na možno učinkovitost sodelujočih dejavnikov. To kaže na sorazmerno šibko prenikanje, neogibno prenasičenje tekočine in začetni neobstoj povezanih vodnih poti. Posamezna območja hitrejšega prenikanja se postopoma povezujejo in ko je prag med začetjem in pripravo prekoračen, se pojavijo prehodi med preniklim in laminarnim tokom. V času priprave se laminarni tok zbira vzdolž najugodnejših smeri znotraj začetnih horizontov, oz. razpok, ki jih povezujejo. Posamezni kanali prevladajo in pritezajo nase vodo iz sosednjih območij začetja/priprave. Tok v teh *zmagovitih poteh* je laminaren, dokler njihov premer ne doseže 5 - 10 mm. Tedaj se prevrže v turbulentnega, stopnja večanja pa zelo naraste (White & Longyear 1962; Dreybrodt 1990).

V času teh procesov je smer vodnega toka v prostoru poljubna - globalno pa se pokorava regionalnemu hidravličnemu gradientu (Slika 3). Začetje, priprava in kasnejše večanje se odvijajo globoko v kamninski gmoti, vendar nastajajoči prevodni sistem slej najde stik s površjem. Glede na krajevne strukturne, stratigrafske in topografske danosti se pojavijo ponori, gravitacijski ali arteški izviri, kakršne pač so krajevne hidrogeološke razmere (Slika 3). Medtem ko se površje vse bolj znižuje, seka vse globlje začetne horizonte. Freatični dvigi na višje horizonte omrtvijo in poslužujejo se jih edino prenikla deževnica oz. občasno poplavne vode iz večjih globin. Tako jamski sistemi postopoma osuševajo; raztapljanje se nadaljuje v enem ali več spodnjih svežnjih, medtem ko zgoraj prevlada vadozno preoblikovanje. Kljub temu se odlomki opuščenih, delno opuščenih ali komajda nakazanih spletov v višjih delih ohranijo. Če spodnje dele prekinejo podori, ali izjemoma led, jih voda lahko ponovno aktivira.

5. RAZLAGA PODZEMSKIH KRAŠKIH POJAVOV S POMOČJO HIPOTEZE ZAČETNIH HORIZONTOV

Če sprejmemo ugotovitev, da vsi členi karbonatne skladovnice niso enako primerni za speleogenezo, lahko s pomočjo hipoteze začetnih horizontov preprosto razložimo oblikovanst kraškega podzemlja.

Navpični in skoraj navpični jaški

Z izrazom jašek v tem besedilu navpične ali skoraj navpične elemente jamskih sistemov. Izraz ne obsega votlin, ki jih jamarji premagujejo s tehniko obvladovanja navpičnic in ki odsevajo neposrden razvoj iz tektonske(ih) razpok(e)[4].

Hipoteza o začetnih horizontih predvideva, da nastajajo v poplavljeni (freatični ali arteški) coni tudi v tektonsko nepoškodovanih gmotah embrionalne oblike jaškov, ki (skoraj) navpično povezujejo (skoraj) vodoravne začetne horizonte. Če je skladovitost skoraj navpična, so začetni horizonti vodila nastajajočim votlinam, ki spominjajo na brezna - le te pa povezujejo kanali, ki sledijo razpokam. Med začetnimi horizonti se agresivna voda pretaka po razpokah in preskoki se pojavljajo na široki fronti. Šele napredujoča *priprava* zbere tok znotraj začetnega horizonta v posamezen kanal; ta pa napaja le nekatere razpoke in povzroči, da se na tem odseku razširijo tudi same. Tok iz začetnega horizonta v smeri proti naslednjemu začetnemu horizontu lahko uporabi katerokoli prikladno smer v prostoru. Zato pri površnem ocenjevanju izvora oblikovanosti jamskega prostora hitro spregledamo, da sta tako rov kot jašek nastala v prežeti coni.

Jaški, ki nastajajo ob razpokah, so v grobem dveh vrst in morejo nastati enako v vodoravnih kot poševnih skladovnicah. Prvi nastajajo vzdolž razpok, kamor se usmerja prenikla padavinska voda, ko je že dosegla prežeto cono in išče poti do najbližjega s začetnega horizonta. V drugem primeru potuje freatična voda ob ploskvi preloma v poljubni smeri, z enega začetnega horizonta na drugega.

Kamini[5] in podobne oblike

V prežeti coni nastajajo jamski rovi v poljubni smeri v prostoru. Ko se gladina podtalnice zniža, preidejo višji predeli svežnja v vadozne pogoje.

Prenikle vode se zbirajo vzdolž začetnih horizontov, padajo po navpičnih jaških ali derejo po poševnih razpokah - ne morejo pa se po podedovanih votlinah vzpenjati. V grobem so možni trije osnovni izidi, ki jih prikazuje Sl. 5.

