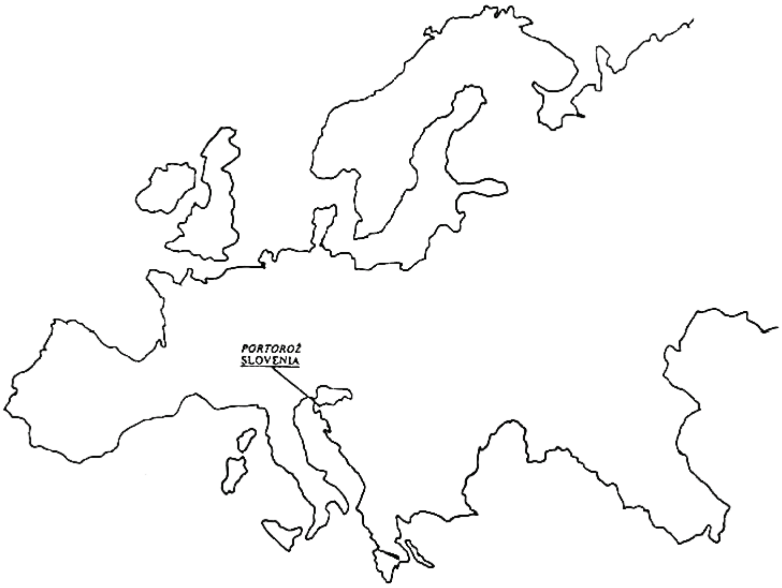
WORKSHOP

ENGINEERING IN KARST



Portorož, Slovenia
September 7 - 9, 1996

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In print: Karst and Cave Science

The Pure Karst Model

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STARTING IDEAS AND PROBLEMS

Few natural phenomena are as widespread, so well studied and yet so poorly understood as karst. The level of current understanding is indicated clearly by a quote from Renault (1977, p.34): "The karst concept reflects an intuitive idea that has been the driving force behind the first explorations and qualitative theories. It now only provides support, of essentially historical interest, for another, far larger and dynamic concept. There are still many obstacles to its development, ... , but the normal progress of research must produce a unified concept of karst phenomena". Renault (oc) points out that several types of definition - geomorphological, speleological, geological, sedimentological, hydrological and so on - are in use. Each of these is adequate within its own context. Confusion becomes unavoidable if trying to consider several definitions at once, either due to the complexity of the karst itself or simply due to historical inertia.

Different interpretations of karst morphology probably reflect projections of ideas from different geomorphological schools into the informational space relating to the karst. Among a half dozen main streams of geomorphological thinking, only ideas related to cycles and to climate seem to have been grasped readily by karstologists. The former view interprets karst relief as a specific set of degenerate fluvial landforms. The latter view is of a specific set of climate-related landforms. The view presented here is that karst is a typical landform assemblage, within which individual landforms are also typical. Karst is regarded as a self-contained geomorphic system, its origin relying primarily upon general physical laws.

In creating ideas about karst geomorphology the backgrounds and opinions of outward looking observers have prevailed. For instance, preconceptions about the norms of relief were inevitable. Applying existing knowledge to the karst, observers intuitively measured the degree of karstification against their existing standards acqured in fluvio-denudational relief. Many modern studies concentrated upon the most spectacular or most readily observable landforms. Phenomena possibly essential to the self sufficient geomorphic category of karst relief were neglected, or even ignored (Renault, 1977).

A typical example is the relatively great interest paid to karst depressions. Great effort being invested in their study but disproportionately little noteworthy information has been acquired. In areas of normal fluvial relief a closed depression is exceptional and worthy of separate study, but there is no reason to believe that this is also true in karst areas. More importantly, until relationships between depressions and upstanding facets of karst relief are clarified, the position "in a karst depression" is just a topographical qualifier, without geomorphological significance. In contrast to the many studies of karst depressions, karst hills in areas of temperate climate have been neglected, or interpreted in non-karstic ways.

