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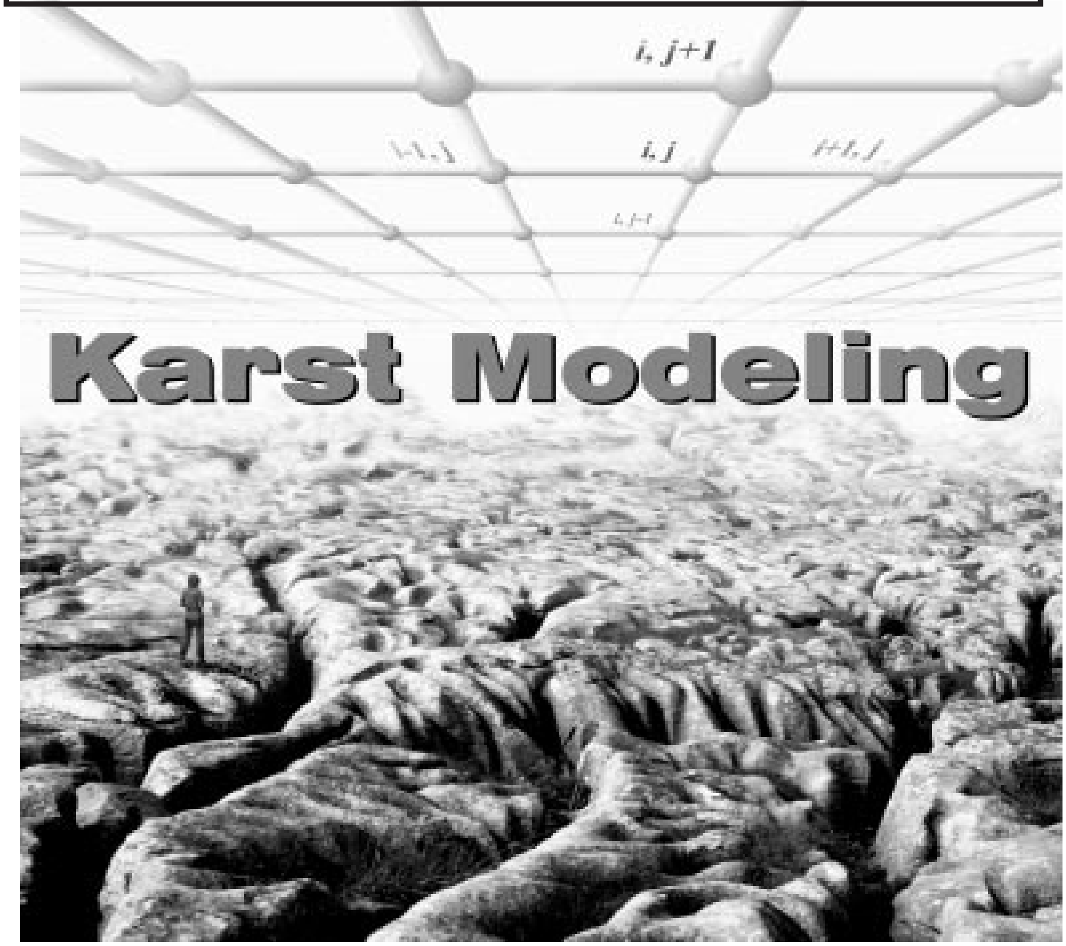

Karst Modeling

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STRUCTURAL EFFECTS ON CARBONATE AQUIFERS

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Abstract

Structural geology affects the behavior of karst aquifers by controlling the overall placement and orientation of the limestone and through fractures. The placement and orientation affect the position of recharge and discharge boundaries to the system, while the fractures serve as pathways for water movement. When creating a conceptual or numerical model of a karst site, it is useful and cost-efficient to consider all of these effects, as well as the geologic and geomorphic history of the area. By understanding structural controls on the genesis of the aquifer, predictions can be made regarding current-day behavior in terms of heterogeneity and anisotropy of flow. Because conduits and fissures mainly form along structurally created discontinuities, structural data can be very useful for understanding aquifer behavior, and determining specific high-conductivity flowpaths.

