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Jovan Cvijić and the founding of karst geomorphology

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Introductory lecture at special session dedicated to Jovan Cvijić at the conference Water Resources and Environmental Problems in Karst, Belgrade, on 14 september 2005

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Abstract Jovan Cvijić was born in western Serbia and studied widely in the Dinaric Kras. His publication of Das Karstphänomen (1893) established that rock dissolution was the key process and that it created most types of dolines, ''the diagnostic karst landforms''. The Dinaric Kras thus became the type area for dissolutional landforms and aquifers; Germanicised as ''karst'', the regional name is now applied to modern and paleo-dissolutional phenomena worldwide. Cvijić related the complex behaviour of karstic aquifers to development of solutional conduit networks and linked it to a cycle of landform evolution. He is recognized as ''the father of karst geomorphology''.

Introduction

The organizers of the International Conference on Water Resources and Environmental Problems in Karst conferred a great honour when they invited this author to be amongst its opening speakers. The Conference specifically celebrates the eminent karst scientist, Jovan Cvijić, who published the first major treatise in this field of study 110 years ago. He was a Professor of Geography at the University of Beograd for many years. As an Emeritus Professor of Geography and Geology from McMaster University in Canada, born and educated in Britain but having conducted most of his research in North America, this author evaluates Cvijić's scholarly contributions from the perspective of one who works within the English-speaking world. It is a pleasure to do so because he was the outstanding pioneer in a subject that still holds fascination after 50 years of working in it.

Jovan Cvijić and his writings

Jovan Cvijić was born in 1865 in the village of Loznica in western Serbia, which is surrounded by karst features. He attended the Academy in Beograd and then undertook advanced studies in Vienna, where he obtained his doctorate in Geography. His supervisor was Professor Albrecht Penck, the leading European geomorphologist of the era. Penck is celebrated for his contributions to alpine glacial geomorphology and chronology but had much wider interests. He was familiar with the northern Dinaric regions and encouraged Cvijić to focus on karst phenomena there. Cvijić was also fortunate to study with one of the foremost tectonic geologists of the time, Eduard Suess, because effects of tectonic deformation are very important everywhere in the Dinaric karst. During his years of graduate studies Cvijić was able to visit and investigate many areas within the Karst itself, plus the

alpine karstlands of Austria and karst in the Punkva River basin of Moravia.

Jovan Cvijić published his most influential and celebrated work, *Das Karstphänomen*, under Penck's aegis in 1893, when he was only 28 years old. He then returned to Beograd to become a university teacher and researcher. A slightly amended version of *Das Karstphänomen* was published in Serbo-Croat in 1895. He was a characteristic academic geographer of his period, studying, teaching and sometimes publishing in a variety of different topical areas, including anthropology and ethnography, as well as careful regional geographic accounts of parts of the Dinaric karst (e.g., Cvijić 1901). He was much influenced by a field tour that Penck took with his students and the eminent American geomorphologist, W.M. Davis, in Bosnia and Herzegovina in 1899. Davis was the author of cyclic landform concepts that dominated the thinking of fluvial geomorphologists and many others in the English-speaking world and beyond throughout the first half of the twentieth century. Inescapably, Cvijić was motivated to look for cyclic behaviour in karst landform evolution. He spent World War I teaching in France, where he was able to visit karsts of the Cevennes, French and Swiss Alps. In 1918 he published his views on karst hydrology, attempting to place them in a cyclic framework. Returned to Beograd, he published a substantial paper on karren (Cvijić 1924) and was working on the most comprehensive review of all of his thinking when he died at the sadly early age of 62 years in 1927.

In the English-speaking world, Cvijić thus is best known and appreciated for his major publications of 1893, 1918 (summarized in English by Sanders 1921), and the incomplete review which was published posthumously in 1960.

Das Karstphänomen (the core of his doctoral thesis) is not a well-balanced work; 52 of its 112 pages are devoted to description and classification for dolines, 23 pages consider poljes, and there are ten pages each for karst valleys, karst of the Adriatic coast, and a typology of karst landform assemblages. Its sequence of presentation, beginning with karren, (the smallest landforms), proceeding through the intermediate scale dolines and concluding with large scale valleys, poljes and regional assemblages, has been copied in perhaps the majority of later textbooks. He is well read, referencing many works by foreign authors (e.g., Sir Charles Lyell on the chalk of Norfolk, England), and his style is always enjoyable because he sprinkles detailed descriptions of local landscapes and features throughout the exposition of his ideas. Marjorie Sweeting wrote that "A study of Cvijić's work is essential for any student of karst morphology" and considered *Das Karstphänomen* to be "...the beginning of karst studies proper" (Sweeting 1972).