An observer whose work is inwardly directed and totally involved in studying karst is not interested in differences between karst and other relief types. Ideally such differences are not even recognised, and there is no preconception or awareness of possible external "norms". The inward looking worker's intention is simply to explain the geomorphic system on the basis of its own internal logic and, by using general physical laws, treat it as an autonomous and self-sufficient natural mechanism. At the logical limit of this approach, such a worker would be concerned with the relief that would evolve if the entire surface of the globe was made of limestone. Different combinations of physical effects do not prove to be specific (karstic in this case) until they are compared with geomorphic categories lying outside the immediate sphere of interest.

What follows is an attempt to deduce the nature of the theoretical model of karst that would be deduced by such an inward looking worker, without reliance upon any knowledge of other geomorphic systems, and regardless of whether its entire physical realisation could occur anywhere on earth. All of the theoretical model's properties derive from ideas within present knowledge of the geomorphic processes involved, but only properties realisable on a completely limestone globe are acceptable. Perhaps more realistically, an ideal set of karst relief properties, which would form under optimum circumstances, may be deduced. Much of this work already exists, though achieved from a different direction, by progressive establishment of the means to discriminate karst areas from other types of landscape. Any schoolbook or monograph presents those principles in similar fashion (e.g. Sweeting, 1972).

In applying this model to natural karst surfaces, the intention is not to find differences between them and some non-karstic geomorphic system, but to ascertain the degree of agreement between reality and the model. In this situation agreements are as important as disagreements. Practical application of the model (Šušteršič, 1987) has shown its potential power, particularly for organising several different phenomena, which may intuitively be called karstic but which display incompatible appearances, into a unique system. If other landforms (such as those accommodating to external non-karstic factors) appear, they may be defined specifically as distortions of karst relief. These hybrid forms are not grouped within a special set of non-pure karst phenomena (commonly termed merokarst), but they are related directly to pure karst landforms and, having crossed this bridge, one to another.

It is anticipated that karst is a self-dependent geomorphic system, as is confirmed almost daily in practice in large complexes such as the Dinaric karst. The theoretical model obtained is an idealised concept, in the same sense that the concept of free fall in an absolute vacuum is idealised. It is referred to as the Pure Karst Model (PKM).

HISTORICAL REMARKS

(DROPPED)

UNDERGROUND KARSTIFICATION

This paper considers the development of karst relief, and emphasises that the state of underground karstification is of paramount importance to its shaping. It will be shown that fulfilment of six basic conditions renders feasible the formation of underground karst, whilst eight conditions must be fulfilled to produce a surface karst landscape.

Underground karst may be viewed as a specialised type of underground water transfer system that evolves towards a tube system. A theoretical well fractured rock (that includes bedding plane fissures) would start to conduct precipitation water at the instant of its emergence. Due to subsequent effects as water passes through, it would change from a porous to a karstic aquifer. Classically a fully developed underground karst is divided into aerated, vadose and phreatic zones. For the purposes of this paper a slightly different distinction, is more appropriate. Considering only unsaturated and saturated3/ underground karst zones, the former is equivalent to the aerated zone, the latter encompasses the vadose and phreatic zones.

The unsaturated zone transmits surface water to the saturated zone and its pores are water-filled for only part of the time. Water courses in the unsaturated zone range from capillaries to vertical free fall jets. Their main distinguishing property is that their activity relies upon the precipitation cycle, so that the whole water quantity is "hanging". As the water descends it enlarges vertical shafts (Frumkin, 1986). The conduit system in the unsaturated zone ensures that water (and dissolved rock) migrate perpendicularly to the surface, or escape from the two dimensions of the surface to another dimension. Because of the included free fall element, activity at lower levels has no effect at higher levels.

The role of the saturated zone, lying below the unsaturated zone, is more complex. Due to interconnected vessel effects, flow is generally directed to the lowest hydraulic surface point, but in detail its direction is arbitrary, controlled only by hydraulic resistance. The first result of initial void enlargement is the creation of a maze that may subsequently develop into a cave system. According to local circumstances this cave system would be further organised into distinctly separated development levels, with the degree of separation reflecting the local effects of interference between karstic and non-karstic factors. The mere existence of the saturated zone effects the unsaturated zone in practically the same way, as the appearance of the insoluble basement.

