What makes a bedding plane favourable to karstification? – The role of the primary rock permeability

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Abstract

Recent studies on the complex 3D geometry of large cave systems around the World allowed us to get statistical evidence of the inception horizon hypothesis. It clearly confirmed the idea that the development of karst conduits under phreatic conditions is strongly related to a restricted number of so-called inception horizons. An inception horizon is a part of a rock succession that can favour the earliest cave forming processes (LOWE, 1992). It can favour the karstification by physical, lithological or chemical deviation from the predominant carbonate facies within the sequence.

In order to understand the reason(s) why a specific stratigraphical horizon is used for cave development we sampled 18 inception horizons of six cave systems as well as the surrounding rock mass. More than 200 rock micro-cores have been drilled and analysed to determine parameters controlling the speleogenesis, and to provide a better prediction of dissolution voids within a karstic rock mass. The analysis of these cores gives a first idea of the different key properties of inception horizons. This paper only presents and discusses the results of the measurements of the primary rock permeability. The initial permeability contrast is not sufficient to explain alone the concentration of karst development along inception horizons. However it is noticed that two types of inception horizons can be distinguished: type 1, where cave inception took place within the inception horizon and where the permeability of the inception horizon displayed a slightly higher permeability than the surrounding rock mass; type 2, where inception took place at the interface between the inception horizon and the rock matrix, and where the permeability of the inception horizon is slightly lower than the surrounding matrix.

Résumé

De récentes études sur la géométrie tridimensionnelle des grands systèmes karstiques dans le monde ont permis de démontrer statistiquement l'hypothèse des horizons d'inception. Il a été clairement confirmé que le développement des conduits karstiques en milieu phréatique est fortement lié à un nombre restreint de ce qu'on appelle des horizons d'inception. Un horizon d'inception est une partie de la séquence de la roche carbonatée qui peut favoriser les processus du début de la karstification (LOWE, 1992) que se soit par des différences physiques, chimiques ou lithologiques du faciès prédominant.

Afin de comprendre les raisons pour lesquelles certains horizons stratigraphiques sont particulièrement aptes à la karstification, 18 horizons d'inception ainsi que la roche encaissante ont été échantillonné dans six systèmes karstiques. Plus de 200 micro-carottes ont été prises et analysées afin de déterminer les paramètres contrôlant la spéléogenèse, et d'améliorer la prévision des vides de dissolution dans un massif karstique. L'analyse de ces échantillons donne une première idée des différentes propriétés principales des horizons d'inception. Cet article ne présente et ne discute que les résultats des mesures de la perméabilité primaire de la roche. La différence de perméabilité primaire ne suffit pas à expliquer la concentration des conduits karstiques le long des horizons d'inception. Pourtant, il est possible de distinguer deux types d'horizons d'inception : le type 1, dont la perméabilité est légèrement supérieure à la roche encaissante et où le développement initial des conduits se fait au sein même de l'horizon; type 2, dont la perméabilité est légèrement inférieure à la roche encaissante et où le développement initial des conduits se fait à l'interface entre l'horizon d'inception et la roche encaissante.

Keywords
Speleogenesis, Inception horizons, rock matrix permeability

1. Introduction

Along the last few years our research focussed on the analysis of the 3D geometry of several among the largest cave systems in the World (more than 1500 km of analysed cave conduits). It confirmed that the development and position of karst conduits under phreatic conditions is remarkably related to a restricted number of so-called "inception horizons" (FILIPPONI & JEANNIN, 2006; FILIPPONI & DICKERT, 2007; FILIPPONI ET AL., 2008). An "inception horizon" – a concept introduced by LOWE (1992) – is a part of a rock succession that is particularly susceptible to the effects of the earliest cave forming processes by virtue of physical, lithological or chemical deviation from the predominant carbonate facies within the surrounding sequence. Probably less that 10% of the existing bedding partings of a limestone sequence are inception horizons and guide more than 70 % of the phreatic conduits (FILIPPONI ET AL., 2008). Our analysis clearly confirmed that the influence of these horizons onto the 3D geometry of cave systems is high.

