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THE ROLE OF GEOLOGICAL STRUCTURES ON GROUNDWATER OCCURRENCE AND FLOW IN CRYSTALLINE BASEMENT AQUIFERS: A STATUS REVIEW

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ABSTRACT
The paper is review on the role of geological structures on groundwater occurrence and flow in Crystalline Basement aquifers. The aim was to study the existing available literatures in order to evaluate structural/lineaments (faults, joints/fractures, folds, shear zone etc.) their influences and controls of groundwater occurrence and flow of bedrock of crystalline rocks of igneous and/or metamorphic origin. Groundwater in the basement aquifers resides/occurs within the weathered overburden and fractured bedrocks which originate from rainfall through the process of hydrological cycle. Remote sensing technique uses satellite imagery or aerial photograph to identify linear features on the ground and attempts to relate these lines to geologic structures capable of transmitting and storing large quantities of groundwater. Faults, joints/fractures and folds act as conduit and make rocks excellent aquifers. These features also, served as channels for groundwater movement which may results to an increased in secondary porosity, permeability and therefore, can results as a groundwater prospective/promising zones in crystalline basement rocks.
Key words: Basement Terrain, Groundwater, Lineament, Movement, Occurrence

INTRODUCTION

Water is an essential commodity with an unparalleled value after air. Groundwater is one of the earth's most widely distributed and important renewable perennial resources occurring beneath the earth surface. Also, groundwater is the essential component of the hydrological cycle, which facilitates that unique behavior of the water on the continent (Mathur *et al.*, 2010).

Groundwater has long been second to surface water in terms of its importance for human use and the attention devoted to it by the general public and water sector managers. However, this perception is quickly changing as groundwater increasingly supplant surface water in many areas of the world as the primary and preferred source of water for all types of use, i.e. domestic, agricultural (crops and livestock) and industrial. This change is being driven by groundwater inherently beneficial properties in terms of both quality and quantity combined with easy access through better and cheaper drilling and pumping techniques (Karen and Mark, 2007).

The increase in population, industrialization and the pressure for development in agriculture has led to the over exploitation of groundwater in most of the places. Over exploitation and unabated pollution of this vital resource is threatening our ecosystem and even the life of the future generation (Jha *et al.*, 2007).

Groundwater development is however complicated by highly variable hydrogeological conditions rendering its management fraught with uncertainty (Taylor and Barrett, 1999). More common is on crystalline basement aquifers where the uncertainty is highest and the groundwater potential least.

The importance of geologic structures in the exploration of oil, gas, water and Ore deposits cannot be underestimated. These structures especially lineaments such as joints, fractures and faults, acts as a reservoir for the deposition of important Ores as well as oil, gas and water.

These structures can be detected in the form of a lineament not only by ground mapping but also more easily using remotely sensed data (such as conventional aerial photographs and satellite imagery). The good correlation between structures mapped in the field and those mapped using the lineament system enable the lineament to be regarded as representative of the structural indication of a particular area (Morelli and Piana 2006).

Remote sensing using satellite and airborne data has become an increasingly valuable tool for understanding groundwater hydrology (Todd and Mays, 2005). Application of remote sensing technology in groundwater resources evaluation has been practiced for about three decades.

Occurrence and Flow of Groundwater

Groundwater is water that exists in the pore spaces and fractures of geologic materials beneath the Earth's surface. It originates as rainfall or snow and then moves through the soil and rock into the groundwater system, where it eventually makes its way back to the surface streams, lakes, or oceans.

Most often, the occurrence of groundwater in basement complex terrains is localized and confined to weathered/fracture zones (Ariyo and Adeyemi, 2009). The occurrence and movement of groundwater, particularly in hard rock areas are governed by different factors such as topography, lithology, structures like fractures, faults and nature of weathering (Janardhana and Reddy, 1998).

Groundwater occurrence in the crystalline basement aquifers is characterized by the presence of a shallow water table and recharge is mainly from rainfall (Sekhar *et al.*, 1994). The water levels have been observed to follow a seasonal fluctuation pattern influenced by the rainfall pattern. This makes the occurrence of groundwater in the basement complex terrain of Nigeria to be highly unpredictable and hence requires a combination of hydrologic, geophysical and geologic surveys to achieve success in groundwater development programs (Olayinka, 1990).

Groundwater flow in crystalline rocks with no intergranular porosity takes place in a connected fracture network. But far from all fractures are permeable, and fracture permeability varies considerably (Banks *et al.*, 1996).