Introduction

The structural geology of an area plays two crucial roles in defining the behavior of a groundwater flow system in karst terrane. First, it establishes general flow directions in the aquifer, and second, it serves as a template for development of specific flowpaths (routes of high hydraulic conductivity). Understanding these structural controls for a given site is an important early step in the construction of a conceptual model. Furthermore, it may give direct insight regarding position and orientation of high-conductivity features such as caves, fissures, etc. Identifying such features is commonly a significant goal within a site investigation.

The broadest structural control is the placement of the rocks in certain orientation and positions by folding, faulting, erosion, etc. When taken in consideration with topography, this establishes the input, output, and no-flow boundaries to the system. Hence, this determines the general direction of flow in the aquifer. The second control is exerted by discontinuities (fractures) present in the rock mass. These include joints, bedding planes, and faults. The position, orientation, and aperture of these features, taken together with the input and output boundary positions, strongly controls the way the system will behave. Both of these controls are strong determinants of the form the aquifer will take as it evolves. In particular, they control the development of high-conductivity pathways (caves, conduits, fissures). A very compelling illustration of the importance of structural effects was developed by Palmer (1975), and is shown in Figure 1. As with most hydrogeologic investigations, geologists working in karst are handicapped by the fact that they are trying to “remotely” understand the aquifer. Only limited parts can be seen (either through wells, caves, springs, outcrops, etc.) and these parts may not be representative of the aquifer as a whole. What conclusions might

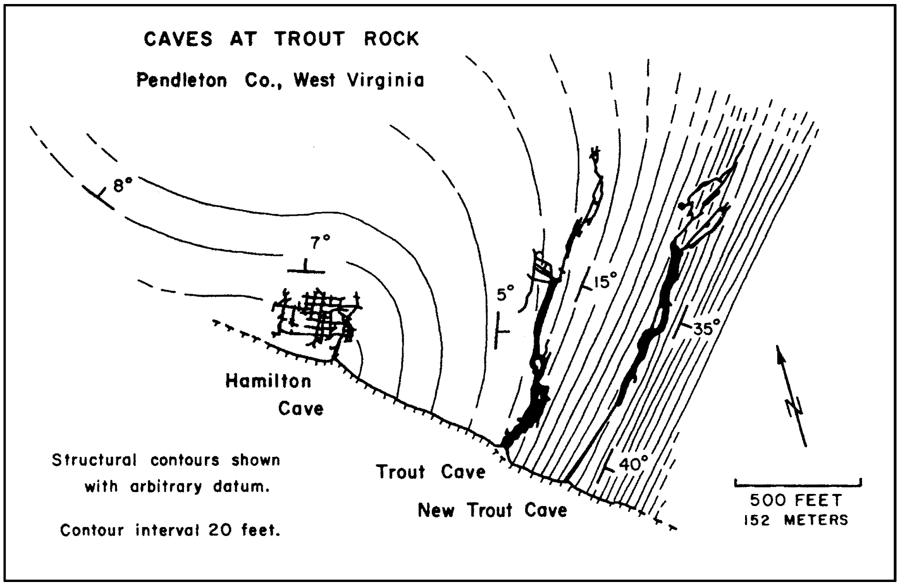

Figure 1: Illustration of one possible effect of structural controls on conduit porosity development. All three caves illustrated were developed simultaneously under similar boundary conditions. Differences in form may result from differences in rock orientation and fracturing. Note that where rocks are gently dipping towards the discharge boundary (southwest) a maze has formed, whereas in the rock steeply dipping normal to the boundary, a simple linear conduit has formed. From Palmer (1975).

a scientist have drawn in the area shown in Figure 1 if the caves had been intersected by boreholes, but had not been mapped? Maybe that there were disconnected voids of similar orientation. Or what if boreholes had not found the caves? Perhaps the assumption of isotropic fracture flow might have been made.