However one main question remains: What makes one specific stratigraphical horizon favourable to karstification and what kind of karst inception processes are dominant? Different descriptions of ”preferred bedding planes” are available in the speleological literature; however the interpretation does usually not consider whole framework of the inception horizon hypothesis and they are simply discussed as “bedding planes” (e.g. Orndorff et al., 2001). Furthermore, in most cases one misses a speleogenetical discussion of the observations. On the other hand in hydrogeological domain research some effort is dedicated in understanding the relation between hydraulic conductivity and texture in carbonate aquifers (e.g. Rovey & Cherkauer, 1994; Michalski & Britton, 1997; Muldoon et al., 2001). These studies demonstrate the existence of links between some specific stratigraphical horizons and zones of elevated hydraulic conductivity. However the question to know if this permeability is primary or due to dissolution voids (karstification) was not addressed. Meanwhile some concrete suggestions are expressed about “why” some parts of the rock succession act as inception horizons but, so far, little analytical confirmation evidences have been presented (e.g. Lowe, 1992; Knez, 1997; Pezdič et al., 1998; Filipponi & Jeannin, 2006).

Several characteristics of the rock mass may play a significant role for speleogenesis. It is known that the karst process follows a positive feedback development; the rock being soluble, water dissolves it and enlarges the voids, which become able to accept more water to flow through, i.e. more dissolution to be active and the voids to enlarge faster (Kiraly, 1975). This loop is self-developing until the system of conduits can absorb the total amount of the water available from the rain with no significant increase of the hydraulic gradient. Therefore we can assume that there are three main aspects that make an inception horizon favourable to karstification (fig. 1): Characteristics controlling the permeability (1), controlling the dissolution rate (2) as well as defining the dissolution capacity of the water (3). The processes under investigation being highly non linear, it is expected that the links are quite complex.

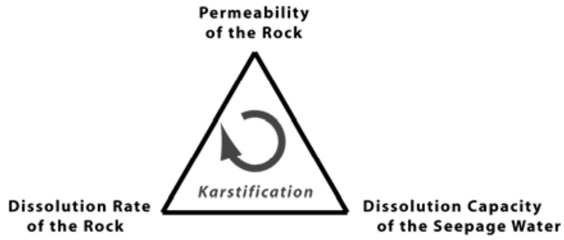

Fig. 1: The process of karstification is a positive feedback loop controlled by factors controlling the rock permeability, dissolution rate and dissolution capacity of the seepage water.

The purpose of this paper is to assess and characterize the primary permeability of inception horizons and to verify if it could be the main factor controlling the development of inception horizons and cave development. Therefore samples along 18 inception horizons of six cave systems were collected. An empirical (statistical) approach has been applied and is presented in the paper. In the discussion part of the paper the statistical results have been linked to a process-oriented approach.

2. Sampling the Inception Horizons

One main challenge in our approach is to assess characteristics of parts of the rock, which are no more existing. In fact the most favourable parts of the rock mass for cave inception have been removed during karstification. Despite this bias one can expect that it will be possible, by choosing appropriate sampling points, to get a qualitative idea of the initial rock properties, or their spatial variation as well as of their role during speleogenesis.

Based on the 3D analysis of cave systems (Filipponi & Jeannin, 2006; Filipponi & Dickert, 2007; Filipponi et al. 2008) as well as on field verifications, we selected a set of inception horizons for further analysis. A total of 18 known inception horizons in six different cave systems were sampled.

