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AQUIFER TYPES OF NORTH AMERICA

Part Two: Consolidated Aquifers

This is the second column outlining the aquifers of North America. The previous column included the unconsolidated or alluvial aquifers and this one focuses on the consolidated aquifers that are generally called bedrock aquifers.

This column is based on an appendix that appeared in *Groundwater & Wells*, Third Edition. It is co-authored by my good friend and mentor, Bob Sterrett. I hope you enjoy this second trip through the aquifers of North America.

Fractures in Bedrock Aquifers

Any discussion of bedrock aquifers needs to include a discussion of fracturing that can cause secondary permeability that often is the dominant flow path for groundwater in consolidated aquifers.

Water production occurs in low hydraulic conductivity rocks through fractures. Fractures are mechanical breaks in rocks that are the result of stress applied to the formations around flaws or heterogeneities in the formations.

The scale of the fracturing varies depending on the type of stress and the composition of the rock. Open fractures are common along relict bedding planes, cleavage planes, foliation, and other zones of weakness in the rocks (Figure 1).

Fractures are generally more widespread near the land surface and decrease in number and size with depth because overburden stresses tend to close the fractures. Therefore, it is more common to find water-producing fractures at shallower depths (less than 600 feet) than at greater depths.

S.N. Davis and L.J Turk found in a 1964 study of well yields from crystalline rocks published in *Groundwater* that mean yields per foot of well were 0.23 gallons per minute (gpm) or 0.015 liters per second (L/s) to 0.30 gpm (0.019 L/s) at 100 feet, but only 0.013 gpm (0.0008 L/s) to 0.04 gpm (0.003 L/s) at 1000 ft (333 m).

The decrease in water production with depth indicates an increase in the unit cost of water with depth. Davis and Turk concluded that unless geologic factors are favorable, wells in crystalline rocks should be less than 600 feet (200 m) deep.

Storage in fractured-rock aquifers generally is low because the total porosities are less than 10% and lower. For wells to be productive in fractured rock environments, the fractures must be connected.

Sandstone Aquifers

Sandstone aquifers originally were deposited as unconsolidated sands that subsequently were buried, compacted, and cemented. Due to their widespread depositional nature, sand-

