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Karst landscape in terms of synergetics: general remarks

Андрейчук В.Н. Карстовый ландшафт с точки зрения синергетики: общие замечания // Спелеология и карстология, - № 13, Симферополь. – 2014. – С. 45-53.

Резюме: *Специфика карстового ландшафта хорошо известна. Автор предлагает посмотреть на карстовый ландшафт как на отдельную эволюционную стадию карстового мегацикла, рассматриваемого как типичное синергетическое явление.*

Андрейчук В.М. Карстовий ландшафт з точки зору синергетики: загальні уваги // Спелеологія і карстологія, - № 13, Сімферополь. – 2014. – С. 45-53.

Резюме: *Специфіка карстового ландшафту добре відома. Автор пропонує подивитись на карстовий ландшафт як на окрему еволюційну стадію карстового мегациклу, котрий розглядається як типове синергетичне явище.*

Andreychouk V.N. Karst landscape in terms of synergetics: general remarks // Speleology and Karstology, - № 13, Simferopol. – 2014. – P. 45-53.

Abstract: *Specificity of karst landscape is well known. The author proposes to look at the karst landscape as the separate evolutional stage of a karst megacycle, considered as a typical synergistic phenomenon.*

PREFACE

Karst areas (landscapes) are of a very specific nature. They have distinctive relief representing a distinct genetic type, a particular water regime and hydrographic network (or lack thereof), specific types of soils (e.g. *terra rossa*), ecosystems of a different composition of flora and fauna species as well as some particular morphological and physiological characteristics in organisms that are adapted to specific (karstic, cave) environmental conditions.

It is well known that this distinctiveness is associated with a particular process that occurs in the earth's crust and on the surface – dissolving certain types of rocks susceptible to dissolution (so-called karst rocks) by circulating water. This process is essentially of a hydrological (hydrogeological) nature as it relates to the impact of water on the rocks and takes place mainly underground. As the hydrological "maturation" of the karst rock massif proceeds, the dissolution is transformed under certain conditions into *the karst process* which in turn "brings to life" a number of other derivative processes (erosion, sinkhole formation, landslides, etc.), so becoming a *system of processes*. Acting together under and on the earth surface these processes shape the relief, and thus the whole landscape, the components of which, both abiotic (rocks, water, air) and biotic (plants, animals), or anthropic (man), by adjusting to each other create a specific and complex environmental system – the karst landscape (KL).

This system (karst geosystem) is characterized by a specific *organization* resulting from the evolution of the process itself, which consists in *self-organisation* (gradual development of the network of channels, formation of underground cavities, etc.). The evolutionary self-organization results in developing a specific *spatial and functional structure* in the karst system (connections and interactions between elements), which is the essence of the organization in the mature stages of development.

In the author's view the specificity of the karst landscape can be depicted and explained in the most thorough way ("from the inside"),using *a general systems paradigm*. It recognizes KL as a complex natural system of a characteristic composition of its elements, their specific spatial arrangement (structure), and the way they interact (function) (Andreychouk, 2009).

The article provides definitions of the basic concepts of landscape and karst, and shows formation of the karst landscape against the background of the evolution of the karst system as a whole, recognised in terms of synergetics (self-organization).

KARST

The term "karst" usually refers to the complex of specific processes, phenomena and forms which occur within areas composed of karst rocks. Karst results from the long-term impact of atmospheric, surface and underground water circulating through the rocks. This

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concept integrates several aspects in a genetic sequence: process → phenomenological → morphological, which hold a specific territory in common.

In the *process (geodynamic)* sense, karst is *a system of processes*, among which the leading role, as if of the "conductor" of "the entire geodynamic orchestra", is the chemical process of rock dissolution in the water circulation cycle within the subsurface zone of the lithosphere[1]. The dissolution process is the "driving force" behind the development of the karst system, which in turns induces other geodynamic processes – both denudation (erosion, gravitational processes, including cave-in and landslide), and accumulation (formation of the residue of dissolving rocks, filling underground cavities with deposits and mineral formations, etc.).

In the *phenomenological* sense, karst processes are associated with various characteristic *phenomena* that are often not found outside of karst areas (disappearance of surface rivers underground, large outflows of groundwater, surface collapse, etc.).

In the *geomorphologic* sense, karst processes create numerous specific *forms* of relief underground (caverns, cavities, channels, caves, cave systems) and on the surface (karren, dolines, depressions, karst valleys, karst towers, etc.).

Karst is an evolutionary product of specific environmental conditions and simultaneously a creator of a specific natural environment. In the first case we are dealing with a whole range of factors (geological, hydrogeological, geomorphological, climatic, biotic, etc.) involved in the process of karst development; in the second case, - with a number of consequences of its impact on the geological substrate, surface and underground water, soil, etc., that are the components of the landscape. Therein lays multifaceted nature of karst and consequently the fact that representatives of particular disciplines in the earth sciences place emphasis on different features of karst definitions.