The unsolved problem of erosional base level may be similarly clarified. It is evident that misunderstanding and a too straightforward application have slowed down the development of several segments of the karst science. In fluvial systems the notion of erosional base involves at least three approximately overlapping conceptions. In karst they are always separated. The notion for fluvial systems covers:

- base of denudation
- base of penetration
- base of negative mass transport (incision in subaerial circumstances).

If considering a river for instance, the first one is the level of the banks, the second is the lower limit of the groundwater body logged by the river and the third is the river bed bottom. Differences of these levels are negligible compared to the whole basin dimensions.

Denudation as a relief forming agent is inevitably a sub-aerial process. So, in karst the denudation base is the lower limit of the unsaturated zone. This is of no importance with regard to the other two bases. The transport base is the lowest point, reached by active streams transporting dissolved mass. In karst it is usually below the piezometric surface. Even in other geomorphic systems the penetration base is only exceptionally in contact with this surface, but this is of no further importance. In karst, it may be defined as a limit, down to which fresh water has replaced sea water that was trapped in the rock after emer- sion. During the formation of the karst aquifer, the entire zone above the penetration base might have been involved. However, in accordance with the first Kirchhoff rule, active streams follow and further enlarge only the less resistant passages, while all of the rest contain stagnant water, though remaining in contact with the former. If hydraulic conditions change, such passive passages may be instantly reactivated producing very undesirable effects when constructing dams on the karst. Thus, the separation of the denudational base from the the other two bases is crucial to the development of karst relief, and to define underground karst.

BASIC CONDITIONS FOR KARST RELIEF DEVELOPMENT

Definition of the karst surface

Geomorphology is intended to explain the geometry of a hypothetical surface, referred to as the earth surface, separating the solid mass of the planet from its atmosphere. When the processes that shape the earth surface are active inside the surface itself, geomorphological studies are confined to two topological dimensions. In the case of karst, which is topologically regarded as an essentially three-dimensional category, things become confused. In attempting to interpret the phenomenon of karst on the level of two topological dimensions, and to present the results in two dimensions as a geomorphological map, the abandonment of the third topological dimension brings about a fundamental devaluing of the information. Several karstologists, consciously or unconsciously, have put aside sharp definitions of the karst surface and so avoided this problem.

This discussion treats karst as a three-dimensional phenomenon. However, in principle the concern is with its topologically two-dimensional surface. The shaping of this surface is understood in terms of its roughness, its derivation) and not in terms of the disposition of masses. This understanding is not far from the general comprehension of the word relief.

Those topologically three-dimensional properties of the karst phenomenon that crucially influence its relief are considered only as their projections. Any components that do not affect the surface, are put aside as of secondary interest. The existence of the unsaturated zone facilitates vertical mass transport perpendicular to the effectively horizontal land surface, and the detailed properties of underground karst are irrelevant. The conditions discussed below are therefore the conditions of existence of the unsaturated zone, and the conditions of karst relief development.

Basic conditions

The pure karst model is best described in terms of basic axiomatic statements. These depend upon the tenet that karst is a self sufficient geomorphic system, and reflect the fundamental properties of karst in general, as established by karstologists during the last century of karst research.

a. A rock mass with an initial potential energy must exist;
b. The strength of the parent rock must support the formation of steep slopes and overhangs;
c. The persistence of rock characteristics must be sufficiently great that any lateral changes of properties are remote and hence negligible within the range of observations;

d. The parent rock's solubility must be uniform to the extent that transition of rock from solid to fluid state (dissolution) dominates over other types of weathering;

e. The initial permeability must be uniform throughout the parent rock;

f. Functioning of the system must not be reduced by climatic aridity;

g. The rock mass must be "open" on at least side to allow development of an unsaturated drainage system;

h. Initial surface slopes must be gentle enough not to prevent precipitation from leaving the surface.

Discussion of the basic conditions

a. Any elevated rock mass contains an amount of potential energy. This is a fundamental condition for any further geomorphic development. If a mass exists that is completely planed to base level, it is featureless and of no further interest to geomorphologists. This important statement has not been clarified well enough in the karst context. It holds true, indirectly, for the present model.

