DEEP KARST CONDUITS, FLOODING, AND SINKHOLES: LESSONS FOR THE AGGREGATES INDUSTRY

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ABSTRACT

Limestone aggregate quarries in deeply penetrating karst terrain often are at considerable risk of artesian inflow from groundwater or surface water channeled through the karstic aquifer. The inflow occurs through what are likely to be complex conduits which penetrate hundreds of feet into bedrock. Rates of inflow can exceed the operation's pumping capabilities proving uneconomic to manage over the long term. Over time, inflow rates can increase dramatically as turbulent flow through the conduit erodes its soft residual clay-rich fill. One recent investigation observed an inflow rate of more than 40,000 gpm from a surface water source. Flood water persistently laden with sediment is an indicator of conduit washout and implies increasing inflow rates over time.

Conduits carrying flood water can exist in a variety of forms: along deeply penetrating geologic faults, joints, or following the path of preferentially eroded bedding. Preferential structural deformation along faults or bedding can enhance dissolution during subsequent interaction with groundwater. The resulting conduit may be a complex combination of many geological features, making the exploration and remediation of the pathway difficult.

Sinkholes at the site can occur within several contexts. Pre-existing subsidence structures can re-activate and subside further, forming new collapse sinkholes within soil directly overlying the conduit. Cover-collapse sinkhole development can be a direct result of increasing downward groundwater velocities and subsurface erosion associated with enlargement of a conduit. Normal operation events such as a quarry blast can also provide a significant new linkage between the groundwater and the quarry, allowing rapid drainage of the groundwater reservoir. With such drainage and erosion of karst-fill, sinkholes will develop over localized water table depressions, most significantly over enhanced permeability zones associated with fractures. Paradoxically, although the rise in quarry water level will lead to regional reduction in the hydraulic gradients, on local scales, drainage of the groundwater reservoir increases gradients and leads to the development of cover collapse sinkholes.

Recommended methods for preliminary site investigation can include a detailed review of geological literature and drilling logs to compile a conceptual model of the site. A fracture trace analysis with EM geophysics can confirm the locations of major faults and fractures. Fingerprinting of the various water sources to the quarry and the water in the quarry is an inexpensive and effective means of identifying the source and likely direction of the groundwater and surface water flow. Automated geophysical equipment on the market for performing rapid resistivity and microgravity surveys speeds up the site screening process during reconnaissance exploration for deep structure. It is recommended that mine planning fully incorporate this information, so that quarry operators can take proactive measures to avoid catastrophic and costly flooding events.

INTRODUCTION

In the USA, quarrying of limestone aggregate constitutes a sizable chunk of the $7 billion per year aggregates industry. Due to the nature of its target resource, the mining of limestone and dolomite is guaranteed to encounter solution features in rock on some scale at all locations. These features may range from micro-scale stylolitic seams of little economic relevance to groundwater-filled cavern systems with the potential to shut down operations and threaten the extraction of tens of millions of dollars of valuable resource. While blasting and groundwater management associated with mining may appear to cause sudden and catastrophic development of sinkholes and other karstic features, in all cases, it is the karst and its underlying geologic / hydrogeologic foundation which came first. Mining, groundwater extraction, and other activities associated with quarrying merely serve to enhance these features and/or encourage their expression at the surface or in the pit.

Experience has shown that karst is unavoidable in limestone terrains, and that remediation of karstic zones is extremely expensive. As a result, the most cost-effective way to approach this issue is through integration of mine planning with an evolving understanding of local geologic, hydrologic, and hydrogeologic conditions. Traditional practices such as abandonment of flooded pits for new, adjacent pits may only provide short term gains if such factors are not considered. In this paper, we will present some lessons we believe are relevant to the aggregates industry. We base these upon our own experiences, investigating, monitoring, and observing remediation of karst-related groundwater problems in Paleozoic carbonate in the mid-Atlantic Appalachian region. We believe these lessons are applicable to most other areas of the world where aggregate mines penetrate karst bedrock.

NATURE OF THE PROBLEM

Water / karst management problems associated with aggregate mining fall into two categories: 1) those that impact the surrounding areas, e.g. development of induced sinkholes on neighboring properties, and 2) those that directly influence management of the pit, e.g. increased inflow or flooding. While both types may occur catastrophically, they are often managed as independent concerns, rather than related phenomena. Our experience has shown that catastrophic quarry flooding frequently poses a risk of induced sinkhole development. And, while sinkholes themselves might not signal the onset of quarry flooding, their formation may indicate the presence of conditions appropriate for flooding to occur.