Geologists regard karst as, above all, types of rocks (of massifs and formations) which undergo specific metamorphoses due to the dissolving effect of water circulating in the rocks and massifs. They consider it as one of the mechanisms for both formation and the destruction of the rock (karstolithogenesis), including the formation of specific mineral resources (known as *karst deposits*). *Hydrogeologists* pay attention mostly to the specific conditions and peculiarities of water circulation in karst rock massifs (i.e. their regime) and the formation of their resources in so-called *karst collectors*, whereas *geomorphologists* emphasize the distinctive types of relief developing in karst areas. *Geographers*, viewing karst in the most comprehensive and multifaceted way, regard it as a *particular type of natural environment* resulting from the system-integrating impact of karst processes on all elements of the environment – the bedrock, water, relief, organic life, soil, etc. The development of karst results in gradual transforming a *non-karst landscape* into *a karst landscape*, i.e. an area of specific relief, water circulation, micro- and mezoclimatic conditions, flora and fauna, and the conditions of human life.

[1] The upper subsurface zone of the lithosphere within which, due to low temperatures, water exists in a liquid state and circulates in a cycle is sometimes called the *hydrolithosphere*.

From these characteristics and others, the science of karst (*karstology*) is composed of a variety of thematic sections, e.g. *karst geology, karst hydrology (including karst hydrogeology), karst geomorphology, karst geochemistry*, etc. These divisions of karstology constitute component disciplines primarily investigating individual parts of the karst environment. Their methodology consists of mainly analytical methods targeting these different components at deeper and deeper levels of exploration. Due to their individual narrow focus they cannot provide an adequate (holistic) study of the karst landscape as a natural system in its entirety. Comprehensive review and research can be provided only by a comprehensive, systems-focused scientific approach to the problem.

COMPREHENSIVE METHODOLOGY IN KARST RESEARCH

A *scientific approach* implies a certain comprehensive vision of reality and a relevant organization of the research process, which means that it is embedded not in the empirical (research aspect) but in the methodological (research methods determined by a certain vision) field of science. The term *approach* has a general scientific status and is universal, as a *comprehensive* or *systemic* approach, the *anthropic principle*, etc. As a rule, the approach is applied to thematic, spatial or historical aspects of the reality to be investigated, which has a relative wholeness, structurality and a complex organization (natural environment, state, community of organisms, Renaissance, landscape, etc.), which requires the researcher to prepare an adequate cognitive structure. Therefore, the application of these or other approaches to research on karst is conditioned by regarding karst comprehensively, as a certain type of *organization*. This may be, for example, *the entire karst as a set of genetically and spatially related processes and phenomena*, *the karst environment* (a concrete karst area together with the human inhabitants), *the karst landscape, karst massif*, etc.

What kinds of comprehensive approaches have application to karst studies nowadays? According to the author, in karstology four main approaches are currently used: the karstocentric, environmental, geosystemic and landscape-systemic approaches (Andreychouk, 2010) (Fig. 1).

<u>The karstocentric approach</u> represents a concrete version of the *centric* approach which implies regarding the studied reality (object, phenomenon, process, area) as a certain organization functioning in the conditions of a strict (genetic) dependence upon particular factors (Fig. 1-1). Within a given approach karst is considered as a derivative of the collective impact of a number of factors and environmental conditions, i.e., the presence of karst rocks, water circulating in the massif, rock fracturing, aggressiveness of water, drainage conditions, and many other, more specific ones (lithology and structure of karst rocks, amount of rainfall, water temperature, etc.) which affect the course of the karst process or the physiography of the karst area. "Classic" examples of this approach may be found, inter alia, in the Soviet karst literature

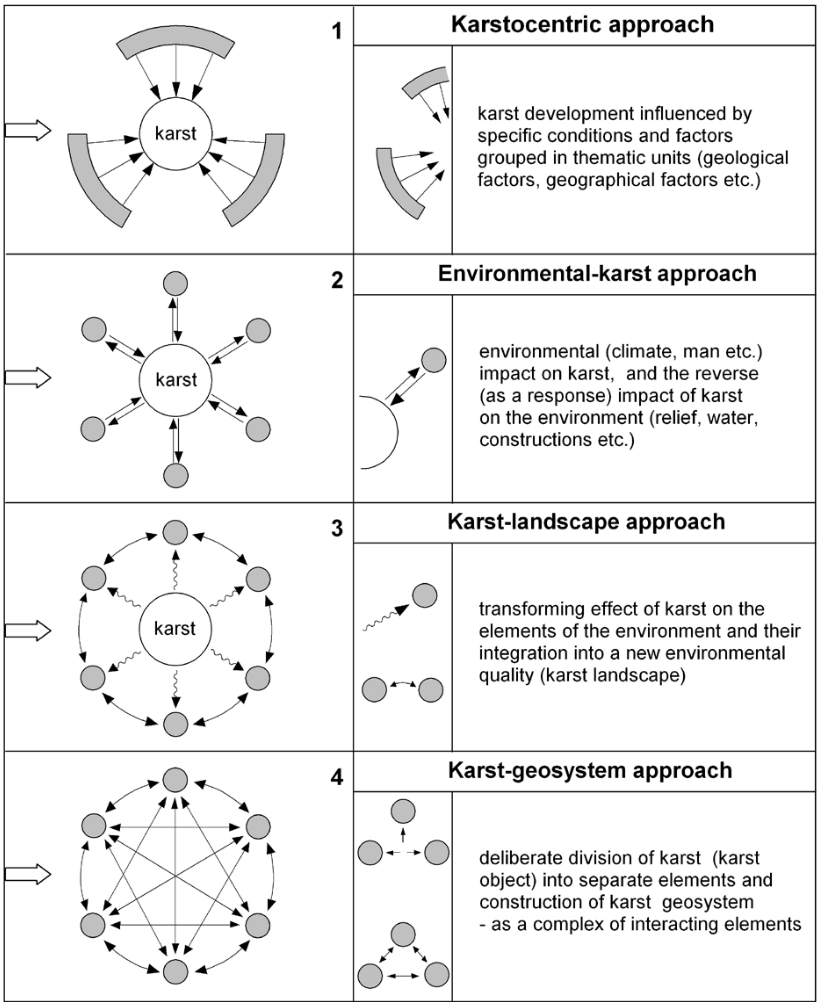

Fig. 1. Main comprehensive approaches to the karst study.