Field observations lead us to remark that three kinds of inception horizons can be distinguished (figure 2):

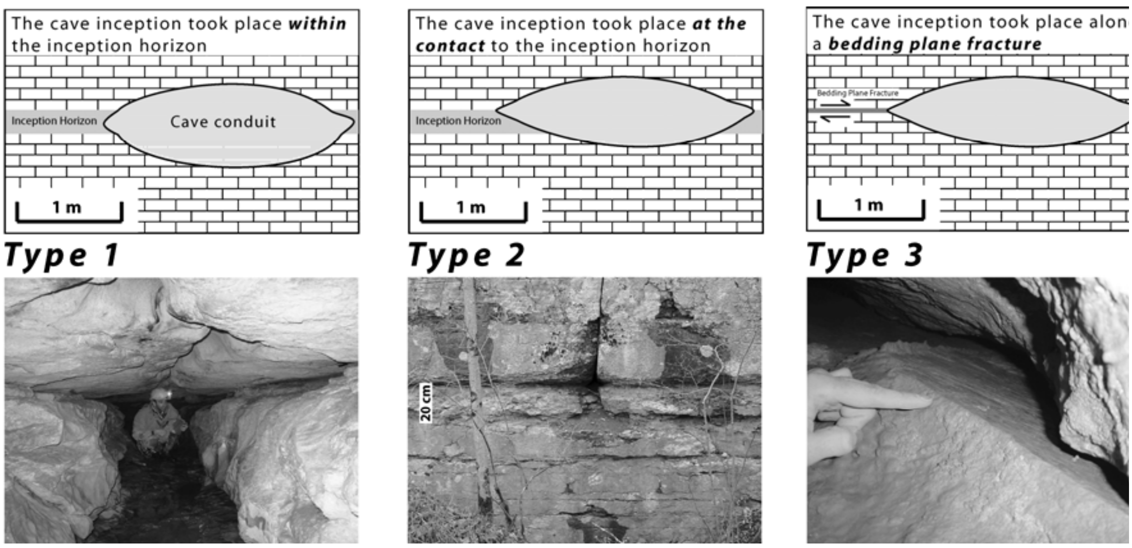

Fig. 2: Three kinds of inception horizons can be distinguished: Cave inception may take place within the inception horizon; at the contact to the inception horizon or along bedding plane fractures. For each type the relation between the conduit position and the inception horizon is sketched in the upper frame. The lower picture provides examples from the field.

Inception horizons where the cave inception took place within the inception horizon (1); at the contact to the inception horizon (2); along bedding plane fractures (3) (interbedded slides). The two first types are linked to lithological properties and the third type to rock mechanical processes.

This paper presents and discusses only results of the permeability measurements of the first two types of inception horizons. The permeability of inception horizons with interbedded slides has not been taken into consideration because the reason for the development of the inception horizon is more obvious: a slippage of just a few millimetres striation, brecciation and surface irregularities enhance openings along the sliding plane and will cause a significant increase in permeability compared to the surrounding rock mass. However an elaborated discussion will be the topic of a further paper.

More than 200 micro-cores (3-5 cm long, diameter of 2.6 cm) have been sampled in order to characterize openings and origin of inception horizons as well as of the surrounding rock mass. Sampling was designed in a way to approach local as well as regional variations of the selected properties. For this propose at least three samples have been taken at a given place of an inception horizon. For some horizons several sampling locations have been selected in order to assess the regional scale heterogeneity.

3. Results

Because of the positive feedback characterising karst development, we expected that the initial permeability of the rock or more precisely the permeability distribution within the rock massif, at early stage of cave genesis is a significant parameter. It is expected that inception horizons have a different permeability than the matrix of the surrounding rock mass. Higher permeability would favour the water to flow through this horizon; whereas horizons of lower permeability would act as low permeability “screen” along (or just above) which water would flow preferentially.

Therefore we measured the permeability of the samples in order to compare their primary permeability. The permeability was measured with an automated gas permeameter (Porous Materials Incorporated, GP-262). The automated gas permeameter measures permeability of porous samples, such as rocks (GOGGIN, 1993), ranging from 0.1 to 50 milliDarcys (1 mD ≈ 10^{-15} m^2 ≈ 10^{-8} m/s) within an accuracy of 0.5%.