In many cases the approach left to the scientist or engineer is inference. Any tools that can guide that inference are a great aid, and should be used. For these reasons, it is recommended that any site investigation in limestone terrane include an evaluation of structural effects on the system. This has proven to be a successful and cost-effective step in various projects including water supply, contaminant transport, and sinkhole prediction. If a digital model of the site is required, this information will also help in deciding the appropriate code to employ. For the purposes of this paper, *structure* is taken in its broadest definition, including both classical structural features, as well as physical boundaries of the aquifer.

Genesis of carbonate aquifers

The history of an aquifer is a strong determinant of its present-day behavior. It is therefore useful to consider a generic conceptual model of carbonate-aquifer genesis, while recognizing that there will be departures from the model in a given setting. This model can serve as a basis for evaluating a given site by emphasizing the consideration of site-specific conditions.

In a limestone rock mass in a humid erosional setting (Figure 2A), initial boundaries are established by the topography. The stream defines local base level and the outputs to the system, while the uplands provide recharge points and input boundaries. In this state, one might envision a flow system approximating slow, Darcian conditions. The overall porosity is usually low in this initial state unless the rock is very young. Because of this, flow will tend to concentrate in the rock discontinuities (fractures). This focused flow results in the enlargement of certain of the discontinuities, a process that may become self-propagating as they grow larger, garnering more flow (Figure 2B). In turn, this leads to shifts in the aquifer boundary conditions.

Given the proper geochemistry, and extensive time periods (usually hundreds of thousands of years), the caves, sinkholes, and conduit-fed springs that characterize most karst areas will develop (Figure 2C). It is of particular interest to determine just which discontinuities are "chosen" for enlargement, and why, because this may allow prediction of preferred flowpaths in the aquifer. Several excellent references are available that cover the evolution of carbonate aquifers (Ford and Ewers, 1978; Ford and Williams, 1989;