of the "50-70s" of the last century (the publications of F. Savarenski, D. Sokolov, some works of G. Maximovich, V. Dublyanski, A. Chikishev, R. Tsykin, and many others). The works of these authors dealt with the issues of "conditions and factors of karst development"[2]. They discussed a spectrum of karst formation factors, which of the factors are more important (essential, crucial), and which are less important, etc. in relation to the central concept of karst, sometimes regardless of discrepancies in defining karst itself. This approach was manifested in the characteristics of the researches carried out on karst, in the structure of the monograph studies on karst of these or other areas, in the organisation of material in reference books (introductory chapters), etc. This approach also has application nowadays, especially in the case of comprehensive studies on karst in a particular area, as well as in works generalizing on karst.

The karst-environmental approach is another version of the centric approach, that is, it implies examining the relationship between the studied object and its surroundings (environment) (Fig. 1-2). This approach is currently employed on a large scale in geoecological studies (*ecological*/*ecocentric*/*ecosystemic* approach – synonyms), in research on the relationship of man and nature (*anthropocentric, anthropic*), etc., *i.e.* when examining the impact of the environment on the object (nature, man, organism, etc.), and vice versa the impact of the object on the surroundings. This approach has been carried out since the time of J. Cvijić on a large scale in karst studies primarily in terms of geographical research, where karst was considered as the environment of human life, including issues of *karst determinism*. This approach found wide application in the countries of the Mediterranean basin, where karst issues have always been associated with the issues of water and its exploitation.

The environmental-karst approach (especially its opposite aspect – the impact of the industrial activities on karst) has revived over the past decades due to a growing economic impact of man on the karst environment (*technogenic, activated*, etc., karst) and the concomitant consequences that are sometimes disastrous, as in induced surface collapse, land subsidence, etc.

The karst-landscape approach is the special (karstic) case of *the landscape approach of the* Eastern-European school that views landscape as a particular territorial, processual and physiographic part of nature as a whole. The landscape approach suggests considering a given area in terms of its entirety whose physiographic specificity is determined by the particular spectrum of natural processes occurring within its boundaries which shape its appearance (volcanic processes – volcanic landscape, aeolian processes – desert landscape, karst processes – karst landscape, etc.). It has been also implied that the compactness of the internal interconnections of the components (bedrock, water, soil, climate, biota and others) in the landscape understood in such a way (Fig. 1-3), due to its characteristic processes is greater than of the external relations of the landscape, which is manifested, inter alia, in the specific physiognomy of the landscape area. It is also believed that the formation of a given genetic type of landscape is generally determined by the so-called "leading process or condition", which integrates and subordinates the activities of other processes, directs the development of landscape and determines its peculiarities. The role of such a condition or process may be played by climate (formation of polar, desert, etc. landscapes), tectonics (landscapes of rift valleys), erosion and landslide processes, etc. The presence of karst rocks and karst which over the course of development gradually subordinates other processes and more and more considerably transforms the landscape to forming a specific (petrogenic, lithogenic) karst landscape can constitute such a leading or growth influencing factor.

[2] The monograph of Dmitriy Sokolov *Osnownyje uslowija i faktory razwitija karsta* (*Essential conditions and factors of the development of karst*), 1962 is the most comprehensive example.

The landscape-karst approach, as described above, is represented mostly in the works of researchers of the Eastern-European school of landscape science. These are the works of N. Gvozdiecki (1972, 1979), A. Chikishev (1982), M. Proskurnyak and V. Andreychouk, (1998, 1999) and the author (Andreychouk, 2007, Andreychouk, Proskurnyak, 1993, Andreychouk, Voropaj, 1993, Voropaj, Andreychouk, 1985) and a number of other papers. This approach seems to be very useful to elucidate the evolution of karst areas (formation of the landscape), and explain the specifics of their natural environment. It is also advantageous when dealing with the issue of land use within karst areas and their protection.

The karst-geosystem approach is a special case of the *systems approach*, which favours considering the object (phenomenon, area) as a system, an appropriate organization of the research process (algorithm research), and often also the application of appropriate numerical methods (system analysis, graph theory, and others) (Fig. 1-4). In the systemic approach the object is presented as a set of elements and relationships between them (structure), and the study itself focuses primarily on the issues of interactions between the elements, because it is just the interactions between the elements that determine the overall (emergent, system-derivatives) properties of the system.

System studies (as well as the entire system methodology) have been finding wider and wider application for several decades in all fields of modern science, including the natural sciences – biology, ecology, and to a lesser degree, geology and geography. Despite many other merits of a cognitive nature, the systemic approach is advantageous also because it allows fairly easy formalisation of the studied object (functional connections of its elements), which paves the way for a wide application of numerical methods and modelling. The systemic approach enables the most complete and appropriate examination of the object, since its application reveals not only the properties of the object, derived from the properties of its components (elements), but also properties induced by the interactions of the elements (structure-derivative properties, *i.e.* comprehensive, systemic). The latter are particularly vital when planning certain activities in the environment, in the landscape, as they allow for detection of trends in development and for forecasting changes. Therefore, general system visions and environmental studies are most forward-looking and effective methodology nowadays.