In the 1918 paper Cvijić demonstrated that he had a much better conception of the nature and variability of meteoric water caves than did most other geologists and geomorphologists (karst or other) of that time. He understood that, in many instances, there was no water table established at depth in the rock when karstification began, and that (in alpine settings at least) the water levels in well developed caves were prone to fluctuate over considerable height ranges in response to spring thaw flooding, creating a distinctive hydrologic zone which is now termed "epiphreatic" (Ford 1987; Ford and Williams 1989). Cvijić then integrated these observations into a clever karst cyclic model that is considered below.

This author first learned of the 1960 posthumous publication of his final work, *La Géographie des Terrains Calcaires*, when attending an international geographical congress in London in 1964, having completed his own PhD thesis the year before. There was no karst textbook or substantive lesser review available in English at that time. Cvijić's volume (Cvijić 1960), had it been known to the author, would have been of great assistance because of his systematic organization and consolidation of thinking on karst hydrology. It is a masterwork 200 pages in length. It is incomplete; his editor and friend, the eminent French geomorpologist, Emmanuel de Martonne, wisely did not attempt to finish the chapters on caves and karst valleys from the notes he left behind. It is also somewhat flawed. At the close of it, Cvijić was attempting to illustrate (and reinforce) the division of karst landscapes into the 'holokarst' and 'merokarst' (mixed with fluvial) types that he had first set out in 1893, when they were based only upon his experience in the Dinaric regions and in Moravia. He now found it necessary to add a third class, terrains that are "transitional" between holokarst and merokarst conditions. As succinct accounts of these new terrains succeed one another (the Grandes Causses, the Lesser Causses, the French Fore-Alps, the Peloponnese, Cuba) it becomes apparent that the number of "transitional" examples may substantially exceed the holo- and mero-karst end members, suggesting that re-classification is needed here. Today, 'merokarst' has been replaced by the notions of "fluviokarst", and of autogenic versus allogenic dominant water sources (e.g., Ford and Williams 1989). The long association between karst scholars of the Dinaric region and France continues; Jean Nicod, doyen of the French school today, has recently published an extensive evaluation that has many features in the style of Cvijić (Nicod 2003).

Jovan Cvijić was a geographer and geologist of his time. His writings are elegant and clear, but only sparsely illustrated by pictures or diagrams. Although he is dealing with the dissolution of rocks by flowing water, there are no chemical formulae or physical equations. No figures attempt to plot values for dependent variables against independent variables, etc. Nevertheless, his contributions to karst science have been fundamen-

tal. Some of the most important ones are considered here.

Jovan Cvijić and "karst"

It is understood that the word "karst" is a Germanicization of the Slavic "krš" or "kras". It means "stony ground" and was applied to regions of the Dinaric Karst (especially the northern or "classical" karst) marked by karrenfeld and doline terrains largely devoid of trees or soil as consequences of deforestation and overgrazing. Gams (2003), Kranjc (1994) and many others have written about the linguistic derivation in detail. Before Cvijić many travelers and some early geologists had used the Kras or Karst placename in association with descriptions of these distinctive landscapes and landforms. Authorities in many languages (Davis 1901; Daneš 1908; Katzer 1909; Sawicki 1909; Herak 1972, etc.), however, adopted "karst" to describe rock dissolutional processes and the landforms and groundwater systems derived from them because Cvijić's "Das Karstphänomen" had established (beyond any doubt) that they are distinct from the standard phenomena of fluvial geomorphology. Thus, historically, the 1893 publication is seen to have been the founding codification of the subject (Roglić 1972; Sweeting 1972). Jovan Cvijić is "the father of karst geomorphology and hydrology".

He was not without competition. His near contemporary, the French cave scientist, Edouard Martel, ("the father of speleology") sought to establish the regional placename "Le Causse" in its stead (Gauchon 1999). "Karst" won out because it had historical priority and the greater weight of Cvijić publication to support it. "Karst" is a confusing term for many scholars and others, however. They can readily understand what the subject matter of "fluvial" or "glacial" (even "periglacial") geomorphology must be—but "karst?" If a new term were established today, it might avoid such regional ascriptions and, with all the poetry of scientists, propose "dissolutional geomorphology" or some similar term. But "karst" is now firmly entrenched throughout the literature in science and engineering worldwide and in many languages. Figure 1 compares its geographical source in the Dinaric region to its potential extent (the global outcrop of carbonate rocks) today.