Unfortunately it was not possible to measure the primary permeability of all micro cores. Samples with clear secondary permeability voids have been removed from the analysis. In some cases it was possible to identify by a simple visual inspection that dissolution voids or micro fractures were present. In other cases thin sections of the micro cores showed occurrences of micro fractures or dissolution voids. Sometimes it was simply not possible to collect an unbroken core.

The measured matrix permeability-values are quite low, generally below 1 mD (table 2). Permeability-values of the surrounding rock masses have an average of 0.16 mD with a standard deviation of 0.15. Permeability-values where karstification took place within the inception horizon (Figure 2, type 1) have an average of 0.17 mD with a standard deviation of 0.05. In all cases where cave inception took place at the contact to an inception horizon (Figure 2, type 2) the permeability-values of the inception horizons were below the lowest measurement limit of 0.1 mD.

Beside the very low values found for type 2 inception horizons it was not possible to distinguish other groups of the values (for example the existence of a minimal permeability value that would be necessary for an inception horizon to develop).

It is to point out that the absolute value of the measured properties has only a subordinated significance: It is mainly the contrast between the properties of inception horizons and the surrounding rock mass which is relevant. Regarding permeability an inception horizon is expected to develop because it is significantly more permeable than the surrounding rock mass and not because his permeability is higher than a given value.

Cave	Cave inception took place	Permeability [mD]		
		above	*inception horizon*	below
Nidlenloch (SO, Switzerland)	**within**	<0.1	*0.40*	0.18
	within	0.12	*0.60*	no data
Gamsalp (SG, Switzerland)	**at contact**	0.14	*0.10*	0.14
Réseau de Covatannaz (VD, Switzerland)	**at contact**	0.11	*<0.1*	no data
	within	no data	*0.24*	0.10
Réseau des Grottes aux Fées (VD, Switzerland)	**within**	0.14	*0.20*	0.11
	within	<0.1	*0.17*	<0.1
	at contact	0.23	*<0.1*	0.90
Hölloch (SZ, Switzerland)	**at contact**	0.17	*<0.1*	0.18
	within	0.18	*0.15*	0.18
Siebenhengste Cave System (BE, Switzerland)	**within**	0.21	*0.14*	0.31
	at contact	0.17	*<0.1*	0.13
	within	0.15	*0.23*	0.16
	at contact	0.09	*<0.1*	0.12
	within	0.10	*0.14*	0.11
	within	0.18	*0.26*	0.08
	within	0.14	*0.11*	0.13
	within	0.09	*0.11*	0.09

Tab. 1: Summary of the permeability measurements.

Considering the relative values (i.e. value of the inception horizon minus value of the rock mass) numbers above 0 mean that the inception horizon has a higher permeability than the surrounding rock mass, and numbers below 0 mean that the permeability is lower. Results presented in Figure 3 makes it possible to distinguish two groups of inception horizons: (1) horizons with a slightly higher permeability than the surrounding rock mass and (2) horizons with a slightly lower permeability. The more or less distinct linear trend in the plot indicates that the rocks above and below the inception horizons are similar and that only the favourable horizon has a different value. The permeability differences are in the order of a few tenth of mD. However a Student's t-Test established that the average of the differences in permeability-values between the inception horizons type 1 and the surrounding rock masses are significant different (level of 95 %) compared to differences between values of the rock mass above and below the inception horizon.