Unfortunately, the systemic approach has not found wide enough application in karst studies. This is due to, on the one hand, quite a narrow range of karst research compared with the overall natural studies, on the other hand, the lack of clearly formulated systemic concepts of karst (karst system visions). Speleological research into water circulation in karst massifs (karst systems performing the cycle: supply – transit – outflow) is an exception here. It establishes hydrological and other relationships between the objects (caves, springs) and areas, first of all. In the case of monitoring the flow of water, a "black box" or "gray box" testing situation takes place when the interior of the massif is inaccessible or only partly accessible: the internal structure of the karst system and the processes occurring within it are deduced based on the measured "input" and "output" parameters. In the situation when it is possible to follow the water circulation in the karst massif by cave exploration examining the links of the karst system inside from the input to the output, "white box" testing takes place.

The systemic approach may have a number of different "methodological configurations", and a variety of *research models* may be created by this approach. However, studying and presenting the material *as a system* remains invariant. This approach is no doubt very forward-looking in karst studies as caves, karst aquifer systems and areas (karst massifs, landscapes) are distinguished by the complexity of their structure and the large variety of processes occurring within them. The systemic approach is known for constituting a conceptual tool to study complex objects and phenomena of reality.

Of course, these examples of comprehensive, as contrasted with partial, analytical, thematic, approaches to the research of karst are largely provisional. Their "methodological weight" is not equal, and they do not exclude other potential approaches. Nevertheless, in the author's opinion they allow determination of the "coordinates" for comprehensive scientific study of karst, revealing the systemic nature and specific organization of the karst landscape.

LANDSCAPE

The literature contains many approaches and countless definitions of the *landscape* as such. In geography it is hard to find a term that is more ambiguous. The mere listing of the definitions would take many pages. In order to sort out the problem, geographers distinguish different trends and approaches to defining this concept, which is by nature a multifaceted and almost inexhaustible concept. In such a situation, the only solution for the landscape researcher is to set out at the very beginning, his understanding of the concept, and to determine the meaning assigned to it.

By generalizing and simplifying the issue, it can be suggested that there is a difference in perceiving and defining the landscape between researchers from Eastern Europe (the countries of the former USSR) and geographers from Western Europe. In the East, in the first half of the 20th century this concept underwent many "mutations" in relation to its original meaning as "the area appearance", "face of region", "area type", etc. The changes consisted in imputing more and more genetic sense to this concept - genetic types of landscape, factors of landscape formation, hierarchy and classification of landscape units, etc. From the primarily physiognomic term (*form*), the landscape transformed into rather a genetic one (*content*). Also its "geometry" changed, from an undulating 2D "surface" landscape became converted into a 3D volumetric "body". Over time, a particular organization was recognized within the "body", which consequently became a holistic formation – geocomplex, geosystem, etc., explored with appropriate methods known as the comprehensive geography methods. Most of the researchers in Eastern Europe still understand landscape in this way.

In Western Europe and in North America the term also has been given various meanings, however always within the realm of a certain invariant physiognomy. The landscape was not treated too specifically and rigorously by Western researchers. Questions of its origin were primarily dealt with in the context of the surface and its characteristics, *i.e.* morphology (geomorphology) and filling in the space (shape, picture, types of terrains, covering of the areas, their land management and arrangement, including aesthetic, etc.). It should be noted that in the two last decades there has been observed a trend towards integration and interweaving of more rigorous Eastern-European (genetic, geocomplex, etc.) with a more flexible Western understanding of the landscape (physiognomical, morphological etc.).

In this study, the author will use the Eastern-European approach – a more "volumetric", genetic and comprehensive. Such an understanding of the landscape – as an entire natural system, facilitates plenty of opportunity to apply a holistic approach and reveal the complex nature of karst landscape and its organization. The formulations given below may serve as a starting point.

The landscape is a natural[3], territorially compact and functionally integrated system consisting of spatially related elements interacting with each other – bedrock, relief, surface water and underground water, climate, flora, fauna and soil. Being a formation structurally and functionally complete, the landscape is characterized by emergent properties which manifest in its dynamics (self-regulatory capacity) and evolution (self-development processes). The landscape is characterized by a particular physiognomy of space (image view, paysage), which is denoted on a map in the form of a specific drawing-pattern. Within the greater landscape there are smaller, hierarchically organized and regularly arranged characteristic territorial units which make up an individual landscape composition (mosaic, pattern).

The landscape is therefore a formation of known territorial dimensions, usually from a few hundred to a few thousand km^2, with a characteristic and complex internal structure. In addition it constitutes an organic part of larger territorial formations (physical-geographic units of greater size – regional, etc.). Territorial dimensions (boundaries) of the landscape system correspond to the area within which the landscape retains its physiognomic characteristics. Typical features of landscape result from the homogeneity of the geological structure, characteristic forms of relief and how they are arranged in relation to each other, hydrographic network, vegetation cover, and characteristic processes occurring within the landscape (geomorphological, in particular). Each landscape is characterised by an individual "barcode" of forces and processes shaping it.