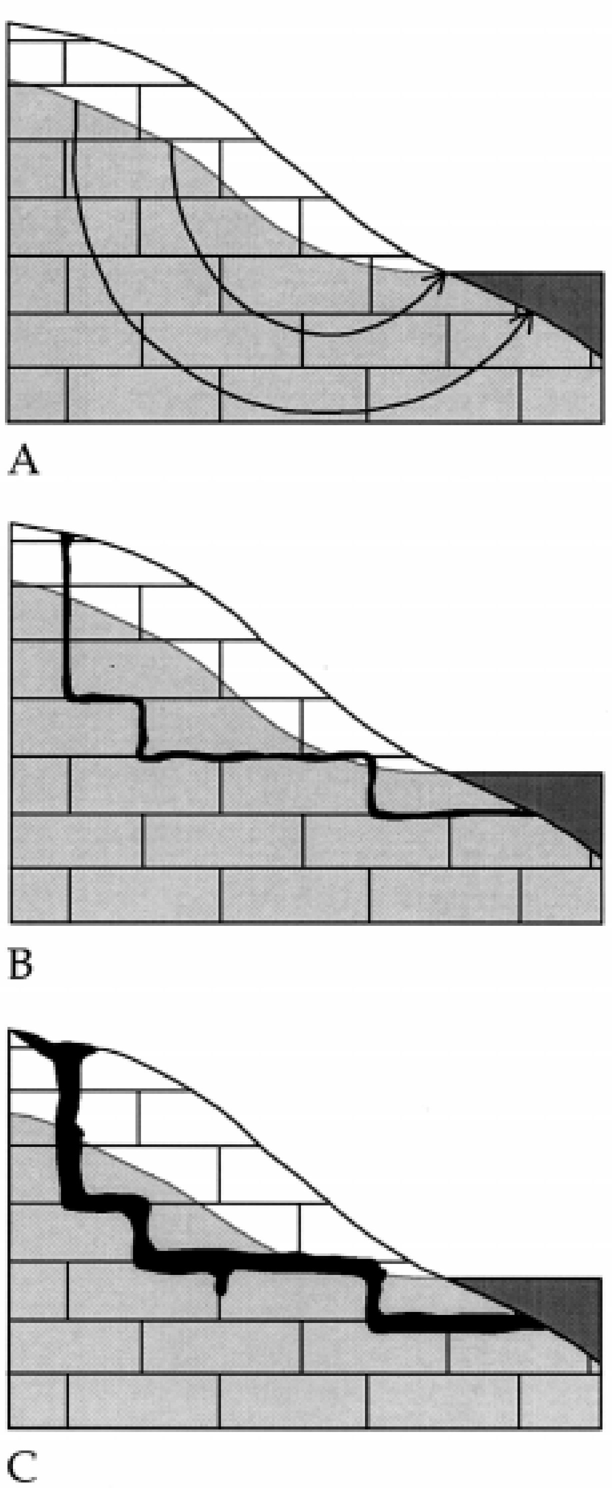

Figure 2: Hypothetical carbonate rock mass in initial, intermediate, and advanced stages of aquifer development. Arrows in Stage A show predicted flowlines for Darcian conditions. In Stage B a preferential flowpath has developed along structural discontinuities, focusing flow in this portion of the aquifer. In Stage C, extended growth of the path has captured most of the flow in the upper part of the aquifer, causing lowering of the water-filled zone.

Palmer, 1991; White, 1969; White, 1977; White, 1988). In addition, a number of works have been specifically concerned with which discontinuities are enlarged (Dreybrodt, 1992; Groves and Howard, 1994; Jameson, 1985)

Methods for gathering and using structural data in carbonate aquifers

Regional and local setting

At the beginning of a project, basic background information on the area should be collected. Frequently this will come from published literature and can include such structural elements as position and orientation of beds, fracture-set orientation, fault position, etc. Depending upon the needs of the project, new field data may be collected by traditional mapping methods (e.g. outcrop mapping of bedding contacts, faults, etc.), or by non-traditional methods (surface geophysics to locate the top of the bedrock, zones of fracture concentration, etc.).

Such information is essential for defining boundary conditions and evaluating geologic effects on aquifer development. This information will initially be evaluated by placing it on maps and cross-sections. In addition, regional information on tectonic and erosional history may also be important. Has the area undergone uplift? The rates may affect the development of porosity at different levels in the rock mass (Polyak et al., 1998; White and White, 1974). Have there been episodes of inundation with seawater? This could result in unique porosity development (Ewers et al., 1989; Michalski and Torlucci, 1988; Mylroie et al., 1995). Is the area on an escarpment or topographic margin? Stress-release fracturing may generate topographically oriented conduits (Sasowsky and White, 1994). Other settings will host different features that control porosity development, and every new area should be examined from this perspective.

Outcrop fracture studies

The statistical characterization of fracture direction and frequency is a well-established technique for evaluating aquifer anisotropy in insoluble rocks. The method relies upon measuring joint orientation along natural or artificial outcrops, with the data usually presented in rose diagrams. Preferred fracture directions may be considered to be preferential flow directions and used to construct an anisotropic hydraulic-conductivity ellipse.

In carbonate aquifers a similar technique can be used, but there is additional complexity. First, it has been shown that bedding planes, as opposed to joints, may be the most preferential flowpaths and loci for conduit growth (Jameson, 1985; Palmer, 1991). In a typical outcrop survey, these may be either unmeasured or undersampled. Second, joint aperture may be more important than the frequency at which jointing occurs. The conductivity of a joint increases as the cube of its aperture, making this a dominant control. It is very difficult to characterize joint aperture, though attempts have been made (Mace and Hovorka, in press). Nevertheless, outcrop data have been successfully used to provide information on preferential flow directions (Jancin and Ewart, 1995).

Borehole studies

While outcrops in the vicinity of a site provide general information on potentially conductive pathways, it is often desirable to gather data directly on-site. In some cases there may not even be exposed bedrock on site to allow outcrop measurement. The availability of inexpensive borehole video equipment now allows the gathering of such data, both in the vadose and phreatic zones. Open bedrock holes as small as 2 inches in diameter can be viewed, and, with an integral depth indicator, the position of fractures can be logged. The addition of a magnetic compass allows measurement of fracture orientation, and side-looking mirrors and lights actually allow viewing and photography of large-aperture fissures and conduits. It is common to be able to identify a single structural feature that is carrying the majority of flow by looking for the movement of fine sediments. Aquatic vertebrates (such as cave fish) or macro-invertebrates (such as springtails) may be occasionally observed, confirming to the most doubting scientist that one is indeed working in an aquifer where fissure/conduit flow is significant.