Hydrological Cycle

The continuous movement of water between oceans, atmosphere and land is known as the hydrological cycle (Figure 1). Considering the inflow is from precipitation in the form of rainfall. Outflow occurs primarily as stream flow or runoff and as evapotranspiration, a combination of evaporation from water surfaces and the soil and transpiration from soil moisture by plants. Precipitation reaches streams and rivers both on the land surface as overland flow to tributary channels, and also by subsurface routes as interflow and base flow following infiltration to the soil. Part of the precipitation that infiltrates deeply into the ground may accumulate above an impermeable bed and saturate the available pore spaces to form an underground body of water, called an aquifer. The water contained in aquifers contributes to the groundwater component of the cycle (Figure 1), from which natural discharge reaches streams, rivers, wetlands and oceans.

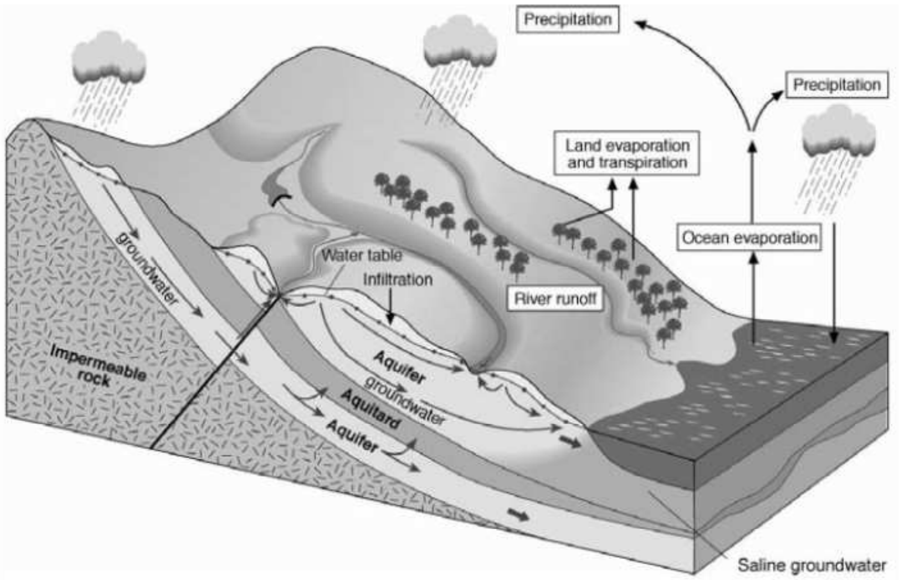

Figure 1: The natural hydrological cycle (after Morris *et al.,* 2003)

Groundwater in the Hydrological Cycle

Strictly speaking, groundwater refers only to water in the saturated zone beneath the water table, and the total water column beneath the earth's surface is usually called subsurface water (Figure 2). In practice, of course, the saturated and unsaturated zones are connected, and the position of the water table fluctuates seasonally, from year to year and with the effects of groundwater abstraction. In volume terms, groundwater is the most important component of the active terrestrial hydrological cycle. Excluding the 97.5 percent (%) of water of high salinity contained in the oceans and seas, groundwater accounts for about one third of the freshwater resources of the world (UNESCO, 1999). If the water permanently contained in the polar ice caps and glaciers is also excluded, then groundwater accounts for nearly all of the useable freshwater. Even if consideration is further limited to the most active and accessible groundwater bodies, which were estimated by Lvovitch (1972) at 4 x 106 km^3, then they still constitute 95 percent of the total freshwater. Lakes, swamps, reservoirs and rivers account for 3.5 percent (%) and soil moisture for 1.5 percent (%) (Freeze and Cherry, 1979). The dominant role of groundwater resources is clear, their use is fundamental to human life and economic activity, and their proper management and protection are correspondingly vital.