KARST IN TERMS OF SYNERGETICS

As previously mentioned, the existing definitions of karst usually refer to one of three aspects: process (karst as a mono- or complex *process*), phenomenological (karst as a *phenomenon* or set of specific events) and geomorphological (territorial: karst as an *area* or *relief* with a characteristic set of characteristics). Just as in the case of the concept of landscape, there are certain differences in the approach to defining karst by Eastern European karstologists and Western European and American karstologists. Typical for the Soviet school understanding of karst as a process or phenomenon, or the unity of the process and the phenomenon (including forms) – placed emphasis upon the process aspect. In Western literature perceiving karst as an area with specific forms and hydrology is dominant, and the territorial-phenomenological aspect, etymologically closer to the source term (Kras/Karst Upland), is accentuated.

Klimchouk and Andreychouk in their article "About the essence of karst" (2010) propose yet another – a systemic approach to the definition of karst, based on the ideas of synergetics and unbalanced thermodynamics of I. Prigogine concerning self-organization in systems and formation of dissipative structures. Karst is being examined from the angle of self-development of permeability structures in karst rocks in the course of interaction between water and rock (aquifer and massif, etc.). The essence of the development and evolution of karst is the staged self-organization of permeability structures (channel networks), manifesting itself in the initiation, concentrating and integrating of underground drainage, and the intensification of the water cycle in karst massif. Karst is defined as a *"water-circulation geosystem" within a certain part of the hydrolithosphere, whose formation and progressive evolution are characterized by self-organization of permeability structure together with formation of integrated systems of channels owing to the impact of a specific speleogenetic mechanism based on the positive feedback between water circulation and dissolution".*[4]

By definition, karst is a progressive evolution of a geosystem with a permeable rock vulnerable to dissolution, triggered by water circulation and speleogenetic mechanisms of self-organization of permeability. *Progressive evolution* is understood as a process of formation and development of new dissipative structures (increase of structural complexity of the system), whereas *regressive evolution* – as a process of their destruction and collapse (reduction of structural complexity). During the cycle of karst (karst megasystem[5]) development the progressive evolutionary trend over time gives way to the regressive one, but this process of formation (integration) and degradation (disintegration) of structures is stretched over time, overlapping and complex.

[3] Nature-anthropogenic in the case of the *culture landscape*.

[4] The principles of this approach were previously employed to define karst by P. Huntoon (1995), A. Klimchouk and D. Ford (2000) and (Klimchouk, 2010a). The same principles constituted the basis for the fundamental monograph *Speleogenesis: Evolution of Karst Aquifers. - Huntsville: National Speleological Society, 2000.*

[5] The term of karst *megasystem* refers to a karst area within which so-called "karst cycle" is realised: the appearing, developing and evolutionary disappearing of karst. Karst is understood as a complex karst geosystem of the entire territory, which functions and develops in accordance with principles of synergetics, passing through the successive phases of development (forming and increasing complexity of the structures) and degradation (disintegration of the structures and reduction of complexity) of the system. It is a provisional, sketchy term introduced in order to facilitate conveying specialist ideas, and as such does not pretend to be conferred a status of a scientific term.

The geosystemic, evolutionary-synergetic approach provides an excellent conceptual theoretical basis for understanding the nature of karst, its position in the evolution of the karst megasystem, and creating a *systemic (geosystemic) concept of the karst landscape.*

KARST LANDSCAPE AS A STAGE OF SELF-ORGANIZATION OF KARST MEGASYSTEM

The synergetic-development model of a natural system assumes that during its development the system passes through stages of known characteristics which are accompanied by a gradual increase in its inner structural complexity. The process of the structure becoming more and more complicated ensues the occurrence of new developmental factors, radically changing (often accelerating) the development of the system and introducing it into a new structural (energetic) state while simultaneously facilitating conditions (so-called boundary conditions) for preserving (consolidating) this state. In synergetics the moment of the emergence of the "revolutionary" factor in the system development is called "the bifurcation point". Bifurcation points determine boundaries of qualitative states (stages) of the development of the system.

The gradual – from bifurcation to bifurcation - qualitative increase in the structural complexity of the system is the core of progressive evolution. However this growth has its time, spatial and structural constraints, dependent on the size and type of system and evolutionary factors. In the course of the development of the system up to the developmental climax, new elements and factors appear (multiply) and together with them relationships[6] between them. Among them, however, negative feedback processes become increasingly important, limiting the development of the system and leading to gradual degradation, i.e. reduction in its structural complexity. This is the essence of regressive evolution of the system, which results in its "death" as a well organized system.

How does this general developmental model describe karst and the karst landscape? In the development of the karst megasystem[7] several phases (mega-phases) can be identified and separated from each other by critical events (bifurcations). This is depicted in Fig. 2, drawn by author upon the basis of the above mentioned article of A. Klimchouk and V. Andreychouk.

The first phase is the stage of *pre-karst* (or *early speleogenesis*). At this stage the karst megasystem has not yet developed karstic quality as such. This is an "embryonic" stage within which the initial permeability structures (fractures and pores) undergo a process of hydrodynamic "maturing". This maturing consists of the impact of water present in pores and fissures on the rock substrate susceptible to dissolution, which results in very slow (lasting tens of thousands or more years), but continuous widening of the fissures, formation of proto-channels together with their gradual hydrodynamic integration into initial networks. The driving force and the main mechanism for the development of proto-channels is positive feedback between the rate of development and the increase of flow. At this stage chemically aggressive water and karst rock are the main elements of the system (not yet karstic) and dissolution is the main process (Fig. 2).