The worldwide acceptance of "karst" has led, as well, to its much greater conceptual extension in geosciences and civil engineering than Cvijić would have imagined. Figure 2 is a cartoon that this author has used for the past 25 years to teach some of its many parts (Ford 1998). The subject matter of karst is no longer limited to the surface landforms and shallow circulation of meteoric water through caves that Cvijić studied. Juvenile waters, sea water, connate waters and gases, are all seen to contribute. Sedimentologists will focus on the "net deposition" zone in the cartoon, considering it to be the most important part, paying close attention to karst weathering horizons and hardgrounds developing in it. Economic geologists, instead, will look deep into the fluid expulsion and mixing zones for economic emplacements of ores. The study of buried and inert "paleokarst" has become a very big subject in its own right; every oil geologist must be aware of it because $\sim$ 50% of the world's oil and gas reserves are believed to be in limestones and dolomites, much of it trapped in karstic porosity.

Jovan Cvijić, lapiés and dolines

Civijić was always interested in the nature and origin of karren (or lapiés, as he termed them when writing in French). They were abundant and prominent in the denuded kras. In a striking simile he likened them to the "badlands" found in steep, erodible fluvial terrains. He was amongst the first to understand that details of lithology (especially petrofabric) can be important in determining whether or not particular forms may develop. Correctly, he supposed that the finest grooved type (now known as "rillenkarren") develop quite rapidly on limestone, although he was in error in supposing that they might "mature" into larger forms. He gave most attention to solutional runnels a few decimetres or metres in length that are oriented down slopes ("rinnenkarren"), and the larger, joint-guided troughs ("klufkarren" or "grikes") that they often drain into. He also introduced the term "bogaz" for a class of longer and wider troughs. Today kluft and bogaz are recognized as components in a sequence that scales up to more extensive "corridor" and "labyrinth" karsts (Ford and Williams 1989, p. 393). Cvijić did not succeed in attempts to discover a coherent altitudinal sequence of forms between the Adriatic coast and high Alpine plateaus.

The key section of *Das Karstphänomen* is Cvijić writings on "dolines". He established this name itself, in a competition with "sinkholes" (which continues to be the preferred term in much English usage). Firmly, he specified that the doline is "the diagnostic karst landform"; if it is present in a landscape, some type of karst (or pseudokarst) must exist there. From his intensive studies in regions of the Dinaric karst, he recognized three principal forms that he termed "normal":(1) bowl-shaped dolines that typically range 10–120 m in diameter, have gentle slopes (up to 12° or so), and diameter/depth ratios around 10:1; (2) funnel-shaped dolines with steeper slopes and diameter/depths ratios of 2–3:1; (3) well-shaped dolines that are only 2–5 m in diameter, 15–20 m deep, i.e., they are a type of shaft. At sites in Montenegro and Hercegovina he found that bowls outnumbered funnels $\sim$ 4:1, in Carniola $\sim$ 6:1, and in Istria $\sim$ 10:1. Well-shaped dolines were comparatively

rare in all regions. These measures and ratios in dolines are the pioneer morphometric measures in karst studies, anticipating major elaborations by Cramer (1941) and Williams (1966, 1972, 1983). It is interesting to compare Cvijić's conception of the cross-section of a typical small doline with that published by Williams 90 years later (Fig. 3).

Šušteršič (1994) has returned to site of the Cvijić classic cross-section of Fig. 3. It was exposed in a railway cutting near Lŏgatec, Slovenia. He found that the Cvijić section missed the true centre of the doline, which had a larger, rubble- and soil-filled, solutional pipe and was modified from funnel- to bowl-form by the accumulation of a little periglacial detritus in the bottom. This author can confirm the typicality of this kind of section because, as a school boy cave explorer, many fruitless hours were spent digging out examples of it on the Mendip Hills of England, always being disappointed to discover that the pipes in the bottoms were scarcely large enough for a rabbit to enter!

