The Importance of Hard-Rock Aquifers
Principaux enjeux liés aux Aquifères de socle

John M. Sharp, Jr.
Department of Geological Sciences
The University of Texas
Austin, Texas 78712 USA
jmsharp@jsg.utexas.edu

Uwe Troeger
Lehrstuhl fuer Hydrogeologie
Technical University of Berlin
D-10587, Berlin, Germany
uwe.troeger@tu-berlin.de

I. INTRODUCTION

Hard- rock aquifers are those rock systems and, in some cases, the overlying regolith, that occur primarily in fractured crystalline (igneous and metamorphic) rocks. In hard-rock aquifers, fractures provide the major (or sole) permeability and, in many cases, porosity and storativity. Thus, the term hard-rock aquifer can also be extended to include rocks with similar hydro-geologic characteristics, such as indurated low-porosity clastic rocks, many (unkarstified) carbonates, and welded tuffs. Hard-rock aquifer systems may also include the weathered upper portions of these rocks. Igneous and metamorphic rocks crop out much of the Earth's land surface (estimates vary from 20 -30%, depending upon how the overlying sediments are considered). Thus, in much of the world, hard-rock aquifers are the only sources of groundwater. These areas include the Precambrian shields of all the continents, the cores of major mountain ranges, and any areas of past or current igneous activity. In other areas they may be an important secondary source of water.

However, hard rocks also form the hydrogeologic basement. Although often exposed at the Earth's surface, they are commonly overlain by sedimentary rocks or by unconsolidated deposits that are from weathering in place (saprolites) or transported by water (fluvial, deltaic, marine or lacustrine processes), wind (aeolian processes), ice (glacial or niveal processes) and mass wasting processes. Compared to hard-rock aquifers, these overlying sedimentary units have been studied much more intensively because they tend to be more productive - they are typically more porous and permeable as well as being shallower and more easily drillable. Sedimentary basins can be up to 10s of kilometres thick. This hard-rock hydrogeological basement is not impermeable; it connects with sedimentary basins on overlying sediments; and its waters interact with overlying units as depicted on Figure 1.

II. HYDROGEOLOGICAL CHARACTERISTICS

Hard-rock aquifer systems in igneous and metamorphic rocks do have some common characteristics, including their vertical zonation and critical hydrogeological features. Fractured media are typically divided into 4 classes (Figure 2): A. Purely fractured media in which all groundwater storage and permeability are in the fractures; B. Fractured formations in which fractures provide the permeability, but there is storage in both the fractures and the matrix; C. Double porosity media in which flow and storage in both the fractures and the matrix must be considered; and D. Heterogeneous media that systems where the fractures are filled with clastic materials. As noted in Figure 2, fracture skins (Robinson et al., 1998) with different properties are possible in all classes.