What unifies these on-site and off-site features is their origin by erosion of pre-existing karst-fill sediment. Karstic voids in the mid-Atlantic region are commonly filled with reddish-brown clayey residual sediments similar to characteristic karst residual soils (Nutter, 1973; Braker, 1981; White, 1988). Sinkholes that develop rapidly in these areas are due to cover collapse in response to direct erosion or piping of residual soils and void-filling sediments (e.g. Boyer, 1997). Somewhat slower-growing cover-subsidence types are also possible (White, 1988). Similarly, catastrophic flooding of quarries from surface water bodies has been observed to result primarily from sediment removal in response to 1) a lowered water table, and 2) erosion by subsurface turbulent flow. While blasting-induced fracturing, or aperture widening may play a role in initiating flooding events, we have repeatedly observed a correlation between increased inflow volume and suspended sediment, clearly demonstrating a relationship between erosion of sedimentary fill and development of significant karstic "conduits."

Cambro-Ordovician carbonates of the mid-Atlantic region that are widely quarried include limestones and dolomites of the Tomstown Dolomite, Stonehenge Limestone, Conococheague Limestone, Grove Formation and correlative units. All of these units are characterized by an intercalation of limestone and dolomite. Significant siliceous layers are present both as intercalated beds and as adjacent map units. Boyer (1997) and Nutter (1973) have both presented evidence that the presence of siliceous sediments adjacent to a carbonate sequence may enhance karstification by producing pore waters unbuffered by dissolved carbonate. Our investigations have also shown that physical rather than chemical properties of some carbonates can control karstification. Within open- to tightly-folded units, boring logs show a tendency for karst zones (fractured rock, voids, and areas of zones of lost circulation) to develop not within specific beds, but at the contacts between them (Fig. 1). We interpret this to result from the competency contrast between limestones and dolomites and the resulting structural disruption during folding. Subsequent dissolution has preferentially enlarged these sheared and disturbed horizons.

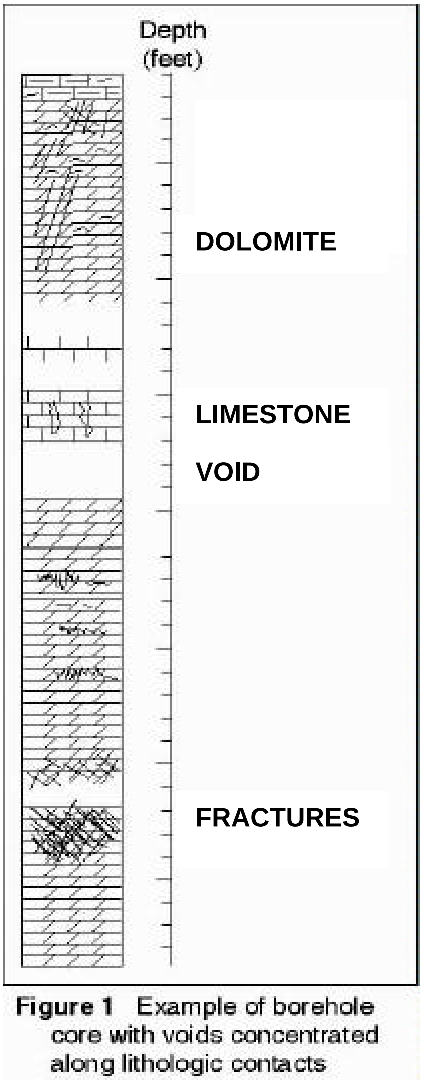

Figure 1 Example of borehole core with voids concentrated along lithologic contacts