The critical moment in the evolution of proto-channels, called "the breakthrough moment", signalises such a degree of their opening that rapid kinetic dissolution occurs along their entire length. After that, water flowing through the entire proto-channel remains unsaturated, which radically changes the dynamics of its growth (acceleration) and of other variables.

The rate of growth and water flow increases by several orders, while pressure in the growing channel decreases causing conversion of boundary conditions and activation of integration process (merging of proto-channels into networks). Proto-channels transform into channels, which means "the birth" of a new systemic behavior – karstic. The evolutionary breakthrough point constitutes the first (of first rank) bifurcation in the development of the karst megasystem, and the moment of the birth of karst (Klimchouk, Andreychouk, 2010).

The rapid development of karst channels, diversification of development mechanisms (for example, the appearance of turbulent water flow in some parts of the system, and hence possible mechanical erosion) leads to integration of the channels, increase of their size, *i.e.* to the formation of simple karst systems – channels and cavities. At this stage a new element – an underground cavity *i.e.* an empty space "enters the game" and becomes an important (if not the most important) factor in the development (symbol c in Fig. 2). This component becomes not only an intermediary between water and rock interacting with each other, but also both the result of their interaction (increased volume) and the cause of the further development of the system (acceleration as a consequence of the positive feedback between the volume – the total surface of the contact of water and rocks, and movement). At this stage we are dealing with *speleogenesis* (the development of channels and cavities) taking place underground, at a certain depth, in isolation from the earth's surface, therefore this early phase in karst development (or karst state) can be provisionally called *hypokarstic*.[8]

During the development of the karst system (the increase of complexity in its structure) different types of bifurcations occur, affecting its development in one way or another (*e.g.*, change in the pressure conditions of water movement by the conditions of free water flow), but not changing fundamentally its trend (second order

[6] As the number of elements in the system increases in arithmetical progression, the number of connections between the elements of the system increases exponentially.

[7] In this work the karst megasystem in the spatial aspect refers to "a volumetric rock body" being a part of the hydrolithosphere built from rocks susceptible to dissolution, wherein, in favourable conditions, karst may develop as a system of a specific water circulation within this body. The projected onto the surface or geologically exposed the upper fragment of the body constitutes a potential or real surface area of the occurrence of karst.

[8] Describing *hypokarst* as a stage of the karst mega-system development is slightly wider beyond the common understanding of hypokarst (underground karst first of all) as a phenomenon generated by water recharging from below independently of seepage from the overlying surface (Klimchouk, 2007, 2010b). In both cases there is a common denominator – the lack of connections with the surface.