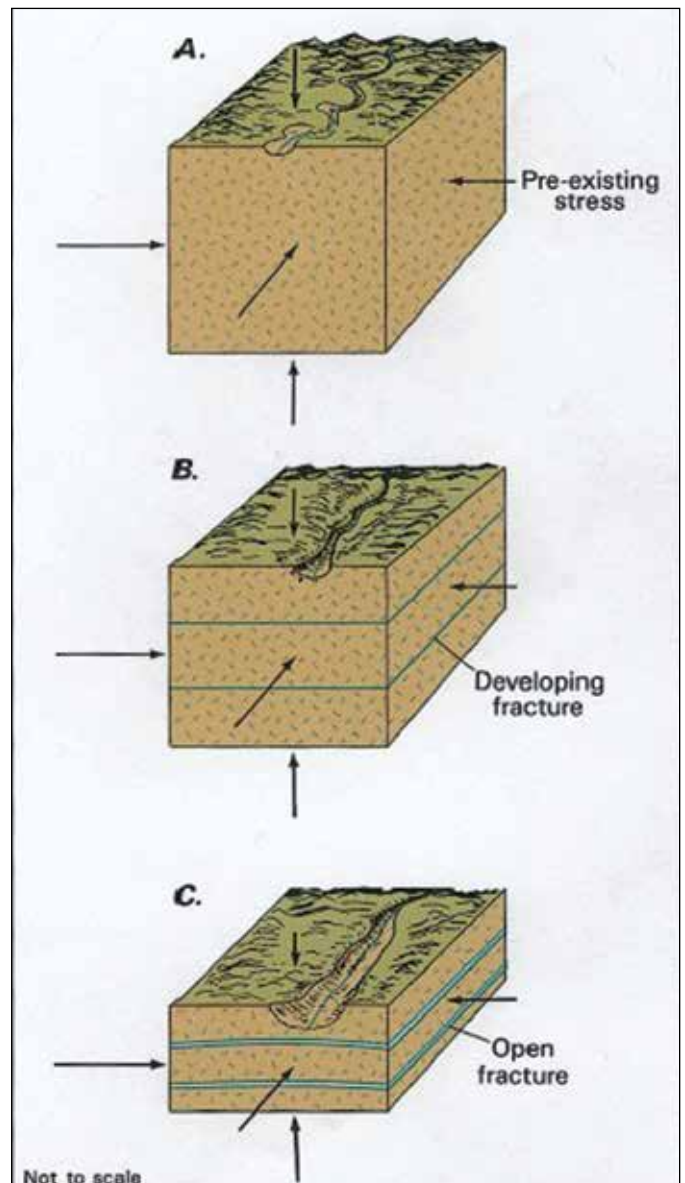


Figure 1. Development of fractures in a rock (USGS).

stone formations can be significant regional aquifers.

The original porosity of unconsolidated sand can be large, but during burial and subsequent compaction and cementation, a significant portion of the original porosity is lost. Thus, the resulting permeability is reduced, and a portion of the

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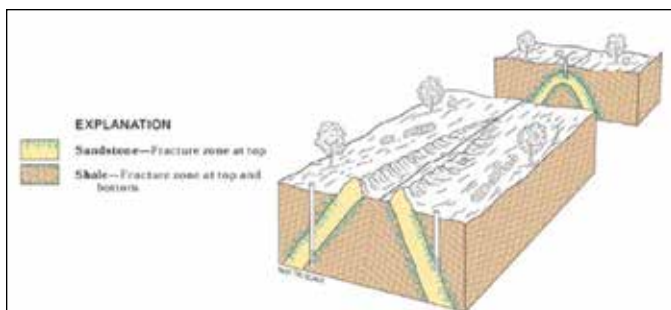


Figure 2. Diagram of fractured sandstone and shale (USGS).

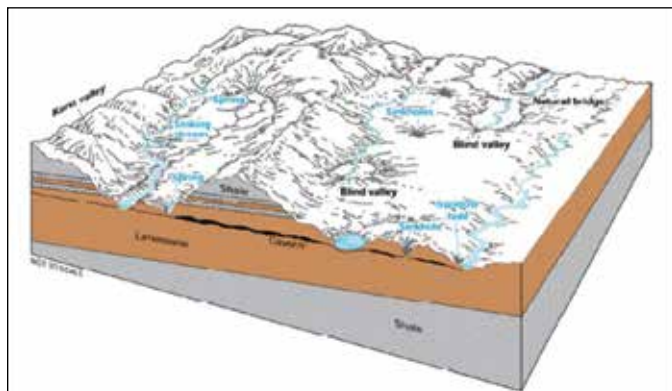


Figure 3. Block diagram of typical karst topography (USGS).

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aquifer's primary, intergranular porosity is reduced.

Secondary porosity such as joints, fractures, and bedding planes form conduits that transmit most of the groundwater through the aquifer. Hydraulic conductivities of sandstone aquifers are primarily a function of the secondary porosity features (Figure 2).

Often, sandstone units are interbedded with siltstones and shales that contain significant amounts of water in storage, but which act as barriers to vertical flow, resulting in confined conditions.

Carbonate Rock Aquifers

Carbonate rock aquifers consist of limestone, dolomite, and marble. The yield of carbonate aquifers can vary greatly from low hydraulic conductivity units to prolific water producers due to secondary porosity. This secondary porosity is the result of dissolution of the carbonate rock. This dissolution is enhanced where joints or fractures occur in the rock. Carbonate formations primarily are deposited in marine environments that have an abundance of skeletal fragments of marine organisms or carbonate sediment. Depositional environments include tidal flats, reefs, and beach environments.