SITE EXPERIENCES

During our experience with the aggregates industry, we have investigated karst and collapse sinkholes at quarries in Paleozoic dolomitic limestone which have experienced flooding following a routine blasting event. In one example, flood waters entered through the floor of the quarry from a source that was initially unknown, but later determined to be a conduit connecting the quarry with a karst cavern network outside the pit and extending to a nearby river. Immediately following the blasting event, inflow originated from the dewatering of the karst aquifer, at a rate of about 15,000 gpm. The inflow carried with it eroded karst-fill from the cavern network and the sediment was deposited onto the quarry floor. Over a period of several weeks the inflow was observed to decrease corresponding to the rapid decline of the water table within the karst aquifer. Large areas of the limestone aquifer contained little or no karst and in these areas the water was unaffected by the inflow from karst. A water storage basin located between the quarry and river received pumpage from the flooding quarry and was observed to drain rapidly into a new sinkhole. This drainage may have led to further erosion of the interconnected subsurface voids, enlarging the continuous connection between the river and the pit, which we call the "conduit." Subsequent river inflow to the pit further eroded fill material from the conduit and the rate of inflow was observed to increase over the next several months to over 40,000 gpm.

CONCEPTUAL MODEL DEVELOPMENT

Figure 2 is a schematic depiction of a generic quarry site which is experiencing groundwater seepage, cover- collapse sinkholes, and is at risk of flooding due to interaction of hydrologic conditions and its karstic limestone. The site geology is typical of the Mid-Atlantic Appalachians. The unit being mined is dolomitic limestone, which is folded into a syncline - anticline pair that plunges gently to the north. The quarry is incised into the folded limestone to well below the water table. The water table is located about 50 feet from the ground surface. A major river (3,000 cfs average flow) flows past the quarry, several thousand feet from the pit. A perennial creek flows to the river and passes close to the quarry.

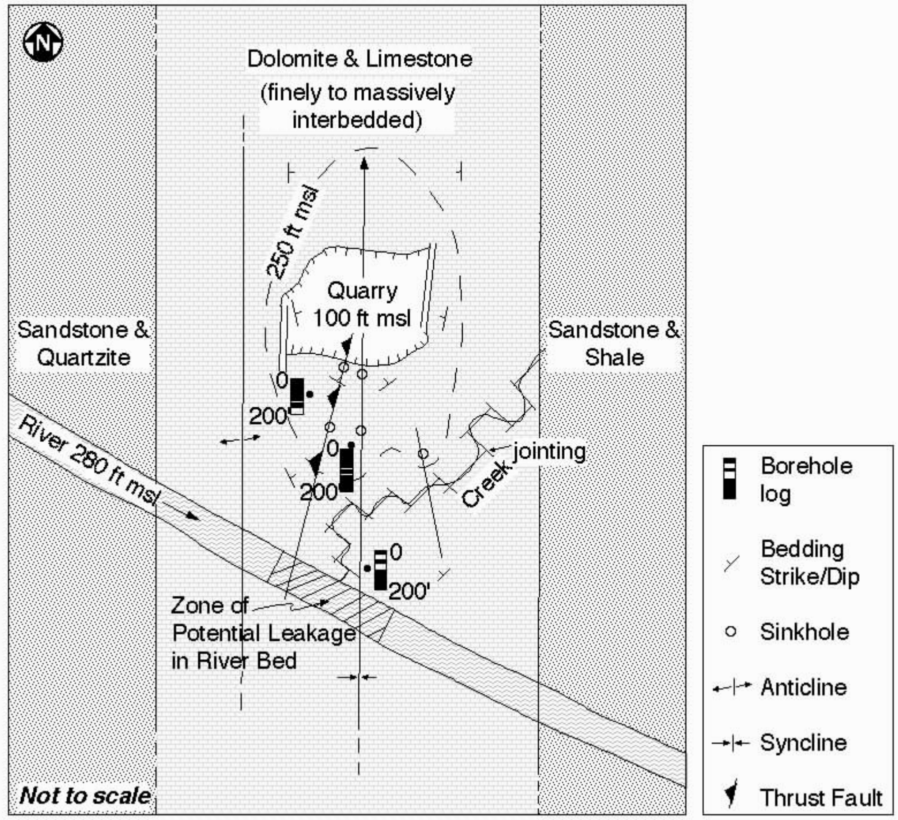

Figure 2 Schematic Map of Generic Quarry Site

The site geologic map shows the axis of the syncline passing through the quarry and extending beyond the river. A minor thrust fault passes from beneath the river and through the south wall of the quarry. A pervasive fracture system is also present. The creek on the property approximately follows the path of the fracture system. Borehole records reveal karst voids in the limestone concentrated in a stratigraphic unit containing interbedded limestone and dolomite. This unit, found close to ground surface near the river, plunges toward the base of the quarry. A water table depression around the quarry is elongated in the direction of enhanced permeability, or along geologic strike of the bedrock. The water table is depressed locally, at the single fracture, and at the reverse fault. Collapse sinkholes have formed since the start of groundwater seepage, at locations over the syncline axis, over the fault, and over the single fracture.