Incidentally, the importance of conductive fractures in boreholes is well known to well drillers working in limestone. They may drill far below the water table before producing significant water from the well, because productivity is frequently correlated to the interception of a single conductive fracture.

Integration of borehole structural information into models may require creativity. Although a great amount of information will be available at individual boreholes, data between them will be limited, and correlation may be difficult. Cross-well packer tests or other techniques may confirm connectivity but add expense. The identification of conductive features in a borehole is clearly useful in designing monitoring and remedial well completions. Appropriate zones can be packed off, thereby reducing the amount of water that must be purged or treated.

Mapping fracture traces

The mapping of fracture traces (also called lineaments, or photolinears) via aerial photography has emerged as a strategy for locating high-yielding water supply wells (Lattman and Parizek, 1964) with great success. Fracture traces are straight topographic, drainage, or tonal features, and are the surface representations of vertical fracture zones. By drilling into these features, a borehole has the double advantage of tapping an extensive vertical feature as well as all of the sub-horizontal openings that the fracture zone intercepts. Well yields have been statistically shown to be greatest when drilling at the intersection of two fracture traces, compared to one or none. These zones not only represent high-conductivity pathways within the aquifer; they also represent preferential zones of recharge to the aquifer. Injection wells drilled on such features are likely to have higher injection capacities.

These factors need to be taken in to account when, for example, anticipating subsidence due to pumping stress, input boundaries to digital models, or siting landfills. Application of the method has its pitfalls, and care needs to be taken when ground-truthing the mapped features. For example, old fence lines or roads typically make excellent photolinear features but have no significance to the underlying bedrock. A useful handbook on the method has been produced (Meiser & Earl Hydrogeologists, 1982).

A similar method involves measuring the orientation of sinkholes. The thought is that elongation of sinkholes will reflect a direction of preferential flow. Ogden, et al. (1989) found that the orientation of sinkholes also mimicked the orientation of cave passages (see also below).

Mapping caves

A cave represents either a past or present route of preferential flow in the aquifer. Former routes are dry, while the presently active ones are wet (at least seasonally). In both instances a map of the cave may provide useful information for modeling present-day behavior of the aquifer. If the cave is presently active, it will show the direction and velocity of water movement in the aquifer. If the active cave is perennially flooded, the mapping may be conducted by SCUBA divers, which is a difficult and dangerous task. If the cave is dry (no longer active), or seasonally dry, it may be mapped with a magnetic compass and fiberglass tape, plus the proper safety gear. Thousands of published maps are available in regional or local compilations. Many more have been produced but not issued as formal publications. Scientists are advised to contact local groups that are knowledgeable about a particular area.

Cave maps can serve many uses in an investigation, dependent upon what is being attempted. The concern of this paper is extracting structural information from cave maps. Remembering that caves usually form along preferential discontinuities in the rock (not along preferentially soluble beds), it is possible to extract information about unseen preferential flow paths by analyzing which paths the cave development has followed. The assumption can be made that unknown caves (or proto-caves) in the general region will follow a similar pattern. For example, Ogden, et al. (1989) accomplished this by measuring the orientation of segments of cave passage and using the statistical distribution of these directions to predict regional flow-direction preferences.

Conclusions

Structural geology controls the overall position and orientation of the limestone, as well as the fractures that develop in the rock and serve as pathways for water movement. Conduits within the aquifer develop by preferential dissolution along some of these structural elements. Using structural data from a variety of sources will aid in the development of conceptual or numerical models of aquifer behavior. The regional structural setting is responsible for setting aquifer input and output boundaries. Outcrop or borehole studies of fracture position, aperture, and frequency allow prediction of anisotropy in the rock mass. Mapping of fracture traces via aerial photography identifies inputs to a high-conductivity network within the rock mass and is useful for siting high-capacity water-supply wells. Mapping of caves provides detailed information regarding which structural pathways were (or are) most preferred for conducting flow in the aquifer.

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