The primary porosity of carbonate rocks is variable, and ranges from 1% to more than 50%. Compaction, cementation, and dolomitization are diagenetic processes that act on the carbonate rocks to change their porosity and permeability.

Enhanced secondary permeability develops after deposition when groundwater that is slightly acidic flows through fractures, creating solution openings (Figure 3).

Precipitation absorbs carbon dioxide from the atmosphere

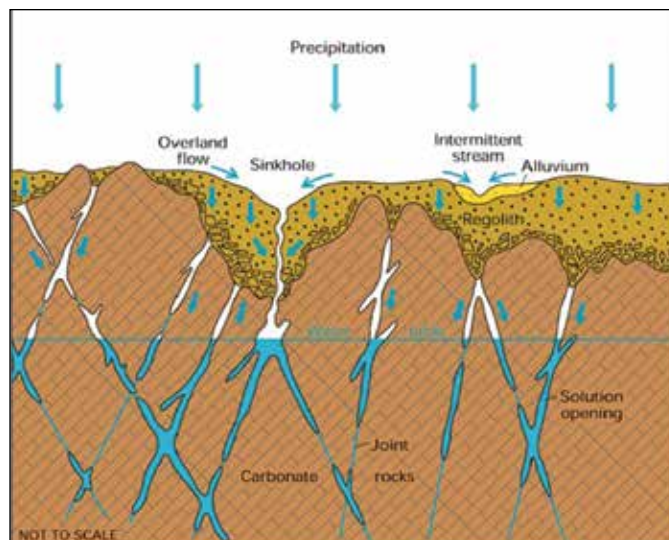


Figure 4. Diagram of karst features in a limestone terrain (USGS).

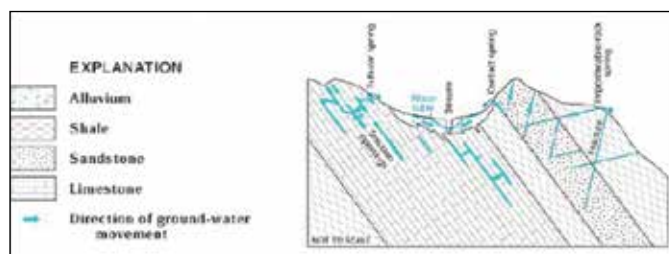


Figure 5. Interbedded sandstone and limestone aquifers showing interaction of groundwater (USGS).

and organic matter in the soil during recharge, forming weak carbonic acid. This acidic groundwater partially dissolves carbonate rocks, initially by enlarging preexisting openings such as pores between grains of limestone or joints and fractures in the rocks.

The water causes dissolution along the fractures, resulting in a series of interconnected fracture systems or caverns that can be tens of feet in width and miles in length.

When saturated, carbonate-rock aquifers with well-connected networks of solution openings yield large volumes of water to wells that penetrate the solution cavities even though the undissolved rock between the large openings has low hydraulic conductivity.

Where carbonate rocks are exposed at the land surface, karst topography can exist, and is characterized by sinkholes and disappearing streams. Recharge to carbonate rocks that have pronounced solution features is rapid—which can be of concern because chemicals dissolved within the recharge water can impact water quality within the aquifer (Figure 4).

Interbedded Sandstone and Carbonate Aquifers

Coastal depositional environments can result in alternating sequences of sand and carbonate rocks. Where sandstone and carbonate rocks are interbedded, it is common that the carbonate rocks are the most productive aquifers due to dissolution along secondary features as discussed above.