The sinkholes have formed where a specific set of conditions exist. Given that most sinkholes develop by collapse of superficial soil, or "cover", into pre-existing voids, activities that reduce the support of such cover materials are likely to promote collapse. For example, seepage of groundwater to a quarry lowers the water table to below the upper elevation of the caverns, causing washout of soft cavern-fill material. Surface water then drains through fissures in soil into the caverns and triggers erosion of a soil cavity over the cavern. The soil cavity grows upward, weakening the support of the shallow ground, which in turn suddenly collapses into the cavity. Figures 3a and 3b show schematically the development of soil cavities and sinkholes. Usually the surface water and entrained soil continue to drain into the collapse sinkhole, causing it to grow in both diameter and depth. Similarly, if the water table is suddenly lowered, for example by excavating into a karst area, groundwater cascades rapidly through the caverns, eroding the soft fill and opening up the caverns to surface water. The collapse sinkholes form within several days of the erosion of the karst fill. Installation and operation of dewatering wells to draw down the groundwater table around a quarry could have a similar impact on the development of sinkholes.

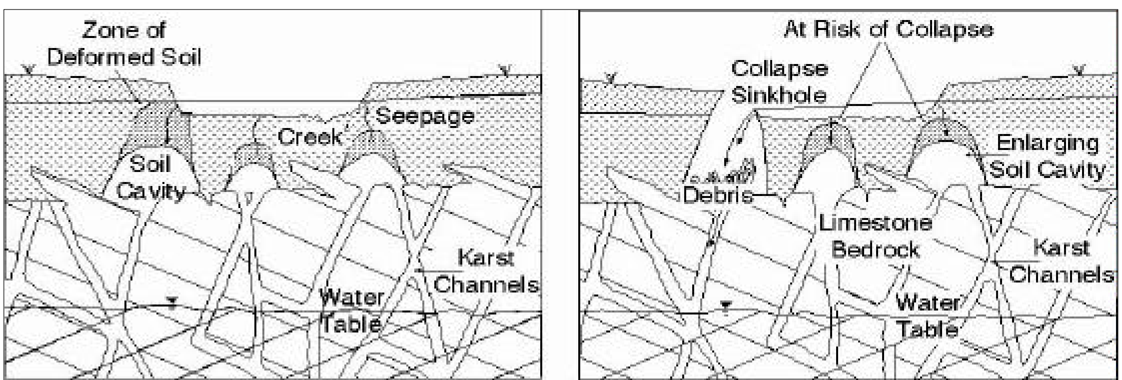

Figure 3a Development of Soil Cavities in Karst Limestone

Figure 3b Soil Collapse Sinkhole

The property in Figure 2 is at risk of flooding and development of additional induced sinkholes. Potential pathways that could develop into "conduits" include the reverse fault, the interconnected joints and the interbedded stratigraphic interval. Catastrophic discharge from the karst aquifer to the quarry will lower the water table, and extend the depression in the water table south towards the river. Seepage losses from the creek will continue to erode the soft-fill from the karst in this direction, leading to the development of additional sinkholes. Initially, clayey fill within the karst caverns forms a relatively impermeable barrier between the river and the quarry. However as more of the fill is eroded and as the zone of open karst enlarges in the direction of the river, the river may begin seeping directly to the quarry. The pathway for this seepage may lie along the north-south oriented jointing system within the limestone. Our experience suggests that the bed of the river directly overlying the eroded karst will eventually collapse over the conduit (shown in Figure 2 as a wide zone across the intersection of river and geologic structure.) The rate of inflow to the quarry will increase steadily over time as the permeability of the karst increases by erosion of fill material. This scenario assumes a constant gradient across conduit while the quarry tries to maintain their dewatering effort.

REMEDIATION – A VIABLE ALTERNATIVE?