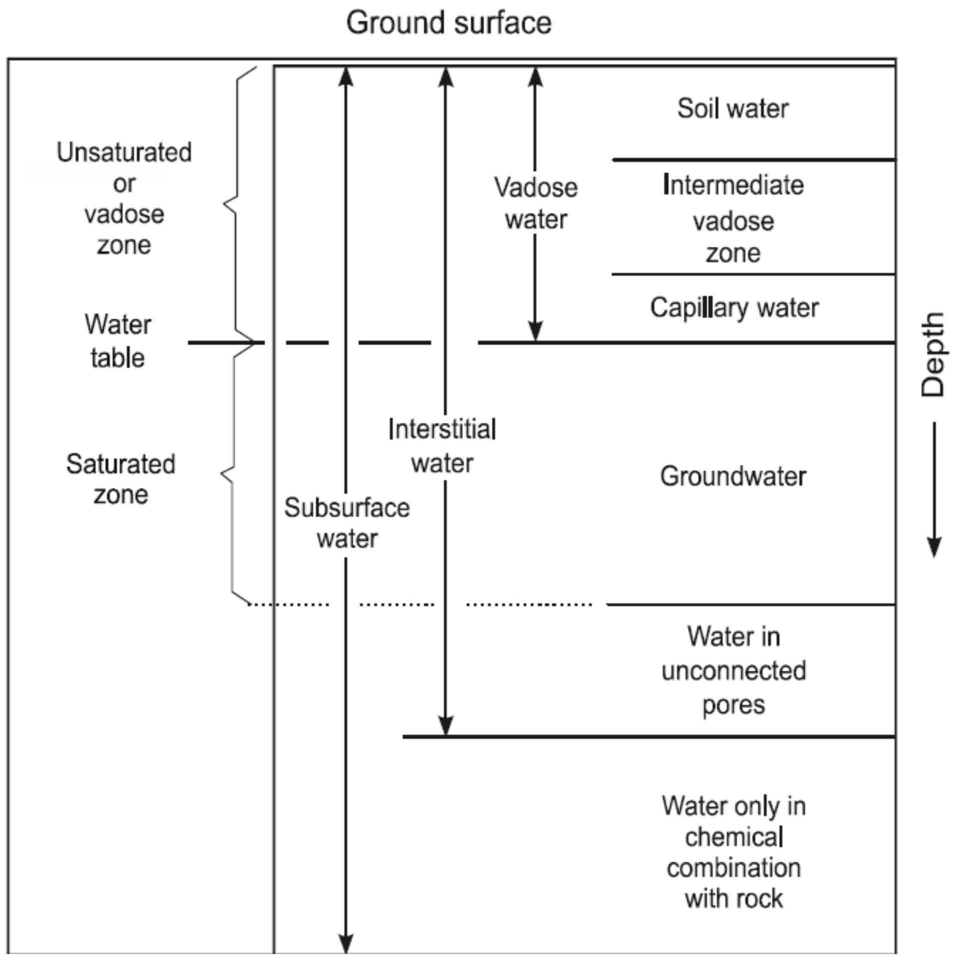

Figure 2: Classification of subsurface water (after Driscol, 1986)

Groundwater Occurrence in the Subsurface Basement Complex

Weathered Zone

The ancient land surface has been exposed to prolonged weathering and leaching which has resulted in a thick mantle of regolith. The weathering profiles have very high primary porosity, and with the resulting high storativity being extremely important to groundwater supplies in areas of crystalline basement rocks (Wright, 1992).

The relationship of weathering processes to permeability is complex and variable. Initial weathering which results in the disaggregation and removal of material in solution without the production of secondary minerals must progressively increase permeability and specific yield. Later production of secondary clay minerals will reduce the value of these parameters and clays could seal fractures in the bedrock. If more aggressive weathering should occur at a later stage, this could result in dissociation of kaolinite and increased permeability (Wright, 1992).

The regolith has a relatively high storage capacity but low permeability (Acworth, 1987) whereas the fissured bedrock has a low storage capacity but a relatively high permeability. Thus a borehole drilled into thick regolith might provide a low yield but more than enough to supply a continuously operated hand-pump, but one that was drilled through thick saturated regolith and into fractures in the underlying bedrock would provide sustained, high yield permeability.