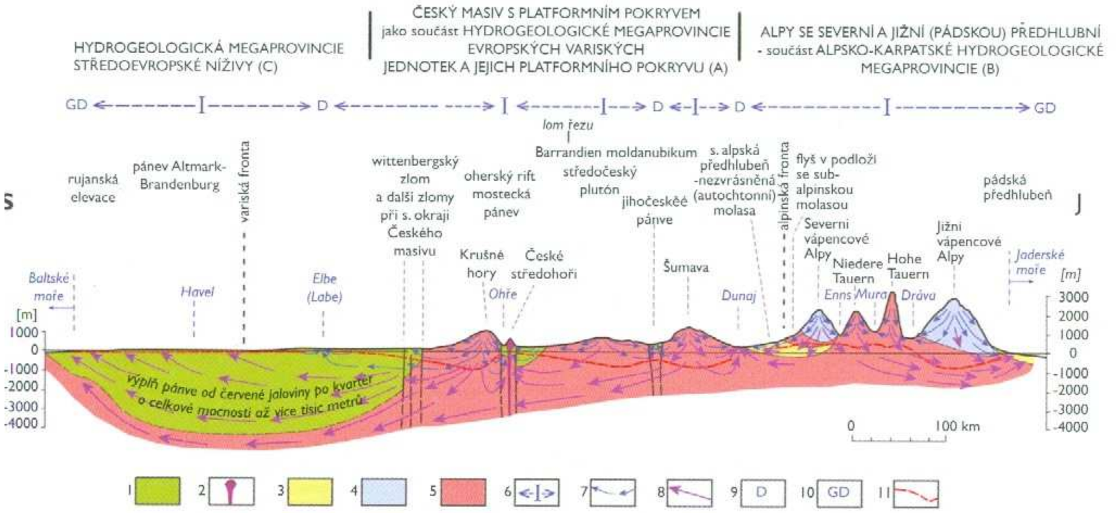

Figure 1 - Geological-hydrogeological cross-section from the Baltic Sea (left) and the Adriatic Sea (right) (Krasny et al., 2014, Plate 3). Inferred flow systems are depicted. In the key: 1 and 3, (green and yellow units) are sedimentary rocks; 2 are Cenozoic volcanic rocks; 4 are Alpine, chiefly carbonate, rocks; 5 are igneous and metamorphic hard rocks; 6-10 represent flow systems (local to regional), and 11 represents the depth of deep saline groundwater.

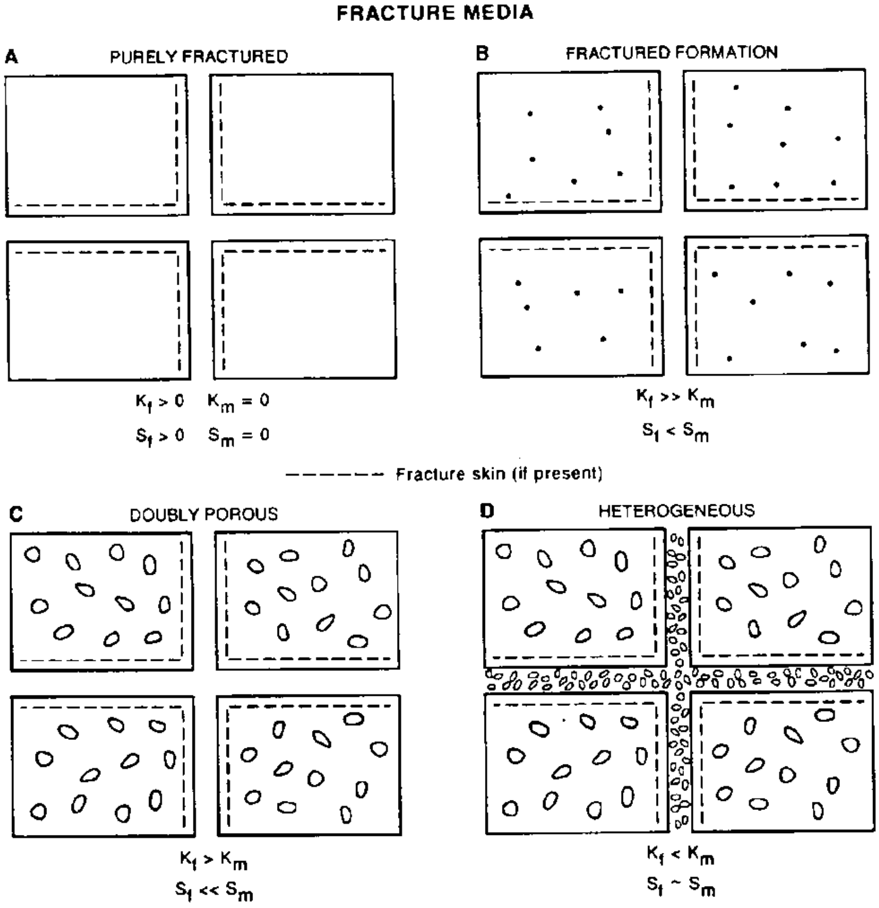

Figure 2 - Types of fractured media (after Sharp, 1993). Types A and B characterize hard-rock aquifers. K_f, K_m *and* S_f, S_m *are the hydraulic conductivities and storativities of the fracture and matrix systems, respectively.*

II.1 Critical hydrogeological features

In fractured systems, the permeability (and transmissivity) is controlled by a number of geological factors. These include:

- The fracture sets - Fractures commonly occur in subparallel sets. The rule of thumb is that there are generally 3 sets of fractures – one subhorizontal and two subvertical that intersect at a high angle, often approaching 90°.
- Fracture orientations – The strike, dip, and general shape of the fractures (I.e., planar, curved, branching, etc.)
- Fracture spacing / density - How close together are the fractures / what is the spacing pattern / how many fractures are there in a given area or volume?
- Apertures – The distance between the fracture surfaces. The general hydraulic conductivity of a single planar fracture is perhaps best estimated by the geometric mean aperture at normal hydraulic gradients (Sharp et al., 2014)
- Roughness and asperity – These are how the fracture surfaces vary from a plane. A number of empirical equations have been presented showing how roughness affects the permeability.
- Connectivity - Fractures can communicate freely hydraulically or diffusely or they can terminate and be closed.
- The effects of varying earth stresses or stress histories on the above properties.