The unfractured portion of the carbonate unit may have

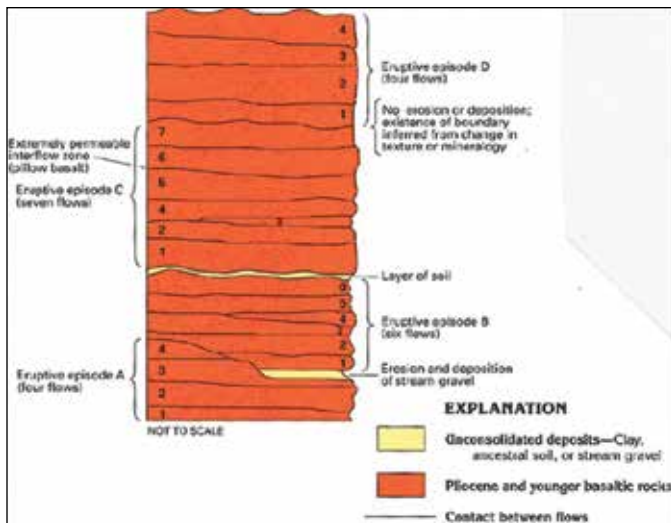


Figure 6. Example of interbedded basaltic flows with unconsolidated sediments (USGS).

low hydraulic conductivities and the sandstone units can have intermediate hydraulic conductivities due to a combination of primary and secondary porosities (Figure 5).

As shown in Figure 4, large quantities of water can move rapidly through the solution openings in the carbonate formations. Upon entering the sandstone units, the water moves slowly through the intergranular pore spaces and small fractures of the sandstone and discontinuous layers of shale.

In many areas, the interbedded nature of the formations impedes the downward movement of water and creates a perched water table from which small springs discharge along surface exposures along hillsides.

The presence or absence of solution openings affects aquifer recharge and discharge and is reflected by the water levels in wells completed in different rock types. The water levels in the sandstone portions of the aquifers rise quickly in response to seasonal increases in precipitation; after the sudden rise, the water slowly drains from the aquifer and the water levels decline.

In contrast, the water levels in the limestone portions rise quickly in response to heavy rains. Following the abrupt rise, the water levels in the limestone decline rapidly as the solution cavities drain. The large openings allow rapid recharge and equally rapid discharge during and immediately following periods of intense precipitation.

Volcanic, Igneous, and Metamorphic Rock Aquifers

These aquifers can be grouped into basaltic aquifers that can be productive and crystalline-rock aquifers that are generally low-producing formations consisting of granites, metamorphic, and other types of volcanic rocks.

Basaltic Rock Aquifers

The hydraulic conductivity of basaltic rocks can be highly variable depending on the cooling rate, number and characteristics of interflow zones which can consist of debris flows, and the thickness of the flow units (Figure 6).

As indicated in Figure 5, basaltic aquifers form in layers of varying hydraulic conductivities that are determined by flow events. Basalt flows tend to develop hydraulic conductivities

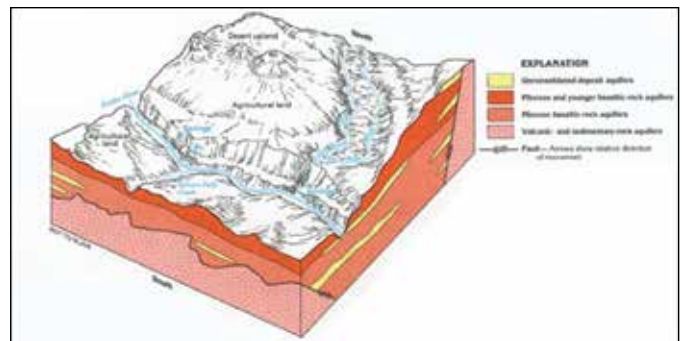


Figure 7. Diagram showing basaltic interflows typical of the Columbia Plateau of the northwestern United States (USGS).