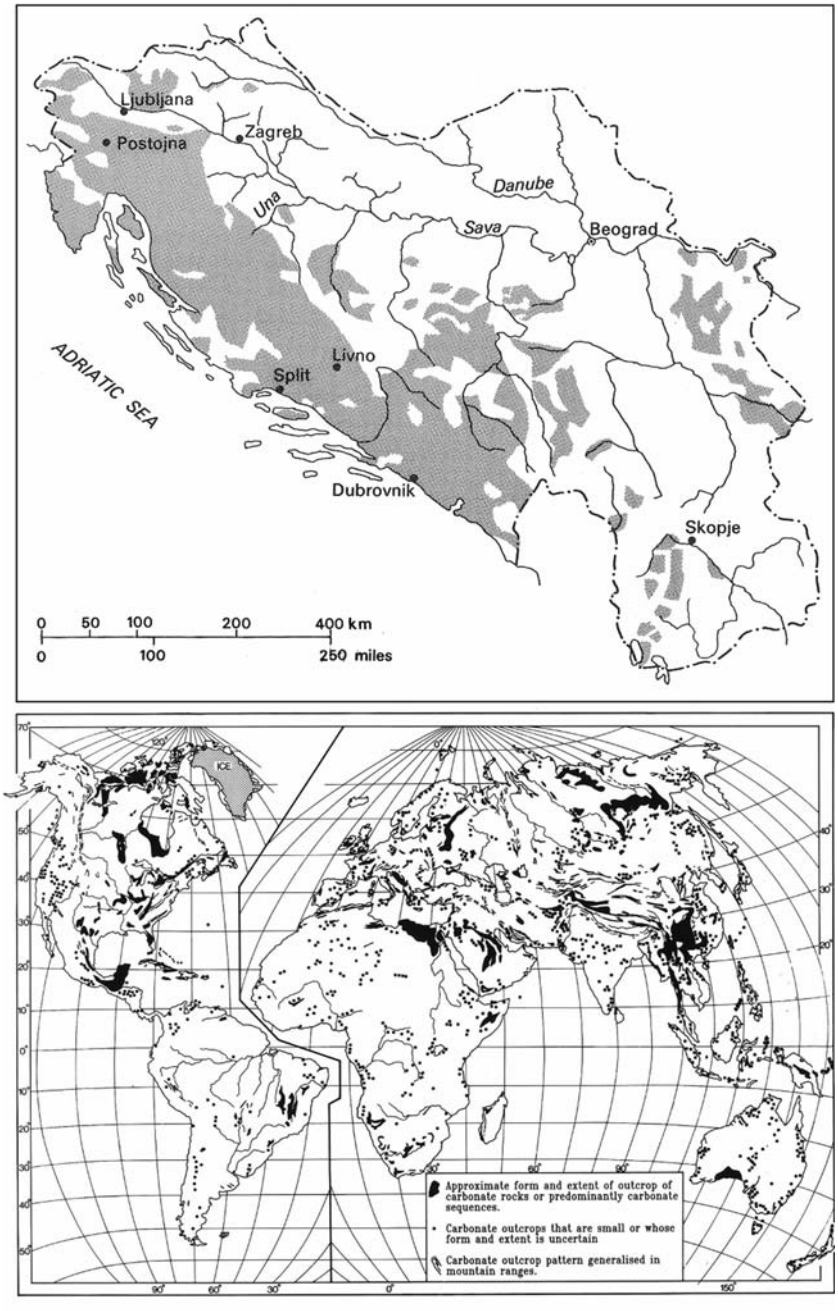

Fig. 1 The geographical range of the concept of karst: the distribution of limestone and dolomite in outcrop in the Dinaric Karst compared to the global picture. Maps from Sweeting (1972) and Ford and Williams (1989)

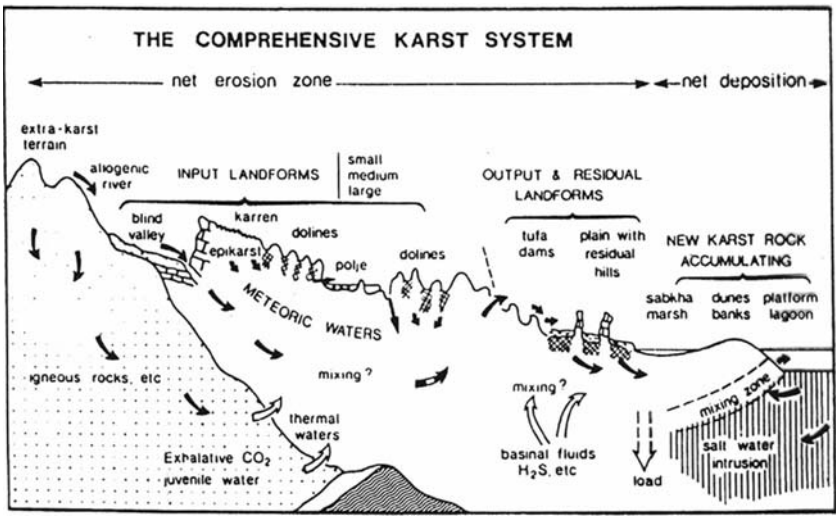

Fig. 2 The comprehensive karst system. Jovan Cvijić considered the input landforms, the circulation of meteoric waters beneath them, and the eroding Adriatic coast. "Karst" has a much wider connotation in science and engineering today