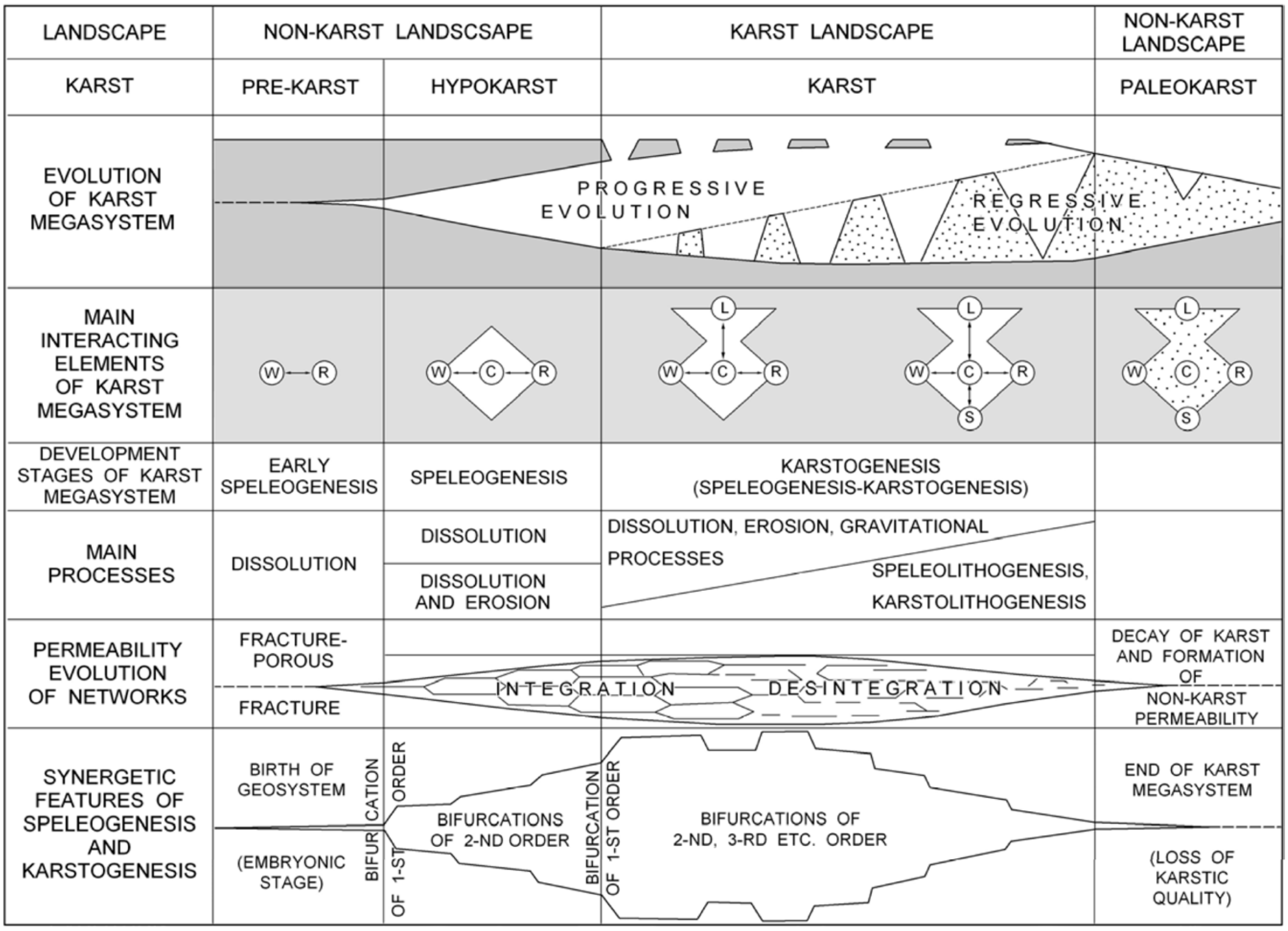

Fig. 2. The conceptual integral diagram of the development of the karst megasystem (W – water, R – rock, C – cavity, L – landscape – outside environment, S – sediments).

bifurcations). A new – *an actual karstic* stage in the development of the megasystem begins at the moment of the system's opening up to the outside (connections with the surface) (Fig. 2).

This is the second fundamental developmental bifurcation after which the "life" of the system is getting very complicated. This opening, which means exposure to multiple and aggressive factors in the external environment, causes major changes in the system's structure and functioning. It is illustrated in the figure 2 by attaching an element-factor L to the model of the system.

The impact of external factors on the one hand, progressively complicates the structure of the system (*e.g.*, as a result of capturing the surface runoff, increasing the volume of underground cavities), on the other hand, initiates formation of processes and feedbacks hindering progressive development (such as collapse of the cave ceiling and formation of sinkholes, filling the corridors and cavities with flowstones, etc.), that is, has characteristics of the regressive phenomenon of evolution – degradation of permeability structures and the structure of the entire system (Fig. 2).

In the context of deliberations in the next paragraphs on the karst landscape, entering this third phase in the megasystem means the "birth" of the karst landscape. It is due to the fact that not only external factors begin to have an impact on the development of permeability structures underground, but also the cavities (which as a result of opening have become caves) and channels start to affect the landscape, transforming it gradually (bifurcations of 2, 3 etc. order) into a new entity – *karst landscape*. The karstic process of the development of permeability structures thus becomes the *relief-forming* factor, and by introducing surface elements into the circulation – water, vegetation, soil, etc. – the *landscape-forming* process.

After having become a part of the external environment, the karst megasystem becomes extremely complicated. The leading mechanism in its development is constituted by multiple interactions between the surface and underground, which integrate it into a very complex natural system with a tiered structure representing a new development state of the karst megasystem. This state or stage can be defined as *karst or karst landscape phase* in the karst megasystem development (Fig. 2), and understood as a whole system consisting of two parts – the underground and surface terrestrial.

At this stage, the development of the karst megasystem is stimulated by numerous processes taking place both on the surface and underground, depending on tens or hundreds of external and internal factors. Between the system elements (components) together with their countless connections, different relationships are formed which operate in favour of its development either progressive or regressive, or sometimes both. An abundance of connections (interactions) justifies a large quantity of different types of bifurcations of low orders which determine development of individual links of the entire system.

The capture of the surface water stream by a ponor, formation of sinkhole and its drainage area, fill of the vadose channel with flowstones, descent of an underground stream into a lower level – these are examples of bifurcations of the second or third order.

Many of bifurcations, especially those related to capturing the surface flow, lead to an increase in the internal structural differentiation of the system. Other bifurcations, especially those associated with the gravitation processes and filling channels and cavities with sediments, result in its destruction (destructuring[9]). Over time, these "destructive" bifurcations grow in number causing "withering away" of functional links between individual spatial elements of the system and thus leading to its degradation. Interestingly, the degradation of permeability structures in the karstifying geological substrate (rock series, karst massif, etc.) means active development (progressive evolution) in the geomorphologic subsystem. The development of surface karst relief significantly reflects degradation of underground structures, hence a shift in time in the destruction of the underground and terrestrial parts of the karst landscape at the karstic stage of the karst megasystem development. For example, the fascinating and unique landscapes of the tropical tower karst, considered to be the quintessence of karst relief, are just the creation of degraded underground circulation. Further destruction of the karst megasystem, *i.e.* its last "bastion" – the surface karst relief, is brought about by external environmental factors. The destruction (planation) of the last elements of karst relief (as long as karst has not "moved" to lower levels – into the depths) is followed by the extinction of the karst megasystem, *i.e.* the of loss of karstic quality in the landscape.