Thus, characterizing hard-rock aquifers is a challenge. Measuring the above parameters can be exceedingly difficult and translating their properties from one scale to another or spatially at the same scale is equally difficult. There are, however, some generalizations that can be made. First, it is found that in hard-rock aquifers the fracture permeability decreases with depth and a "rule of thumb" is the chance of finding sufficient permeability in wells deeper than 100 m are small. Second, wells sited in valleys are more productive where the valleys were formed in response to a greater density of fractures. Third, at a large enough scale, permeabilities may approach a maximum (Clauser, 1992), provided that the most transmissive features are sampled adequately. Fourth, it is difficult to predict where and how quickly solutes, such as contaminants, are transported. This is sometimes referred to as Black's Law – "When dealing with fractured systems, contaminants appear at places not predicted and faster than predicted."

Five broad ranges of transmissivity as determined from pumping tests were compiled by Krasny and colleagues (Figure 3). These data show that the transmissivity of hard rock aquifers varies by orders of magnitude, but transmissivity is not always low.

II.2. Vertical zonation

Finally there are some generalizations that can be made about the vertical distribution of hydrogeologic properties in hard-rock aquifers. Krasny and Sharp (2007), Krasny et al. (2014), and Deere and Patton (1971, who presented from the standpoint of site characterizations for construction) generalize the vertical zonation in hard rocks; these are summarized in Table 1. The hard-rock environment can be divided into three vertical zones:

Upper / local (weathered) zone formed by regolith, colluvium, talus, etc. often juxtaposed with mostly Quaternary alluvial, fluvial, glacial, or lacustrine deposits. The thickness is commonly several meters but can be much thicker. Where sufficiently thick and permeable, these strata can provide productive local aquifers and the underlying hard-rock systems are not exploited. Where these strata are thin, of limited permeability, or polluted, the underlying hard-rock aquifers are needed.

In many areas the overlying sediments are not transported materials, but develop from weathering *in situ*. Table 1 (following the references) and Figure 4 show this scenario. The uppermost layers are subdivided into the standard soil horizons with B soil horizon (zone Ib) typically having the lowest permeability. This zone includes the weathered rock zone where, in residual soils, the greatest permeability is typically in the transition zone (zone IIa) from saprolite (the C horizon) to partly weathered rock. In some systems, the weathered rock zone and the underlying fractured bedrock can be considered a single aquifer system. Figure 4 characterizes residual soils on metamorphic and plutonic rocks.