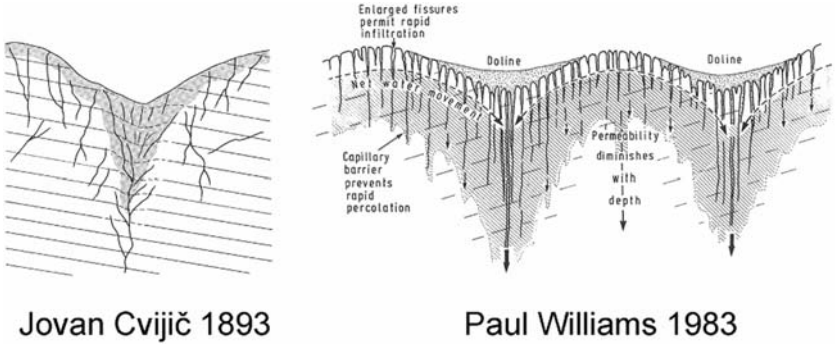

Fig. 3 Jovan Cvijić (1893) conception of the form of a dissolutional doline compared with Paul Williams' (1983) model showing the relationship of doline and epikarst. Cvijić diagram is based upon a cross-section exposed in a railway cutting near Lõgatec, Slovenia. I believe that Cvijić would approve of Williams elaboration

Cvijić also gave clear definitions and descriptions of alluvial dolines (closed depressions formed in unconsolidated sediments by piping of detritus into underlying kluftkarren or similar karst voids–now termed "suffosion dolines"), snow dolines in the Alps, true collapse dolines ("einsturzdolinen"), and compound dolines or "uvalas". His subclassifications of "jamas", (depressions which open into underground spaces), are less clear. He considers "avens" that appear to terminate in small, shallow voids to differ from "Trebič-type" depressions that end in solutional conduits descending into caves of explorable sizes. Genetically, there is probably no difference between them in origin, and it is not clear how they differ from his earlier class of well-shaped dolines. He also describes karst windows, which are collapses that expose open cave passages, often with streams flowing across the floors.

A very significant part of this section of *Das Karstphänomen* is a powerful refutation of the notion that many or all of the normal bowl and funnel dolines are degraded remnants of einsturzdolinen, i.e., products of mechanical collapse upwards from a cave below rather than of dissolution focused downwards from the surface. The collapse origin of dolines had been a major contention of many earlier workers. The importance of Cvijić's (1893) demonstration of the predominance of dissolution may be likened to that in astronomy a few years later, when G.K. Gilbert showed that the craters of the Moon must be caused by meteorite impacts rather than by volcanic explosions from internal sources. Here Cvijić conclusively established the quantitative importance of dissolution in karst landscapes.

Turning his attention to the distribution of dolines within a given area, Cvijić used potent but qualitative expressions such as "wannenlandschaft" (pitted landscapes) or the more colourful "blättersteppige" (blistered relief) but did not take the next step and demonstrate that their individual catchment basins often interlock with the consequence that they occupy all of a surface, a condition now termed "polygonal karst" (Williams 1993). He did, however, report that approximately 60% of the total area of Montenegro lies within the rims of dolines, a statistic that always impresses general audiences! He also suggested that the climatic contrasts between the summer-dry Dinaric karst and wet-all-year Moravia explained the sharper morphology

of the Dinaric dolines, but now it is understood that lithologic and structural differences, coupled with Tertiary blanket sand fillings in Moravia (Musil 1993), are the principal controls. Although he considered the idea that the Mediterranean climate might support some distinctive type of karst, Cvijić never went to the extremes of the climamorphic school of karst geomorphology that flourished in Europe during the two or three decades after his death; he understood the competing effects of geological variables too well.

As a footnote here, readers may be amused to learn that Jovan Cvijić's declaration that the doline is the diagnostic karst feature can have unexpected consequences. In environmental lawsuits in the United States today if, for example, a petrol station standing on a half hectare of land underlain by limestone is accused of contamination of nearby karst springs because of a leaking gasoline tank, the indignant defense may be that "there is no doline on the property; therefore, the station is not located on karst and cannot be responsible for the pollution"!

Jovan Cvijić, poljes, karst groundwater and cycles of erosion

In his publications of 1893 and 1901 Cvijić gives very thorough descriptions of the geomorphology and seasonal hydrology of a majority of the great Dinaric poljes. Guided by his studies with Albrecht Penck, he recognized that in many of them the form and history of development have been affected by the considerable deposits of alluvium and colluvium that were swept in during cold phases of the Alpine ice ages. However, he considered that the fundamental controls were tectonic, the products of tilting or foundering of great blocks segregated by faults. This is generally accepted for the Dinaric poljes today.