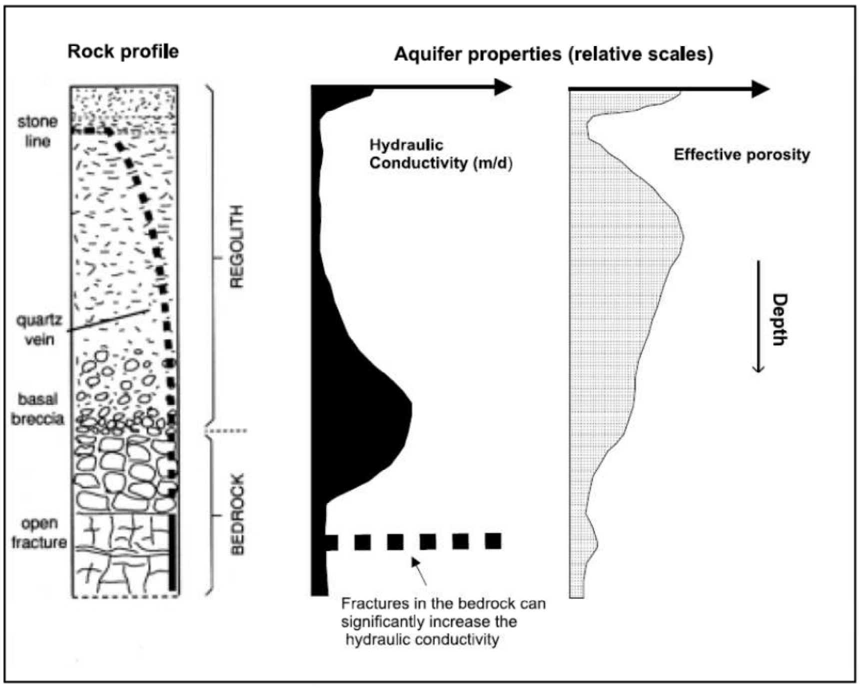

Figure 3: Variation of permeability and porosity with depth in basement aquifers (based on Chilton and Foster, 1995).

Permeability and porosity in the weathered zone are not constant but vary throughout the profile (Figure 6). Porosity generally decreases with depth; permeability however, has a more complicated relationship, depending on the extent of fracturing and the clay content (Chilton and Foster, 1995). In the soil zone, permeability is usually high, but groundwater does not exist throughout the year and dries out soon after the rains end. Beneath the soil zone, the rock is often highly weathered and clay rich, therefore permeability is low. Permeability is likely to be low when the regolith is derived from rocks rich in ferromagnesian minerals, notably biotite, which converts easily to secondary clay minerals.

Towards the base of the weathered zone, near the fresh rock interface, the proportion of clay significantly reduces. This horizon, which consists of fractured rock, is often permeable, allowing water to move freely. Wells or boreholes that penetrate this horizon can usually provide sufficient water to sustain a hand pump.

Deeper fractures within the basement rocks are also an important source of groundwater, particularly where the weathered zone is thin or absent. These deep fractures are tectonically controlled and can sometimes supplies of up to one or even five l/s of groundwater. The groundwater resources within the regolith and deeper fracture zones depend on the thickness of the water-bearing zone and the relative depth of the water table. The deeper the weathering, the more sustainable the groundwater yield.

Fractured Zone

The fractures are form due to deformation and stress conditions, resulting in anisotropy within the aquifer (Boulding and Ginn, 2003). Where fractures are present, the groundwater flow is affected by the Remote sensing technique uses satellite imagery or aerial photograph to identify linear features on the fracture density, orientation, aperture connectivity and rock matrix (Witherspoon *et al*., 1987).

It has also been noted that fracture permeability reduces with increasing temperature. As temperature increases with depth, thermal expansion in rocks takes place which leads to reduction in fracture aperture and corresponding decrease in permeability. Further, the permeability is also affected by cementation of precipitated cements such as silica, calcite and clay. Filling the pores which will eventually caused the decreasing of both porosity and permeability as well weathering also affects permeability.

Lineament

According to Hobbs (1904) lineament refers to a significant line on the landscape, having a straight or curved layout, caused by joints or faults that reveal the architecture of the geological substratum. O'Leary *et al.* (1976) defines lineament as the simple and complex linear properties of geological discontinuity surfaces, arranged in a straight or slightly curved line pattern. Discontinuity is a collective term refers to joints, fractures, folds, veins, cleavage, foliation, shear zone, faults and other contacts. Lineaments are natural, linear surface elements, interpreted directly from satellite imagery and have been called fracture traces, and many other names (Garza and Slade, 1986).

Relationship between Lineament and Groundwater

Lineament analysis is used extensively in groundwater investigation to locate high-yield water wells on fractured bedrock (Edet *et al*., 1998). It is used to infer groundwater flow path and storage, as well as the transmissivity, hydraulic conductivity and storage coefficient of the geological formations.

ground and attempts to relate these lines to geologic structures capable of transmitting and storing large quantities of groundwater. The success of lineament analysis is usually measured by the magnitude of the yield produced from wells in close proximity to lineament; wells on or near lineament often exhibit higher yields (Mabee *et al.*, 1994). However, the connectivity and density of fractures is an important control factor for water flow in the hard-rock media (Berkowitz, 1995).