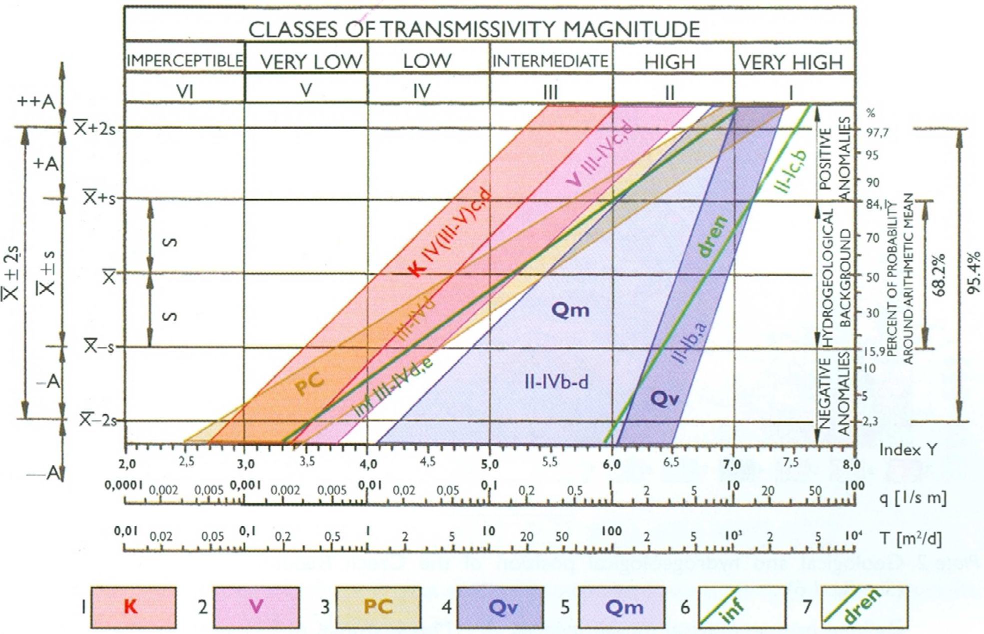

Figure 3 - Typical transmissivity ranges for selected hydrogeological environments (Krasny et al., 2012, 2014). 1 - near surface hard rocks; 2 – crystalline limestones, etc.; 3 – shallow Paleozoic/Mesozoic basin sedimentary rocks; 4 and 5 – Quaternary alluvial deposits along main water course (4) and smaller water courses and terrace deposits (5); 6 and 7 – shallow Cretaceous sandstones on summits and slopes (6, the recharge zones) and in valleys (7, the discharge zones).

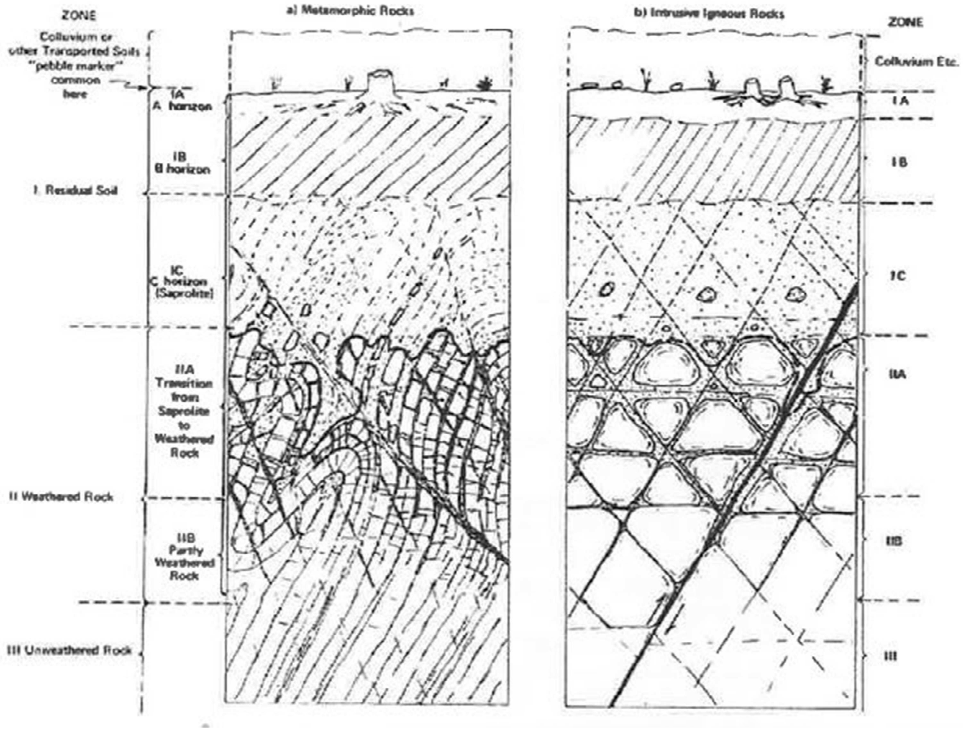

Figure 4 - Typical sections of weathering zones in residual soils developed on metamorphic (left) and plutonic rock (right) (Deere and Patton, 1971).

Middle / regional zone represents fractured bedrock to depths of tens or hundreds of meters. Fracture openings depend mostly on exogenous geologic processes so that permeability generally decreases with depth.

Lower / retarded zone where permeable fracture and fault zones are relatively scarce. Deep fractures can sometimes act as isolated, more or less individual hydraulic bodies. On a regional scale, these may form interconnected networks enabling extended and deep, regional and continental/ global groundwater flow to reach great depths. Deep drill holes have on occasionally encountered highly permeable fracture zones. Under suitable structural conditions or in specific rocks (e.g., granites, quartzite, etc.), mineral and thermal waters may ascend along deep faults.

The boundaries of these zones depend on natural conditions, but human effects (under-ground mining, excavation, blasting. etc.) can also be important. In addition, changes in global climatic zones (e.g., permafrost), topography, and other regionally prevailing features can also affect hard-rock hydrogeology.