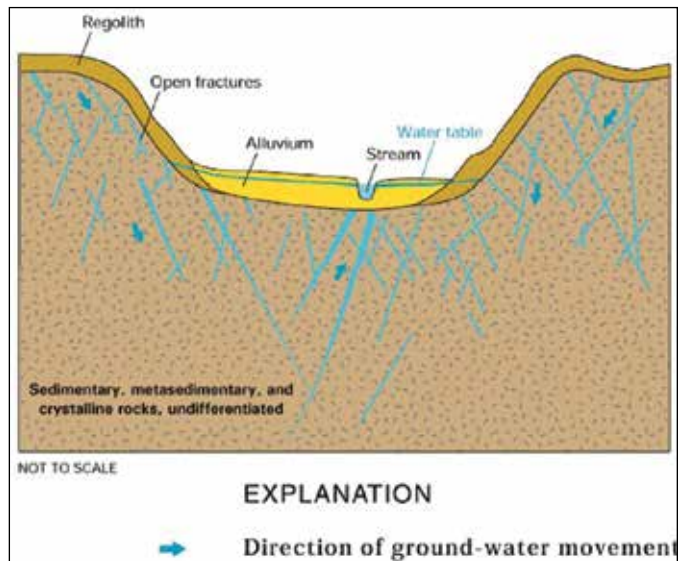


Figure 8. Diagram of groundwater flow system in sedimentary-crystalline rocks (USGS).

that are determined by flow events. Basalt flows tend to have high hydraulic conductivity zones that develop at the tops and bottoms of the individual flows.

Cooling features such as fractures and joints generally develop in the upper and lower parts of each flow while the center tends to remain fluid and continues to move.

Vesicles that result from gases escaping from the molten rock can develop at the top of the individual flow. Slow cooling prevents the center from developing open spaces, resulting in low-permeability zones between two more-permeable zones. Thin flows cool more quickly than thick flows, resulting in aquifers that are fractured and vesicular-like.

Basalt flows commonly overlap, and as shown in Figure 5, can be separated by alluvial materials. The alluvial materials were deposited on basaltic units during times of low volcanic activity and were covered by later basalt flows. These alluvial units also can be significant localized aquifers.

Extrusive Volcanic Rock Aquifers Other Than Basalt

Extrusive volcanic rocks can have highly variable hydraulic properties depending on how the rocks were formed. Primary porosity in volcanic rocks are generally low, thus secondary porosity (such as fractures) represents most of the total porosity.

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Extrusive volcanic rocks, such as tuff and ash deposits, can have hydraulic properties like fine-grained sedimentary materials (e.g., high porosity but low permeability). In situations where the volcanic rock fragments are hot when they are deposited, they can become welded and create hydrogeologic units of low hydraulic conductivity (Figure 7).

Lava flows (such as flows with high silica content, for example rhyolite) tend to be thick, dense flows having low hydraulic conductivities. Fracturing creates secondary porosity and hydraulic conductivity. Typically, production zones in volcanic rock are associated with secondary hydraulic conductivity features such as fractures and joints.

Granitic and Metamorphic
Rock Aquifers

Granite and metamorphic rocks generally are low-water-yielding formations that transmit water through secondary fracture permeability (Figure 8), as previously discussed. Metamorphic rock aquifers also include metamorphosed sediments (e.g., quartzite, slate). If frac-

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turing in these rocks is not significant, then these formations act as aquitards or zone boundaries that impede flow.

Water flow can be increased in these rocks through aquifer stimulation such as hydrofracturing. Hydrofracturing is discussed in Chapter 11 of *Groundwater & Wells*, Third Edition.

Summary

Quite often we work in a relatively small geographic area where we understand the geology and the aquifers that are present. At times the geology of an area can be complex and create an interesting situation.

I have learned that hydrogeology also

influences well construction and drill rigs that are used in different parts of North America. In glacial terrains, wells might target the sand layers that can be relatively shallow and interbedded with tills, clays, and silts. These wells are often telescoping completions. On the other hand, in the Southwest and the West, the wells tend to be deeper and are single string completions.

Hopefully this provides a bit of a background of the aquifers in the area you are working with to develop a water supply or investigating as part of a hydrogeologic study.

There are more resources available for specific locations if that is required. I find it helpful, if available, to look at the outcrop of formations that I am developing as a water supply. Being able to see the geology on a larger scale gives me a better feeling of what I anticipate encountering at depth.

Sometimes the cuttings from the borehole only tell a small portion of the story of what is encountered, and a bigger picture allows us to make better decisions about the well completion or hydrogeologic study. www.welljournal.com

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