If the underlying rocks of an absolute plain are karstified, transport of material may continue below the surface, just as it would before total planation. However, because the plain is at base level (in its classical geomorphological sense), the saturated zone must be in contact with the surface, preventing the formation of karst relief. If a surface karst pre-exists, its typical forms disappear. The surface becomes featureless after erosion down to the base of denudation, though the erosional base (in the current sense) is not reached. In such conditions hydraulic resistivity in the fully inundated underground karst prevails over superficial resistivity, and water courses become more or less concentrated at the land surface. Consequently, underground karst erosion may slow down limiting to zero, but it must be stressed that this is a secondary effect, not an inevitable outcome.

b. This condition is not meant to apply to sub-aerial situations, as any rock is strong enough to support some degree of relief. The mechanical strength needed for development of underground channels is much greater, regardless of the type of underground karstification.

A good example is provided by periglacial limestone (Norian and Rhaetian limestone = Dachsteinkalk) gravel in the Ljubljana basin of west-central Slovenia. In the non-cemented sediment no karst effect has been detected, even though water flowing through it become saturated with carbonates. Portions of the same material, barely cemented to produce a relatively unresistant conglomerate, display underground (shafts and caves), as well as surface karst features (sinks and dolines). The parent rock is nearly pure limestone, and is well known as one of the most karstifiable rocks in Europe.

In contrast, some strong rocks not normally considered karstic, support limited underground water movement. They display supposedly typical karst features (such as collapses and pocket valleys) if they are barely solid enough and do not produce debris that blocks underground channels. Several kinds of sapping, developed in very different rocks (Navajo sandstones, trapps) are good examples.

Conditions a. and b. are general, and they are necessary for any relief to appear in any geomorphic situation.

c. The basic intention of this model is to predict the relief that would develop if the entire globe was composed of limestone, an ideal that is acknowledged as a geological impossibility. However, as no geomorphic system produces forms of infinite dimensions, and trans-environmental effects are spatially limited, it is sufficient to shift observations far enough from the borders to meet the limits of the primary axiom. The demand is, however, three-dimensional, to encompass both the lateral and the vertical extents of the rock mass. There may be few limestone complexes in the world to satisfy these conditions, but some, such as the Dinaric Alps in former Yugoslavia, Albania and Greece, do comply.

Past omission, or a not strict enough consideration, of this principle probably accounts for the bulk of the eclectic notions contributing to karst geomorphology. From one viewpoint many non-karstic effects in otherwise karstic areas have not been distinguished from purely karst effects. Thus karst was seen "obviously" as a special case, or derivative, of fluvial systems. On the other hand, in some areas limestone overlies a shallow impermeable basement, or it is confined between strata nonkarstic rocks. In some such cases many karst relief features have not developed, though the underground is heavily karstified.

d. The solubility of bedrock is such a readily accepted element of karstification that it is frequently interpreted as the philosophers' stone of karstology. Yet the situation is not simple. All rocks are soluble to some extent, even those claimed to be insoluble. Thus, the term "soluble" must be interpreted in a relative way, such that rock dissolution must exceed the effects of all other weathering processes.

Several puzzling relationships displayed by the most significant karstic rocks (limestone, dolomite and gypsum) draw attention to another aspect of solubility, namely its uniformity. Karst features on dolomite either do not differ from those on limestone, or dolomite behaves like a semi-karstic or even non-karstic rock. In contrast, gypsum is several times more soluble than limestone, but its karst phenomena appear no more pronounced than those on limestone.

From the karst viewpoint, the crucial factor is the possibility of unconstrained vertical mass transport, so that voids always remain capable of transmitting water. Consequently, mass must leave the rock surface in solution, otherwise the process is impeded from the outset. The necessity for uniform solubility of the parent rock is thus dictated by the karst itself.

Dissolution of just some mineral components suffices to establish a limited weathering process on bare granitic rock surfaces, bringing about the formation of dissolution forms. This process is, however, insufficient to establish stable underground drainage and, hence, vertical mass transport. Some loosened grains, including the dominant quartz, are insoluble, and these fill any initial pores in the parent rock. The amount of those components may be sufficiently small not to affect mass transport on the surface, but can block it completely underground.