III. THE FUTURE OF HARD-ROCK AQUIFERS

Understanding the characteristics and sustainability of hard-rock aquifers and indeed hard-rock hydrogeologic systems is challenging. First over much of the globe, including Africa and the Indian subcontinent, hard-rock aquifers are a major water resource and populations in these areas are growing rapidly. In other areas, hard-rocks are a secondary source for domestic and local water supplies that become critical during times of droughts, infrastructure failures (e.g. water pipeline breaks), or when other water resources become polluted or overdrawn.

In addition, crystalline rock systems are commonly encountered in construction and tunneling and are sites of mining activities or of potential geothermal energy production. They are also being examined as sites for storage of high-level radioactive (or other) wastes because of the limited permeability at depth. Methods and challenges for characterizing hard-rock aquifers and their sustainability apply in these situations as well.

Mining and geotechnical engineering. Many metal (e.g. lead, zinc, gold, silver, etc.), and uranium deposits occur in hard rocks. Underground mining and tunneling commonly requires dewatering of hard-rock systems (Hokr et al., 2014).

Oil and gas production. There are numerous examples of hydrocarbon in crystalline rock reservoirs (Petford and McCaffrey, 2003) and the process of hydraulic fracturing is allowing for exploitation of rock previously considered impermeable by which we are essentially creating fractured formations (category B in Figure 2).

Geothermal energy. The future of hot, dry rock or engineered geothermal systems depends upon analysis of deep fractured systems, either natural or created, that we need to harness the Earth's deep thermal energy (Evans et al., 1999). The difficulty of studying flow in fracture systems at depth where higher temperatures occur is the main obstacle. In Germany (Groß Schönebeck), the results of stimulation of fractures have shown that only 10% of the theoretical calculated flow could be achieved (Zimmerman et al., 2008). If this resource can be tapped economically, it will be immense with few contamination issues.

Waste disposal. In Sweden (e.g., Neretnieks, 2013) and Switzerland (e.g., Smith et al., 2001), hard-rocks have been investigated as repositories for high-level radioactive waste and higher than expected flows of water through fractures have been encountered. In Montalba (South-France), a test site for radioactive waste disposal of France in granites was closed after the observation of intensive groundwater flow has showed high permeability in these hard rocks (Pistre, 1992).

Understanding fractured hard-rock systems has great challenges, but they are important and may become increasingly so for their use as a water resource, as hosts for mineral and hydrocarbon production, geothermal energy, and waste disposal. Amongst the chief challenges in their utilization are:

- how to characterize and parameterize these very inhomogeneous systems,
- upscaling from lab to well field or from well field to regional scales, and
- finding appropriate data to validate or test numerical models of fracture system hydrogeology and transport of solutes, colloids, and heat transport.

The findings of this conference can provide insights into these unique fractured rock systems and, hopefully, guidelines for future productive research.