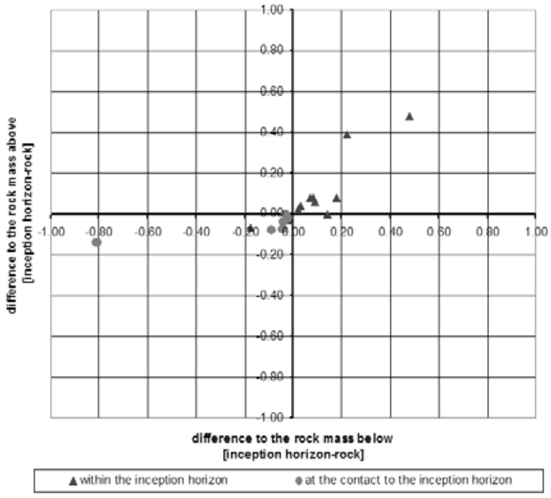

Fig. 3: Diagram of the difference in permeability between the inception horizon and the surrounding rock mass (above/below). It is conspicuous that type 2 inception horizons (dots) all plot in low-right quadrangle, i.e. corresponding to situations where the initial permeability of the inception horizon is lower than rock matrix permeability. Type 1 inception horizons mostly plot in the up-left quadrangle, i.e. where initial permeability of the inception horizon is higher than the surrounding rock-matrix.

4. Discussion

In order to understand why karst occurred only along some specific stratigraphical horizons it is necessary to understand processes of early stage of speleogenesis. The so called period of the "cave inception" can be defined as starting as soon as the permeability of the rock mass increases steadily due to dissolution processes. One may expect that at this early stage of the evolution dissolution is low and slow, therefore contrasts in permeability are still moderate and the influence of the hydraulic gradient is restricted. In other words flow is still diffuse and distributed within the whole rock mass. However some horizons tend to increase their permeability slightly faster than others, preparing the later development of karst conduits (e.g. LOWE, 1992; FILIPPONI ET AL., 2008). When relief becomes steeper, higher gradients do occur, what reorganizes the flow path and selects a few horizons which provide the weakest resistance to flow (i.e. in which are parallel to the hydraulic gradient). This phase of cave gestation ends when the first conduit is big enough to produce a change from laminar to turbulent flow all across the karst system ("breakthrough"). From this point on conduit development is fast and caves can reach human size within a few thousands of years. This corresponds to the phase of cave development (e.g. DREYBRODT ET AL., 2005).

In cases where cave inception took place within the inception horizon (type 1) samples of the inception horizon displayed a slightly higher permeability than the surrounding rock mass (9 of 12 inception horizons). The reason for that is that this slight difference in permeability was sufficient to concentrate flow and dissolution along those planes.

Darcy's equation gives a linear relationship between flow rate and permeability. Therefore the difference in flow rate between inception horizons and the surrounding rock mass is in the order of ±50 to ±70%. This means that flow velocity through the inception horizons is 50 to 70 % higher than through the matrix of the surrounding rock mass and therefore that karstification should also be enhanced. Although values are small and contrasts are low compared to the total range of permeability found in a karstified rock, this contrast of 50 to 70 % of the initial conditions may be large enough to produce a flow concentration and a preferential development of karst along those horizons.

Some theoretical background makes it possible to estimate the minimal time duration required for developing a network of karst conduits from initial state to turbulent breakthrough (e.g. DREYBRODT ET AL., 2005, PALMER, 2000). These authors give the theoretical breakthrough time (duration of the gestation phase) for a single fracture assuming that boundary conditions during the karstification do not change (e.g. hydraulic head, Pco_2, water temperature). This latter assumption is quite consequent because, in reality, boundary conditions change often according to changes in outside (surface) conditions (meteorological, climatic and landscape evolution). However the estimated breakthrough time gives an order of magnitude of the time required for the development of a karst conduits.

In this model we introduced the initial aperture width of the initial fracture by calculating the equivalent permeability of a single fracture. The measured permeability of our samples correspond to an equivalent single fracture width of around $3*10^{-5}$ mm, what would give a breakthrough-time of more than 10^{16} years (depending on the hydraulic gradient as well as on the length of the flow path) (figure 4). Note that a change in the water temperature and/or partial pressure of CO_2 would change the breakthrough time of one order of magnitude at the most. The lithological properties of the rock mass (EISENLOHR ET AL., 1999) may have a stronger effect. Obviously our understanding of the relationship between the rock properties and the empirical parameter used for the breakthrough time estimation is still not sufficient (DREYBRODT ET AL., 2005).