The relationship of lineament, fracture and groundwater is studied by Mabee *et al.*, (1994), Sander (1997). They agree that a high density lineament indicate in general the presence of groundwater. Hung *et al.* (2002) suggested that fractured rocks could be analysed by studying lineament with the help of lineament indices.

Lineament indices are defined as lineament frequency, length, and intersection) and rose-diagrams.

Many previous authors have been considering that lineaments extracted from remote sensing data indicated fractures in the Earth's crust. For instance, Kaneko (1967) stated that about 60 to 70% of lineaments interpreted on aerial photographs correspond to fractures. Some authors inferred that only major lineaments reflected crustal structures (Lattman, 1958; Matsuno, 1968).

The absence of visible fractures and lineaments may not indicate absence of water bearing geological units.

Significance of Lineament

Lineaments like joints, fractures and faults are very important in hydrogeological studies and may provide the pathways for groundwater movement (Sankar, 2002). Presence of lineaments may act as a channel for groundwater movement which results in increased secondary porosity and therefore, can serve as groundwater prospective zone. The extension of large lineaments representing a shear zone or a major fault can extend subsurface from hilly terrain to alluvial terrain. It may form a productive groundwater reserve. Lineaments that favour groundwater occurrences are tensional features which are related to the main direction of tectonic stress, a view supported by Caponella (1989). In addition, according to Dainelli (1989), in crystalline rocks, fracture zones and fracture crossing points are generally the ideal sites where groundwater may occur. The best sites for location of water boreholes are the highly weathered areas and areas of high fracture density with cross-cutting lineaments. These locations are where groundwater occurrence is most promising (Obiefuna *et al.*, 2010).

Therefore, areas with high lineament density may have important groundwater prospects even in hilly regions which otherwise have nil groundwater prospects.

Lineament mapping is considered a very important tool employed in different disciplines to solve different problems in an area. For example, solving Engineering problem in site selection for constructing (dams, bridges, roads, etc), seismic and landslide risk assessment, hot spring detection and hydrogeological research (Sabins, 1997).

Lineament Analysis in Nigeria

Edet *et al.* (1998) delineate areas to be targeted for exploring groundwater potential in Cross River State, South-south of Nigeria. Black and white imagery as well as aerial photographs was employed in the study. Parameters evaluated include lineament (lineament-length density and lineament frequency) and drainage (drainage- length density and drainage frequency) patterns.

Their study shows that, the lineament length density in crystalline basement area has a medium–high rating, whereas the sedimentary terrains generally have a low rating. In addition, Edet *et al.* (1994) has earlier stated, high lineaments frequency are obtained in areas where basement rocks outcrop are closer to the surface (thin overburden aquifer) whereas low lineament frequencies are characteristic of areas with deeply buried basement rocks (thick overburden aquifer).

On the basis of lineament studies by Edet *et al.* (1994), hydrotectonic models were developed for the crystalline-basement area of Cross River State. These models include:

1) Areas of thick regolith generally associated with major lineament boundaries. Most of these zones are capable of storing and transmitting large quantities of water. However, permeability is low where the regolith consists mostly of fine-grained materials.
2) Major lineament zones: These areas provide better targets for groundwater than joints because of their greater widths, greater lengths, and better interconnections with other fractures.

Bala (2001) employed the LANDSAT 5 Thematic Mapper (TM) to evaluate the groundwater potential of basement aquifers in Northwestern Nigeria. He produced a Hydrospectral map which was interpreted for presence of groundwater in the soft overburden aquifer in relation to depth to the water table. He also produced fracture density symbological map based on symbol assigned by the author, and proposed a classes of low, intermediate and high chances of finding fracture.

Obiefuna *et al.* (2010) applied SPOT image (satellite imagery) to assess potential areas of groundwater occurrence in Mubi, Adamawa State. They analysed lineament density map, lineament intersection and rose-diagram. The rose diagram indicated three major trends namely, NW-SW, NE-SE and N-S. The drainage pattern is also structurally controlled.