The most important outcome of his polje studies, in this author's opinion, was the appreciation of the highly variable nature of most karst aquifers that investigations of their hydrology gave him. He recognised that this must be due to the existence of organised networks of dissolution conduits within them. Some poljes at higher elevations never flooded, although they could swallow substantial rivers at individual ponors in their floors; to discharge them large pipes must be passing through the rock. Elsewhere, seasonal lakes might accumulate at different elevations in adjoining poljes and smaller basins, indicating that there could be rapid oscillations of level in any water table. Estavelles (ponors that function either as sinks or as springs, depending on the hydrologic conditions) were also common. Any permanent lakes were usually perched on impermeable alluvium or clastic rocks. In his 1918 paper, Cvijić observed that karst groundwater divides often did not match surface topographic divides. There were few cave rivers that were not interrupted by siphons. He reported on fresh water springs that were known to depths as great as 130 m below sea level along the Adriatic coast, arguing that this was strong evidence that in any given region most karst flow must be converging into just a few master conduits; this is now known to be correct, although the complementary role of Quaternary sea level variation in drowning coastal springs was not fully appreciated in 1918.

These studies led Cvijić first to support an early karst water model by Katzer (1909), whose diagrams picture the underground as a multi-level collection of solutional conduits able to discharge all of the groundwater being supplied to them. The alternative proposal at that time was by Grund (1903) whose model is close to that for a standard granular aquifer, showing stagnant water below a seasonal surcharge of floodwater that is slowly drained.

Cvijić (1918) begins his own theoretical enlargement of Katzer's ideas by imagining the situation where the limestone extends far below an adjoining ocean. The regional base level of erosion then must be determined by hydraulic gradients projected inland from sea level. Clearly, this is appropriate to the Dinaric setting. However, he did not pursue it further but instead drew the more deterministic karst hydrologic evolutionary model that is shown in Fig. 4. In this he seeks to integrate the hydrologic ideas with his conception of a karst cycle of erosion. The karst rocks, A, rest on an impervious base, B, that is above the general base level of the region (e.g., above sea level if close to the coast). The line, a–b, marks the lower limit of effective groundwater circulation at the beginning of karst dissolution, i.e., the water will discharge as springs into a valley, v, that conveys an allogenic river, or into the flat-floored depression to the left of it which may be taken to be a tectonic depression that is a potential polje. As time elapses, I and II, fluvial entrenchment of the valley stimulates the conduit network to both enlarge and to extend deeper, creating a permanent vadose zone (1), a seasonal flood zone (2) and a basal phreatic zone (3). In III and IV the karst rock is progressively reduced to outliers on plains forming on the impervious base.

Figure 5 shows the more sophisticated 3D attempt Cvijić then made to display his conception of the sequence of surface morphology that might accompany such hydrologic development. The initial geologic structure is more complex than in Fig. 4 (and more realistic for the Dinarides) because of the folding and inclusion of a graben to serve as a proto-polje. The notion of a landform cycle that may repeat itself is suggested by the presence of a lower limestone that may become karstified in turn when the intervening impermeable stratum is dissected and stripped away. An

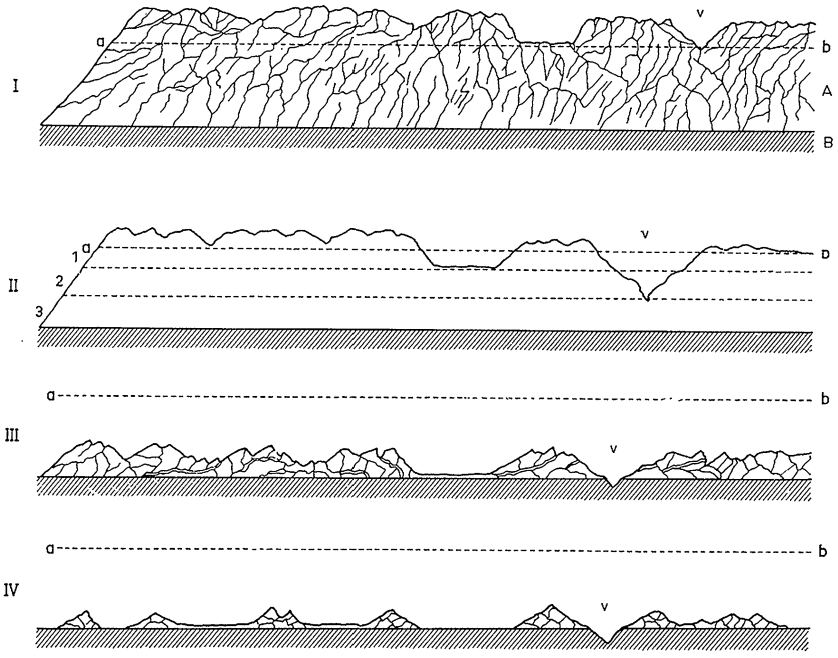

Fig. 4 The evolution of groundwater circulation and the development of karst relief; the model of Cvijić (1918) adapted by Roglič (1972)