Figure 4 is a generalized example of the costs of grouting remediation versus the resultant flow reduction that might be expected for a difficult inflow remediation problem. The creation of permanent barriers by attempting to construct grout curtains across the conduit, has proven to be a technically challenging problem. Our observations of grouting remediation projects found them to be trying for both the site owner, and the engineering firm implementing the remedy. The primary challenges lie in the erodeability of the soft sediment which remains in the cavern during the placement of a grout plug. During remediation, the plug material (e.g., roofing tar or cement grout) conforms to the surfaces of the fill material in the cavern, temporarily stopping the flow. Fissures immediately form in the soft sediment against the grout curtain. Water flowing through the fissure erodes the soft sediment leaving the plug suspended in sediment and useless. Attempts at forcing grouts (cement-type suspension grouts) into these fissures prior to placing the plug material into the flow conduit are only occasionally successful.

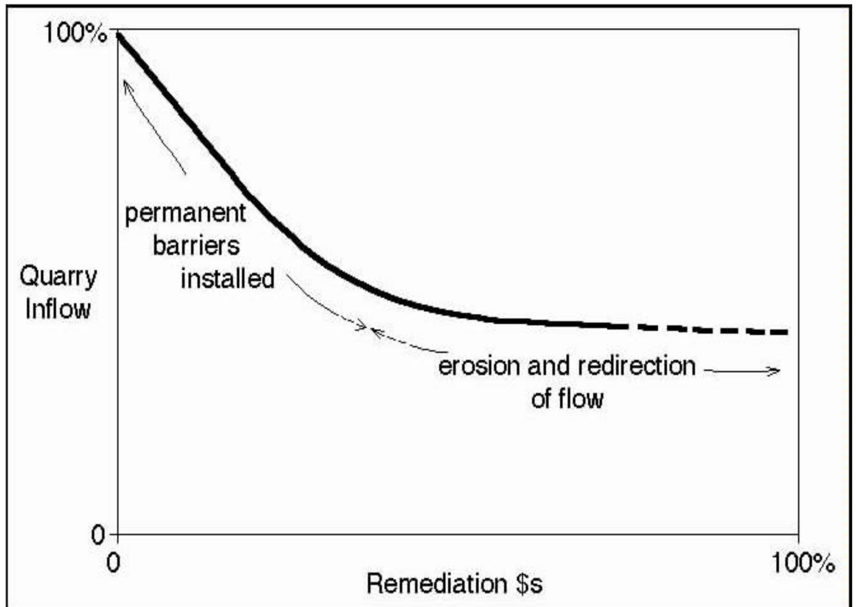

Figure 4 Remediation Cost vs. Quarry Inflow

Psychologically, the lure of grouting success is very powerful. Temporary successes, when achieved, promise the possibility of finally sealing the conduit. Presuming that the sediment erosion problem can be eliminated, the grouting time, materials, and costs mount. The length of time required for a full-fledged grouting program to stop flooding can last months (small voids) to years (massive caverns), and the costs can mount to $10 million or more during that period of time. If we calculate the cost of remediation of flooding inflows, based on several recent experiences, estimates would fall in the range of $500 / gallon per minute of inflow. When we think of flooding inflows on the order of 40,000 gpm, the costs prove to be staggering to an aggregate operation which markets its product at $7 / ton of material.

A PROACTIVE APPROACH TO MANAGING QUARRIES IN KARST LIMESTONE

The risk of ground failure and flooding can be managed using a mine expansion plan that incorporates knowledge of karst geology and hydrogeology. Features must be located which signal risk of ground failure and the potential for flooding. Such features may include existing sinkholes, surface water impoundments, creeks or streams flowing across the property, surface exposures of karst bedrock, and points of entry of large quantities of water into the soil or “swallow holes”. Published and unpublished geologic maps will yield information on geologic boundaries, lithology, and structure. Geologic records from existing borings, such as those used for mineral reserve delineation, can be examined to locate karst zones and the water table. Usually the mining of a property has obscured the original ground features. Therefore, historical aerial photographs of the property should be examined to identify linear features caused by differences in soil type, soil moisture content, surface drainage patterns, and distinct changes in vegetation types. The fracture trace analyses provide information regarding the general occurrence of fractures, which control the development of most solution cavities. The analyses can give sufficient information to locate focus areas for further investigation although it does not provide accurate locations of fractures in the field.