Anudu *et al.* (2011) used LANDSAT 5-TM (Thematic Mapper) imagery to investigate groundwater potential zones of Wamba and adjoining area of Nassarawa State. The study produced a drainage network map, lineament density map and rose-(azimuth-frequency) diagram. Drainage map was superimposed on the lineament map, which shows that drainage pattern is structurally controlled as drainage flow directions generally follow the structural strike orientation of the lineament in the area. The rose diagram also shows NE-SW and NNE-SSW directions which are the major trends in the area.

A groundwater potential map was generated for Ekiti State, Southwestern Nigeria, based on the relationship between coefficient of anisotropy and borehole yield. The hydrogeomorphological, lineament density, lineament intersection density thematic maps presented by Bayowa, *et al.*, (2014), the coefficient of anisotropy map were integrated for proper classification of an area into groundwater potential zones. The zones were classified into very low, low, moderate, high and very high groundwater potential zones. Borehole yield data were used to validate the final groundwater potential map.

Faults and its Hydrogeologic Roles

Faults are fracture in earth materials along which the opposite sides have been relatively displaced parallel to the plane of movement.

Faults act as conduit and make rocks excellent aquifers. On the other hand, faults act as drains, lowering water table and thus affecting the distribution of groundwater (Mulwa *et al.*, 2005). Fault act as barriers to the flow of groundwater if filled with impermeable material such as silts and clays. These factors have a strong influence on the aquifer yields through boreholes, static water levels, flow and hence distribution of groundwater. Therefore, the amount of water available in a faulted region would be influenced.

Faults are commonly described as zones consisting of a fault core and a surrounding damage zone, which differs structurally, mechanically and petrophysically from the undeformed host rock (protolith) (Caine *et al.*, 1996).

Fault-zone architectural components include a fault core, defined as the part of a fault zone where most of the strain is accommodated and that often is composed of fault rocks such as clay-rich gouge or mineralized breccias or other cataclastic rocks (Caine *et al.*, 1996). The second common component is a damage zone that often envelops the fault core and is related to the growth of the fault zone. Damage zones are commonly composed of open and mineralized fractures, small faults, folds and other strain features (Caine *et al.*, 1996).

Fault-zone architectural styles, or combinations of each of the components, result in distinctive types of fault zones. Composite deformation zones (CDZ) have both common fault-zone components: a core and a damage zone surrounded by the protolith. Example fault-related permeability structures might include the composite deformation zone where the core is low-permeability gouge and higher permeability open fractures in the damage zone, making the fault zone a combined conduit-barrier to groundwater flow where flow is enhanced parallel to the strike of the fault but impeded across the fault. Conversely, a distributed deformation zone (DDZ) may act as a conduit relative to the protolith if many of the internal fractures are open.

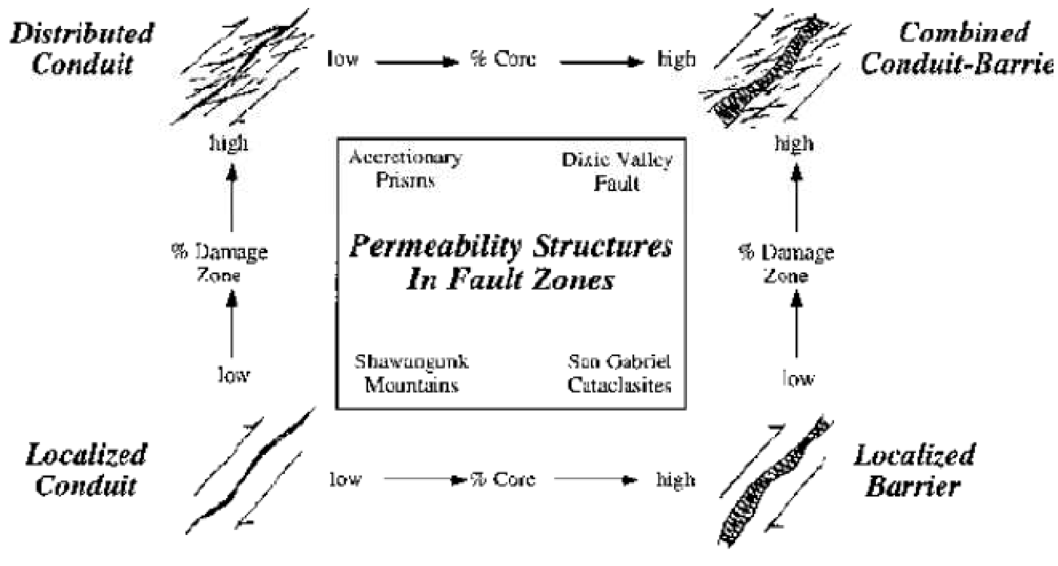

Figure 4: Conceptual scheme for fault-related fluid flow (source: Caine and Forster, 1999)

It is generally recognized that, in the influence area of faults and fracture lineaments, the fault core and central zone have low permeability while the outer damage zone has enhanced permeability compared with the surroundings (Evans *et al.*, 1997; Henriksen and Braathen, 2006).