This statement may be applied to relationships among the previously mentioned karstic rocks. Omitting any really insoluble impurities, which are negligible in the Dinaric karst, all three rocks are completely soluble. Limestone and gypsum dissolve homogeneously. There is hardly any difference between the solubility of crystal grains and cement, and no nests of exaggerated resistance to dissolution appear. Dolomite has a double role. In some situations it dissolves uniformly, like the other two rock types, and where this occurs there is no great difference between the three. In other situations a faster dissolution of some portions of cement brings about the formation of a sort of dolomitic silt. This is itself soluble, but at a slower rate than it is produced. It tends to block pores completely, and so inhibits karstification (Zogović, 1966). Dolomite's relatively poor mechanical resistance produces a similar effect on a different scale. Even temperate climatic conditions may reduce dolomites to gravel by freeze-thaw weathering, producing more or less the same effect as the non-uniform solubility. From the mass transport viewpoint it is irrelevant whether material blocking vertical mass transport is produced by dissolution or in another way, or whether the particles themselves are soluble or not, as there is no difference in effect. Thus the actual intensity of dissolution is of little importance (it merely controls the velocity of the processes), but its uniformity is critical.

Increased solubility of granitic rocks under tropical conditions establishes several similarities in relief formation between them and limestones. Some similarities are mentioned above, but another example is provided by rivers. On both rocks river beds are guided by geological structures, rather than other factors, as there is a lack of bed load that would cause abrasion or deposition at suitable points.

Increased rock solubility in some climates causes parallels with limestone surface shaping, but it has nothing to do with karst. Fulfilment of conditions a. to d. alone is insufficient to form a true karst but, if fulfilled, they render feasible the development of characteristic surface phenomena in any soluble rock.

e. Rock porosity is divisible into several types, according to its origin. Pores may form during early or late diagenesis and tectonism. Such a distinction has no relevance to this consideration, as water will penetrate accessible openings of any type, under gravity and obeying certain hydraulic laws. The expression "initial porosity" is much more useful, encompassing all possible voids, including bedding planes, before water started to enlarge them and create a karst aquifer.

The question of structural guidance is excluded from this discussion intentionally, and initial porosity is assumed to be more or less uniform, if not isotropic. This condition, which prevents relief features from being projected through a possibly highly anisotropic and generally linearly organized structural grain, is more or less fulfilled in the highly fractured Dinaric Alps. Sinking water generally has a choice of possible voids, and is able to pursue a preferred route when penetrating downwards.

If epeirogenesis were the most important energy inducing agent most fissures, except bedding, would form after uplift. This would necessitate an arbitrary long pre-karstic fluvial phase, and would provide a solid basis for the cyclic explanation of karst. On the other hand, if the Dinaric karst formed in the wake of an active orogeny, no impediment exists to the idea that an initial porosity predated uplift and the mass has been karstified since the moment of emergence. Time orientated studies of the Dinaric karst suggest that the latter possibility more closely fits the facts (Milovanović, 1965).

f. As water is the mass transport agent, little can be added to the initial statement. The steadier the precipitation, the more rapid is the progress of unsaturated zone karstification. Irregular stormy weather impedes downward penetration of water to establish a vertical drainage system, and the surface remains similar to any other semiarid one, ignoring bedrock differences.

Fulfilment of conditions a. to f. can enable development of underground karst phenomena, while the surface develops in another way.

g. This condition is close to the first one in its effects and requires no further discussion. Any change in the impermeable border of a limestone mass, whether erosional or tectonic, affects the level of the saturated zone. This affects the vertical extent of the unsaturated zone, and hence may affect the superficial karstification.

h. Precipitation water gathered on the surface has no special affinity to either sub-aerial or underground percolation, but it must follow hydraulic rules. If the surface is relatively gentle, water may sink into the ground. When the surface is steeper, as for instance in pyramidal glacial mountains, water will run away on the surface, as it usually does in other high mountain geomorphic systems.

True karst relief, conditioned by a completely developed and properly functioning unsaturated zone, appears only when all eight conditions are fulfilled.