The existence of a fault or fracture network can be determined beneath thick soil cover using electromagnetic geophysical methods. These methods map changes in the ground conductivity as the geology varies. Traverses with the instruments are typically run across the linear feature, and in the areas where steeply dipping fractures occur, the overburden would increase in thickness, resulting in a higher conductivity. Detailed maps of these geologic features should be completed for use in mine expansion planning, and for more focussed geophysical prospecting of deep-lying karst, discussed below.

Geophysical logging of groundwater temperature and flow direction in boreholes has, in our experience, been successful at identifying a flow conduit between a creek or river and the quarry when the source of the floodwaters is surface water drainage to the conduit. Similarly, chemical fingerprinting methods using naturally occurring compounds (e.g., bicarbonate) and trace-level contaminants (e.g., pesticides) as tracers and/or stable isotopes of water can be invaluable in identifying the source of inflow. Water which is thermodynamically saturated with calcium carbonate would likely have its source in the local limestone aquifer. If undersaturated, the water may be seeping from a local creek or river. Pesticides are often found at trace levels in creek or river seepage, and their occurrence can indicate seepage inflow. It is best to calculate mole ratios of the pesticides and match the ratio to possible sources of inflow, due to the ubiquitous nature of pesticides in the environment.

Recent advances in resistivity geophysical equipment have also made possible the delineation of caverns to depths of several hundred feet in bedrock. Our experience with automated, high-resolution dipole-dipole resistivity surveys in karst showed the system to be rapidly deployed, highly reliable after a quality set-up, and able to survey 1,700 linear feet of terrain per day using 84 electrodes. During exploration surveys, electrodes are spaced at 20 feet. The line can be re-surveyed with electrodes at closer spacings to more accurately delineate karst features. A geophysical survey completed across the suspected pathways of a conduit at several locations can locate the pathway and map its trend. A survey should initially include areas of known subsurface conditions such as areas of massive bedrock, and a cavern associated with a collapse sinkhole, for calibration.

A drilling program can also be used to explore the resistivity anomalies, geologic faults, and fracture networks, for karst. Open, water-filled karst can indicate rapidly flowing groundwater that has eroded the sediment fill. These open flow zones can represent potential flooding conduits to the quarry in the future. Each borehole should be completed as an observation well. And routine monitoring of the water table in the karst should be conducted. This ambient water table condition is compared to the condition during inflow. The water table within an inflow conduit will be lower in elevation than the surrounding aquifer. This observation is a proven method of focussing a remedial action on the source of the problem. Measuring water temperature in the borehole within the zone of karst can be useful to corroborate the water table information on the pathway of seepage inflow. Periodically updated water table maps, used in combination with top of bedrock information, can be used very effectively to locate potential sinkhole collapses.

CONCLUSIONS: LESSONS FOR KARST MANAGEMENT ON MINE PROPERTIES

- Risk from flooding and collapse sinkholes at aggregate quarries can be managed with a mine planning process that includes detailed information on geology, hydrology, and hydrogeology.

- Blasting and groundwater extraction, in all cases, serve to reactivate and enhance karst, leading to sinkhole development and possible flooding.

- Sinkholes can form by any combination of processes that remove sediment and water from a pre-existing cavern and focus surface water into the soil. Managing quarries in karst terrain is optimized by locating the conditions leading to collapse and mitigating them, as feasible, prior to catastrophic failure.

- The cost of remediation of sinkholes and flooding inflows is staggering as compared to quarry revenues.

- Proper planning requires compilation of information on geology and hydrogeology, locations of mine water storage ponds, sinkholes, swallow holes, ground lineaments, shallow and deep karst, and the water table. The water table will require regular monitoring as an indicator of aquifer dewatering and as an indicator of areas of potential concern for collapse or failure.

REFERENCES

Braker, William L., 1981, Soil Survey of Centre County, Pennsylvania, U.S. Soil Conservation Service, Washington D.C., 162 p.

Boyer, Bruce, W., 1997, Sinkholes, soils, fractures, and drainage: Interstate 70 near Frederick, Maryland, Environmental and Engineering Geoscience, 3, 469-485.

Nutter, Larry J., 1973, Hydrogeology of the Carbonate Rocks, Frederick and Hagerstown Valleys Maryland, Maryland Geologic Survey Report of Investigations No. 19, 68 p.

White, William B., 1988, Geomorphology and Hydrology and Karst Terrains, Oxford University Press, New York, 464 p.