Recognition of Faults in the Field in Crystalline Basement Terrain

A number of criteria are used to decipher the presence of faults, though in a specific case only some of the features may be present. Some of the more important criteria include:

1) Displacement of key beds;
2) Presence of features indicating movement on fault surface such as slickensides, mylonite, breccia, gouge, grooving etc;
3) Evidence of mineralisation, silicification, along fault zones;
4) Alignment such as springs alignment, pond alignment, vegetation alignment, rectilinearity of a stream;
5) Indication of sudden anomalous changes in river course, such as knick points, offset of streams, anomalous or closed meanders etc.;

Effect of Faults on Groundwater Regime

Faults may affect groundwater regime in numerous ways, some of the more important being the following:

1) It is well known that faults may have such effects as truncation, displacement of beds. In this light, the distribution and occurrence of aquifers may be affected by faults as locally an aquifer unit may get displaced/truncated (Figure 5. a, b).
2) A fault may bring impervious rock against an aquifer, which would affect groundwater flow and distribution (Figure 5. a).

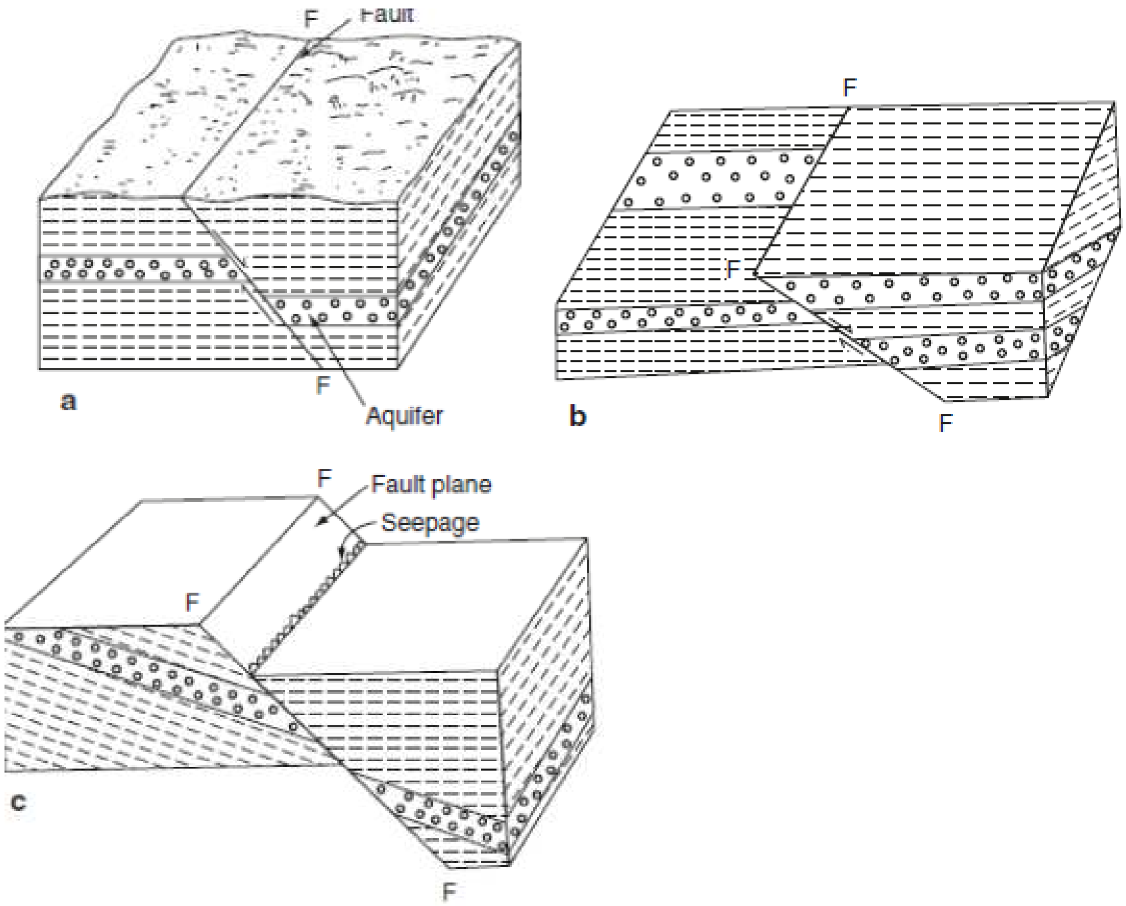

Figure 5: Effects of faults on aquifers (source: Singhal and Gupta (2010)

3) Truncation of an aquifer by a fault may lead to seepage and formation of a spring line along the fault (Fig. 5. c).