In order to see if the permeability difference between the inception horizons and the surrounding rock mass can explain the concentration of karst development along inception horizons, we assumed that those have the same lithological properties as the surrounding rock mass. Therefore in this hypothesis the variation in primary permeability would be the only reason for a faster karstification of the inception horizons. If so, we can use the figure 4 to roughly estimate the breakthrough time duration. Using the measured permeability time durations are several orders of magnitude higher than the age of the rock (10^8 years). We could thus conclude that the contrast and absolute values of the primary permeability is, in most cases, not the main factor that makes a stratigraphical horizon favourable to karstification. However we know that our data set is biased.

The above discussed estimation of the breakthrough time does not take into account other factors than the primary permeability, assuming that the permeability distribution within the inception horizon is homogeneous, i.e. that no variations in litholotical properties occur at a microscopic scale and that the karstification takes place all over the horizon.

Field observations show that cave conduits mainly developed at the intersection between bedding planes and fractures (e.g. JAMESON, 1985; LAURITZEN & LUNDBERG, 2000; FILIPPONI ET AL. 2008) i.e. bedding planes are dominant but fracture still play a role. One reason for this field evidence could be that fractures occur later in the history of the rock mass, i.e. during the speleogenetic phase of the cave gestation or even later during the cave development phase. The intersection of bedding plane horizons by fractures increases the permeability along intersection lines (KIRALY, 1969) by orders of magnitude.

Our data show that in the six inception horizons of type 2 (inception took place at the contact to the inception horizon), permeability is slightly lower than in the surrounding matrix, meaning that the bedding plane had act as a low permeability "screen" along which water flew preferentially. However under low gradient conditions, like they prevail during the speleogenetical phase of cave inception, this screen effect is probably marginal because the low hydraulic gradient extends parallel to the inception horizon.

5. Conclusion

The analysis of the 3D geometry of conduit networks of different large cave systems around the World showed that the development and position of karst conduits under phreatic conditions is remarkably related to a restricted number of so called "inception horizons". To understand why those particular stratigraphical horizons are favourable to karstification we sampled 18 inception horizons as well as the surrounding rock mass of six cave systems and measured their primary rock permeability.

The measured primary permeability is generally very low (some 0.1 mD ≈ 10^{-16} m^2). However a correlation could be established between cases where cave inception took place within the inception horizon (inception horizon type 1), in which permeability is slightly higher than that of the surrounding rock mass. In inception horizon of type 2 (inception horizons where cave inception took place at the contact) permeability of inception horizons is lower than that of the surrounding rock mass.

A theoretical approach linking the initial permeability of an inception horizon and the time duration required for turbulent breakthrough to occur has been attempted. It shows that the contrast in primary permeability between the slightly more permeable inception horizons and the surrounding rock mass can not explain the cave development along inceptions horizons. The permeability is so low that it would take billions of years to reach turbulent breakthrough. Thus the observed permeability values will not allow a karst conduit to develop in reasonable geological time scale (age of the rock ~10^8 years).

However three facts are not taken into consideration in this theoretical approach:

1) Bedding planes and fractures do not occur at the same time during the history of a rock massif. Whereas the inception of the bedding planes begins just after the diagenesis, the occurrence of fractures is a later phenomenon (maybe occurring during the phase of gestation). Our permeability measurements reflects the situation before the beginning of the karstification (i.e. at the beginning of the inception phase), whereas the permeability of an inception horizons at the end of the inception phase will probably be at least one order of magnitude higher.