It should be noted that the transiton of karst or the karst landscape into a new non-karst (or paleokarst - see below) quality, which is its final degradation, is of a temporary nature, evolutionary (not acute). Between these karst states (stages) there is no clear boundary, and there is no fundamental (of the first rate) bifurcation behind it, as it is the case at other stages. Bifurcations as such, are an indispensable element of progressive evolution, and their role (of the first-, second-, third rate) is greater in the initial stages of the system development, when there are still not too many elements and links affecting each other. Over time, as the complexity of the system grows, the number of bifurcations there increases, and their role in the development of the system decreases proportionally. At a certain stage (in our case – a mature karst landscape), along with a rapid increase in the number of bifurcations, there is observed spatial dispersion (location) of bifurcations over the links of the megasystem and consequent reduction of their factorial status in relation to the entire system.

INSTEAD OF CONCLUSION

Karst stage (karst or the karst landscape – Fig. 2) is not a mandatory step in the development of the karst megasystem. Owing to the change in the character (sign) of tectonic movements – from the positive (uplifts) to negative (down), the second bifurcation, *i.e.* opening of channels and cavities may not occur. Then the karst system, having been filled completely or partially with sediments, evolves towards the paleokarst state (phase). However, during the next change in the direction of tectonic movements (uplifts), re-karstification may take place and the megasystem may achieve the state of the karst landscape.

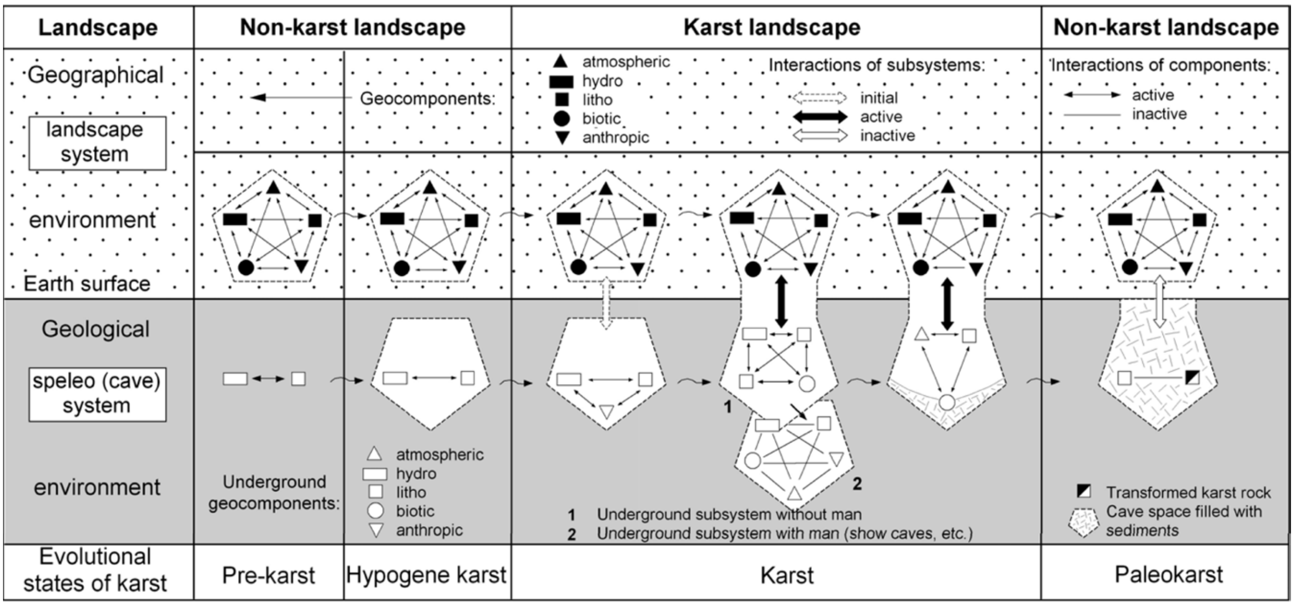

Fig. 3. An overall evolution of the karst landscape structures against a background of the karst mega-cycle.

[9] Development of accumulation processes means appearing in the system structure the next element – sediments (gravitational, aqua-mechanical, chemogenic, biogenic, etc.) (S on Fig. 2). It also means that one more "player" gradually enters the game (development factor), whose importance in the system development (in this case its degradation) will be continuously growing.

The evolutionary impact of the tectonic factor – the earth's crust movements – on the karst landscape is of the key important. The vertical direction of tectonic movements determines the course of the entire karst cycle. In the case of tectonic uplifts facilitating karst development we deal with a "normal" development cycle, wherein KL "emerges" from the karst mega-cycle and gradually transforms into a more and more independent and autonomous (self-organizing) landscape system until "self-extinction" (Fig. 2). In the case of stabilisation or changing the movements direction to lowering, which are accompanied by the loss of the interaction energy by the relief (degradation of erosion bases), KL disappears without realizing its development potential[10]. Fig. 3 illustrates an overall evolution of the landscape structures against the karst mega-cycle. The evolutionary reality, of course, is much more complicated and presented scenarios represent only a few simplified examples.

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[10] In this case we can speculate on "evolutionary losses". Against the background of the evolutionary development of the landscape of a certain terrain, the karst-landscape stage (if in the geological section of the terrain there are karst rocks, and tectonic elevations lead to their exposure) may leave a conspicuous evolutionary trace in the form of specific species of plants and animals which developed in a particular karst environment. The fact that such an environment facilitates a distinct specialization of organisms and formation of new species (not only underground) is confirmed by ecologists' researches. The number of endemic types there may reach over a dozen percent (in Tsyngi de Bemaraha Reserve in Madagascar even more). Without any doubt, karst stages in the development of a certain terrain on our planet contributed greatly to the development of its organic matter.

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