IV. ACKNOWLEDGEMENT

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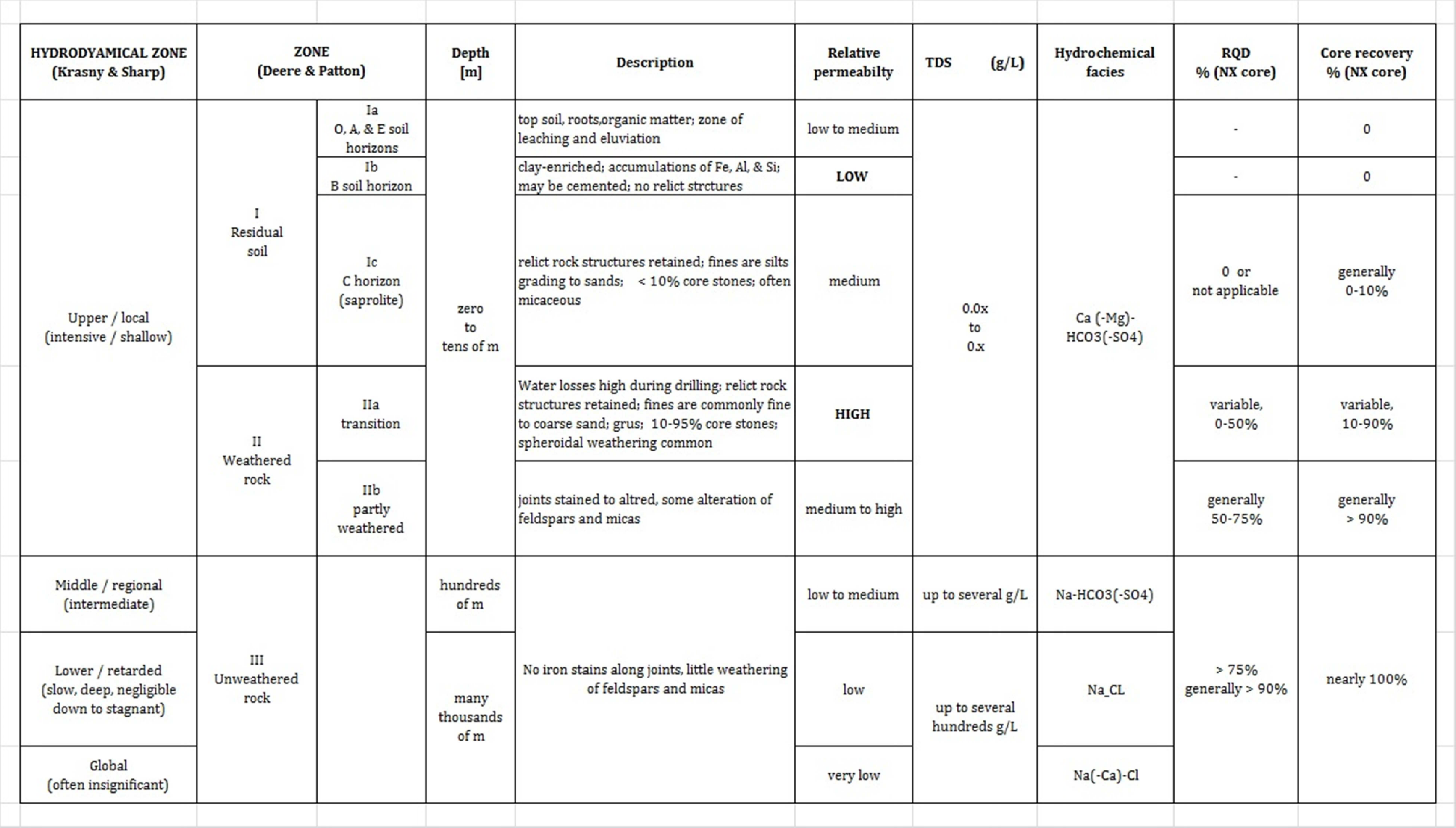

HYDRODYAMICAL ZONE (Krasny & Sharp)	ZONE (Deere & Patton)		Depth [m]	Description	Relative permeabilty	TDS (g/L)	Hydrochemical facies	RQD % (NX core)	Core recovery % (NX core)
Upper / local (intensive / shallow)	I Residual soil	Ia O, A, & E soil horizons	zero to tens of m	top soil, roots,organic matter; zone of leaching and eluviation	low to medium	0.0x to 0.x	Ca (-Mg)-HCO3(-SO4)	-	0
		Ib B soil horizon		clay-enriched; accumulations of Fe, Al, & Si; may be cemented; no relict strctures	**LOW**			-	0
		Ic C horizon (saprolite)		relict rock structures retained; fines are silts grading to sands; < 10% core stones; often micaceous	medium			0 or not applicable	generally 0-10%
	II Weathered rock	IIa transition		Water losses high during drilling; relict rock structures retained; fines are commonly fine to coarse sand; grus; 10-95% core stones; spheroidal weathering common	**HIGH**			variable, 0-50%	variable, 10-90%
		IIb partly weathered		joints stained to altred, some alteration of feldspars and micas	medium to high			generally 50-75%	generally > 90%
Middle / regional (intermediate)	III Unweathered rock		hundreds of m	No iron stains along joints, little weathering of feldspars and micas	low to medium	up to several g/L	Na-HCO3(-SO4)	> 75% generally > 90%	nearly 100%
Lower / retarded (slow, deep, negligible down to stagnant)			many thousands of m		low	up to several hundreds g/L	Na_CL		
Global (often insignificant)					very low		Na(-Ca)-Cl		

Table 1 - Vertical zonation in hard-rock aquifer systems and associated residual soils (after Krasny and Sharp, 2007, 2014, and Deere and Patton, 1971). RQD stands for rock quality designation is the total length of rock core pieces greater than 10 cm in length, divided by the total core barrel length. The NX diamond drill core diameter is about 55 mm.