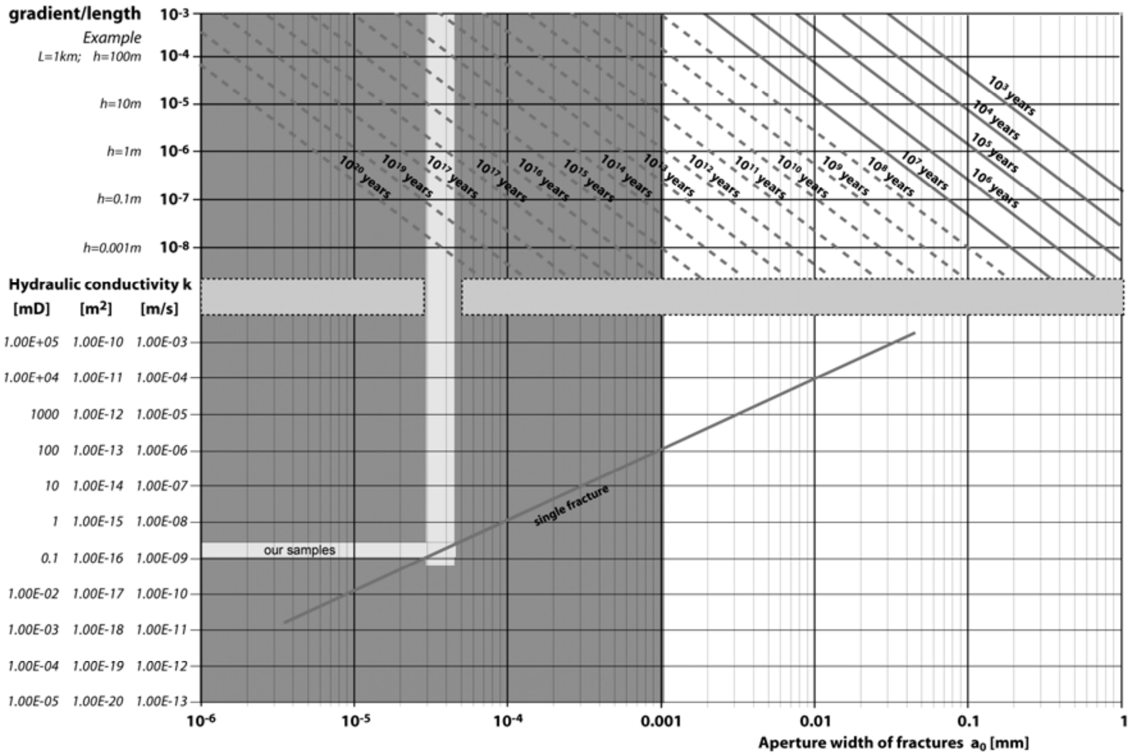

Fig. 4: Estimation of the breakthrough time: The lower part of the diagram shows the relationship between the permeability and the aperture width of an equivalent single fracture. The upper part of the diagram gives an estimate of the time required to enlarge a given initial fracture to turbulent breakthrough for different hydraulic gradients as well as flow distance. Dashed lines are extrapolations of a graphic given by PALMER (2000).

2) The initial permeability of bedding planes inception horizons is low (as measured), but inception horizons are often intersected by fractures. Bedding planes with the largest permeability (inception horizons) just before their intersection by fractures are supposed to give intersections with the highest permeability too, but with values orders of magnitude higher than without fractures.

3) In this paper our analysis focused on permeability measurements. Several other parameters are supposed to play a significant role in the inception hypothesis. Contrasts in dissolution rate (e.g. Mg-Ca contents) and/or increasing of the dissolution capacity of the seepage water (e.g. by the weathering of pyrites) could significantly influence the inception process. Samples showing indications of those processes have been removed from our data set in order to assess the initial permeability (without any dissolution process), what produces a significant bias.

Further investigations are being carried out in order to fully address the characterisation and weighting of the key parameters that make a bedding plane favourable to karstification.

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