Opuščeni višji rovi in njihova nadaljevanja

Slika 6 prikazuje zveze, ki se pojavijo, kjer začetni horizont naleti na razpoko in se razvoj nadaljuje vzdolž obeh. Tak razvoj je starejši od pomembnejšega raztapljanje vzdolž razpoke. Če si po tektonskem dvigu vadozni tok najde pot vzdolž neke starejše zveze vzdolž razpoke, se bo ta širila dalje. Ko raztapljane znotraj dotlej še nenačetega predela končno utre novo pot razpoke, začetni horizont postopoma omrtvi, nižja, nova pot pa se širi dalje.

Poplavljeni odseki rovov

Prehodni rovi se često "končajo", kjer se stakneta strop in vodna gladina. Nastane položaj, ki mu pravijo jamarji sifon, smrk ali "ujeta voda". Slika 6 je shematiziran dvodimezionalen prikaz možnih izidov, kadar se zveze vzdolž vodilnih razpok med dvema začetnima horizontoma lahko pojavljajo v različnih smereh. Prvotno so zveze med dvema začetnima horizontoma poplavljene in mnoge se bočno raztezajo na velike razdalje. Najpreprostejši izid je kratka, zalita cev, ki se spušča ob leziki in ponovno dvigne ob ploskvi preloma. Bolj zapletene se vejijo tudi v bočni smeri in lahko vključujejo številne člene, ki so jim botrovale enako razpoke ali prelomi, kot začetni horizonti.

Splošno o nastanku jam v več nadstropjih

Med vprašanji, ki so v ospredju že vse od prvih pisanih/tiskanih razprav o spelogenezi, je vprašanje nastajanja jam v različnih višinskih pasovih. Večina zgodnjih del je iskala časovnih odnosov med "nadstropji", pri čemer je veljalo za samoumevno, da je najvišje "nadstopje" najstarejše in najnižje najmlajše. Hipoteza začetnih horizontov to gledišče popravlja, saj predvideva, da se je začetje vseh kanalov, v vseh "nadstropjih" lahko odvilo približno istočasno, v freatičnih/arteških pogojih.

Ker se površinska oblikovanost in zato hidrogeološke razmere s časom spreminjajo, se gladina podtalnice spušča in postopoma pade niže od najvišjega in večinoma najbolje razvitega svežnja. Kraške vode se preusmerjajo proti najglobljі zarezani površinski dolini, ki seka kraški prevodnik. Podzemsko pretakanje se, največkrat vzdolž razpok, postopoma prestavlja na nižje ležeče začetne horizonte, v višjih pa vladajo vadozne razmere.

6. ZAKLJUČKI

Večina članka obsega razpravo o temeljnih mislih, ki jih sprejema danes veljavno razumevanje spelogeneze, ali pa so neko vlogo odigrale v preteklosti. Nekatere so postopoma prešle v pozabo, a pri celostnem pogledu na spelogenezo spet pridobivajo veljavo; posamezni pogledi, ki so obveljali za splošne, pa se zdijo danes manj uporabni.

Hipoteza, o kateri razpravljamo na tem mestu, obstoječih modelov razvoja jam ne nadomešča, iz njih ampak raste. Predvsem plete vezi z mislimi, ki so doslej veljale za manj pomembne. S tem, ko jih skušava upravičiti, razvijava nove razlage, vendar ostaja osnovna speleogenetska dogma nedotaknjena. Predstavljena kvalitativna hipoteza omogoča delovni model, ki naj spodbudi empirično raziskovanje.

(Prevod France Šušteršič)

Prevajalčeve opombe:

[1] *Pri prevajanju besedila, ki novim mislim šele utira pot, so težave pri iskanju primernih izrazov neogibne. Da bo branje lažje, sem se naslonil na članek Prispevek k slovenskemu speleološkemu pojmovniku (Šušteršič, Knez, Naše jame, 37, 1995, str. 153-170). Polno pa se zavedam, da je to izhod za silo, saj je tam eksplicitno zapisano (str. 154), da besedilo nima normativnih namenov in da je predvsem namenjeno nadaljnji razpravi.*

[2] *Angleški izraz* inception *je nedvomno izpeljan iz latinskega neologizma* inceptio, *ta pa iz glagola* incipio *(=* začeti, začeti se*) (Bradač 1937: Latinsko slovenski slovar. Jugoslovanska knjigarna v Ljubljani, Ljubljana, str. 249). Zato menim, da je moje slovenjenje vsebinsko in formalno pravilno. Vsekakor ne vidom razloga, da bi na latinski koren cepil slovensko obrazilo in skoval še eno nepotrebno tujko več.*

[3] *Med naštetimi tujkami ima slovensko soznačnico edino izraz* aquifer *(=* vodonosnik*). Da bi bilo besedilo enotno, sem tudi to ohranil v poslovenjeni izvirni obliki.*

[4] *Anglosaško pojmovanje navpičnih kraških votlin se zdi nekoliko ohlapnejše, kot slovensko, terminologija pa enako nedosledna. Uporabljeni izraz* jašek *je pač izhod za silo.*

[5] *Angleškemu izrazu* aven *še najbolj ustereza naš* kamin. *Seveda pa sta obe besedi predvsem jamarski in izražata tehnično zahtevnost, manj oblikovanost, zagotovo pa ne izvora.*