important feature of this picture is the insight given into Cvijić's ideas on the initiation and spread of dolines. They appear first on the interfluves, draining into local valleys that retain surface stream channels in the limestone because the underlying solutional porosity is not yet sufficient to absorb all of the water. Progressively, dolines increase in number. Some develop in the floors of the higher valleys, converting them into one of the dry valley types defined in *Das Karstphänomen*. Others enlarge laterally to become uvalas. The sequence ends with a few residual karst hills on the divides of a fluvial landscape incised into the impermeable rocks below.

Cvijić's model in Fig. 5 has many problems. It is not readily apparent how the initial valley pattern has been incised from previous cover strata, or why the apparent allogenic valley loses its water without showing dolines, or why a limestone gorge is erased. It is not clear how the polje base level is regulated. One senses that Cvijić did not really believe in this model. It does not have the intellectual completeness in sequence of form and evolution that is seen in a model of 1914 by Grund because the real Dinaric complexity of structure and lithology that Cvijić felt compelled to include in his thinking prohibited any such simple progression. He did not return to it in his late work. Cyclic modeling in karst studies then gave way for many years to climate-control geomorphology, as noted. Recently, cyclic conceptions are returning, however. For comparison, Fig. 5 also displays Zhu's (1988) model of the possible evolution of landforms in the great karstland around Guilin (Guangxi, China). The limestone there is up to 4,000 m in thickness, while the karst topography within it has local relief of 200–500 m. Zhu is able to model without including any impermeable basal stratum, and derives dry valleys, polygonal karst, marginal poljes and more extensive lowland corrosion surfaces, without emplacing any special tectonic features such as graben. More recently Ahnert and Williams (1997) have further simplified the settings, developing computer models that begin with undeformed karst surfaces that have many points of converging or diverging flow upon them. After the passage of a number of time steps, these models reproduce forms similar to Grund's conceptual doline and cockpit models.

In this author's opinion, Cvijić understanding of karst hydrology in fractured limestones was fundamentally correct. It allowed for the possibility that there can be initial fluvial erosion on limestone before the aquifer is sufficiently opened by dissolution to swallow all precipitation and runoff. It recognized zonal organization within the developing aquifer, and that zones may be lowered subsequently in a stepwise manner. Recently, similar but more detailed concepts have been published by Audra (1994) (see also Klimchouk et. al. 2000; Palmer and Audra 2004) based on his careful study of examples of the many new cave systems discovered in the Alps during the past 50 years. Cvijić's views rested on a strong empirical base, his immense experience of hydrologic behaviour in the Dinaric Karst. It is this empirical foundation that has placed Dinaric hydrologists and engineers in the forefront of design and groundwater management for many years now (e.g., Milanović 1981, 2000; Mijatović 1984; Bonacci 1987). European readers may be surprised to learn that many