The conditions are, to a great extent, hierarchical and, from the PKM viewpoint, lack of fulfilment of some lower conditions mitigates against fulfilment of some higher one. Combinations violating this rule are relatively scarce. They include forms that are intuitively viewed as karstic, but which are totally unrelated one to another and may not easily be ranged into a unique system. Different imperfectly developed "karsts" (according to the PKM) become comparable and buildable into a unique system, by considering what they are missing. Using Cvijić's standard terminology, only one holokarst exists, but several merokarsts may appear, even if they lack mutual similarities.

REALISATION OF THE MODEL

Fundamental forms of the surface karstification

Karst relief shaping depends initially upon the spatial configuration of the active agents. The most important mass transport medium in the karst is precipitation water, as in most other temperate climate geomorphic systems. By assuming that drainage net organisation is crucial to the surface outlook, the fundamental difference between karst and non-karst relief may be established. In nearly all non-karstic situations mass transport is organised superficially and its pattern is an adsorptive linear net. The dendritic drainage net and its complement, the mountain crest pattern, are clear examples. Expressed in set theory terminology, the intersection of the transport system and the surface is the transport system itself (Fig 1a).

In completely karst circumstances surface rock is dissolved and (from the surface viewpoint) removed to some other dimension, nearly in situ. Such a surface is continuously lowering and denuded underground phenomena (caves) appear at the surface. The karst surface organisation reflects total karst mass drainage organisation rather than directly reflecting itself. In direct contrast to most geomorphic systems, it is not built into the surface but is perpendicular to it, forming a three dimensional tree pattern. The intersection of the drainage system and the surface is a point array (Fig 1 b). Consequently, in the limiting situation, forms associated with pure karstification may be reduced to a point array, whereas those comprising a fluvial system always remain an array of linear elements (links).

The fundamental elements of the karst surface are thus centrically organised depressions and elevations. Climatic variations may bring about different superficial appearances, but the inherent centricity remains. This factor alone is the essence of the striking visual similarity between Dinaric high plateaux and some tropical karsts. Surface landforms organized in other, non-centrical, ways reflect either a linearly imposed (anisotropic geological setting) or non-karstic interference in karst development. In both cases the basic conditions are not fully realised and the karst is incomplete in the PKM sense.

If such a comparison is reasonable, the parts of the karst drainage system that intercept the surface may be related to the area of influence of first order drainage links in fluvial systems. Positions described as "in a depression" or "on an elevation" differ little from ones such as "a little bit upstream or downstream" along a first order stream in a fluvial system. Fluvial system elements range from the dimensional order of rudimentary streamlets in areas of sheet flow, through to enormous streams (and antithetical mountain crests) of the highest orders. In contrast karst relief elements are scaled very strictly. Using the comparison introduced in previous paragraph, the statement that the maximum dimension of a karst relief element may not exceed the dimensions of a vertical drainage element influence area becomes inevitable. Lacking comprehensive data any attempt to estimate these dimensions in absolute units is intentionally avoided, but one certain constraint is apparent. Even if the concentration of vertical trickles was not limited areally, the very dimensions of the saturated zone streams impose rigid restrictions. The largest karst springs in the world are impressive, but compared to the surface flows, their discharge is very modest. No underground Amazon is to be expected!

The karst surface is not permeable down to its infinitesimal elements, but is a mosaic of blocks, each as impermeable internally as blocks of any igneous rock. It must be re-emphasised that the karst surface conducts water between these blocks. Precipitation water flows on the surface of the blocks just as it does on the surface of any non-karstic geomorphic element of the same dimensions. It appears that such blocks must be no smaller than several decimetres, otherwise the second basic condition is violated. So, karst relief landforms are constrained by two dimensional limits, spanning four size orders, imposed by the basic axioms of complete karstification.

True karst relief consists of centrical depressions and elevations, while fluvial relief is built up of valleys and crests. Regarding relief elements from this viewpoint, linear karst surface elements, such as dry valleys, must reflect either structural predispositions or non-karstic interferences. In the former case the relief may achieve maturity, but the ultimate landforms are not displayed because the initial porosity is highly anisotropic. In the latter case, maturity is either not achieved or the third basic condition is violated.