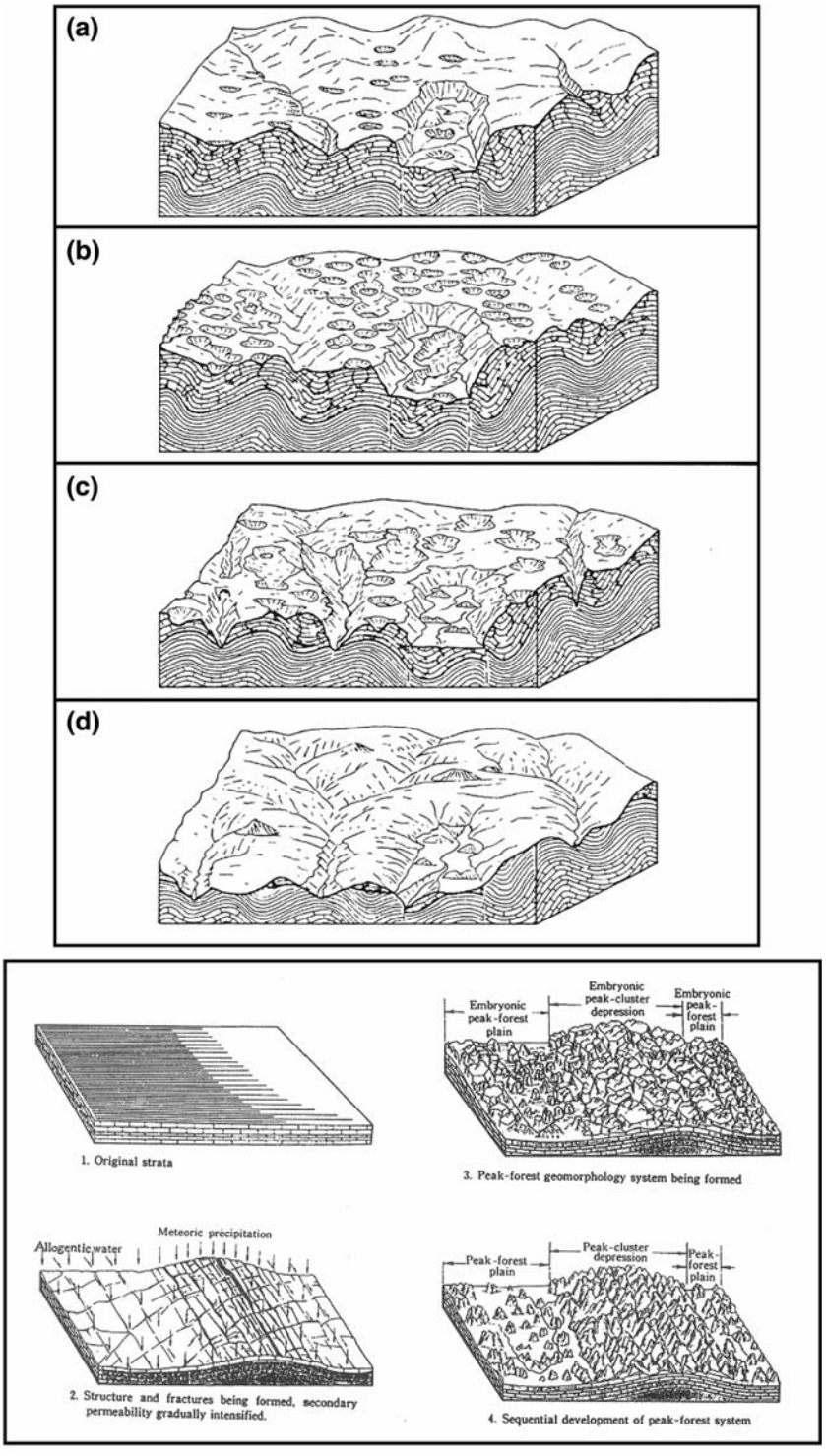

Fig. 5 *Upper frames*. Jovan Cvijić (1918) model of the cycle of erosion in a karst terrain, *Lower frame*. A model by Zhu (1988) for the development of karst landforms in the Guilin region, Guangxi, China

practitioners in North America and elsewhere have yet to understand the reality that there is always solutional conduit development beneath a karst landscape. For example, they may contemplate an example of Cvijić's bowl-shaped dolines in the Kentucky karst that is as much as 100 m in diameter, and believe that the runoff focused into its bottom will then diffuse into the limestone matrix at flow rates calculated from their laboratory measurements of the hydraulic conductivity of hand specimens of the limestone!

Is the Karst good karst?

Jovan Cvijić made major contributions to geomorphology and hydrology through his studies in the Dinaric Karst that began more than one hundred years ago. Historians of these sciences consider that it was "*Das Karstphänomen*" (1893), which confirmed that there existed landscapes of dissolutional origin that were truly distinct from the fluvial landscapes of neighbouring regions. These landscapes and processes thus came to be named "karstic" in recognition of the home of their study in the West. It is ironic, therefore, that the Dinaric Karst appears to specialists today to be a rather poor type area in which to investigate the development of dissolutional landforms, caves and aquifers on soluble rocks. This is because its geological structure is much too complicated for general evolutionary modeling purposes (Ford 2002). Plate tectonic compression with deformation and differential uplift has created staircase sequences of topographically closed basins rising from the Adriatic coast. Many basins host poljes that, because of their magnitude, dominate the karst morphology and hydrology. Karst scientists know now (as Cvijić could not) that nowhere else in the world is there such a pattern of large, complexly linked, tectonic poljes; they are magnificent—but atypical. Around Postojna at least, it is now being suggested that the older cave systems themselves are being torn apart by strike-slip fault movements (Šušteršič 2000). To these complexities should be added the regional impact of the Messinian Crisis (when the Mediterranean dried up for one half million years during the Pliocene), of the smaller sea level oscillations of the Quaternary, and of fluvial, glacial or periglacial injection of clastic debris from adjoining flysch terrains. The intellectual history of the subject might have been quite different if Albrecht Penck had found a travel scholarship to send Jovan Cvijić to study the much more simple low plateaus and karst plains of Indiana, Kentucky and Tennessee!

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