4) Faults create linear zones of higher secondary porosity; these zones may act as preferred channels of groundwater flow, leading to recharge/ discharge.

Fractures and Joints

Conventionally, a fracture or joint is defined as a plane where there is hardly any visible movement parallel to the surface of the fracture; otherwise, it is classified as a fault. Joints are fractures whose primary direction of opening is perpendicular to their walls and that are not filled with mineral precipitates. Fractures filled with mineral precipitates will be referred to as veins. Joints are formed by tectonic, brittle deformation etc.

Joints occur as well-defined sets along the bedding planes at right angles to the bedding (longitudinal), while cross-joints are normal to these, and oblique-joints cut at acute angles to the cross-joints. The longitudinal and cross-joints are formed by extension fractures, but near fold hinges longitudinal joints may form conjugate shear fractures (Roberts, 1982). High intensities of joints lead to increased permeability and connectivity, while bedding planes allow for preferential flow.

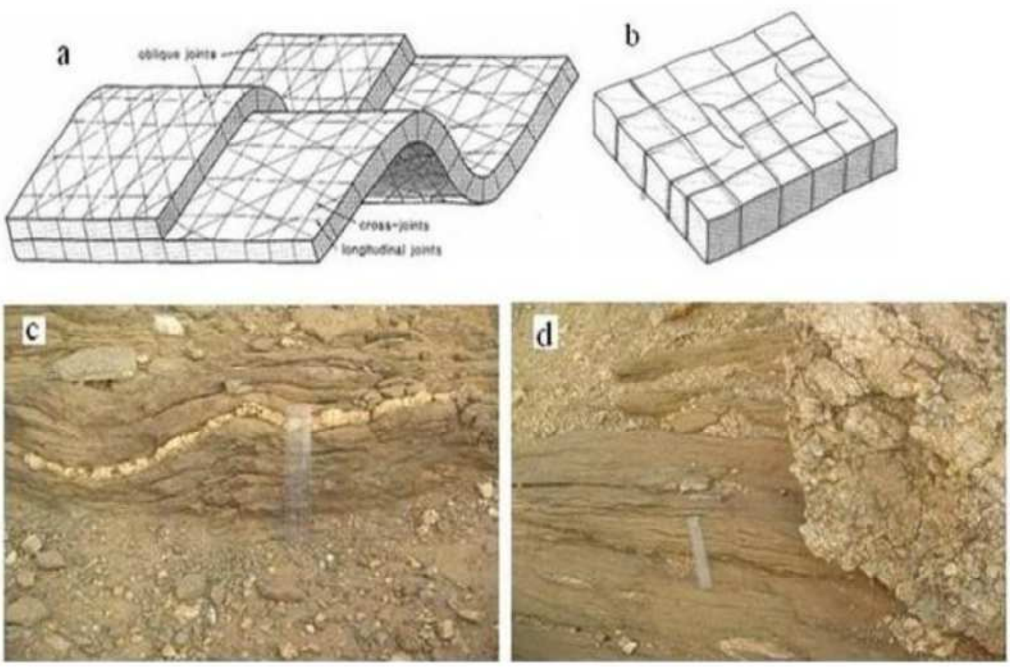

Figure 6: Field photograph of joint sets in fractured rocks (a, b). Joint patterns in folded, showing strong bedding joints, (c) and (d) showing bed, long and cross joints (Roberts, 1982)

Role of Fold on Groundwater Flow

Fold is a bend or buckle in any pre-existing rock as a result of deformation. Folds are best displayed by structures that were formerly approximately planar, such as layering or bedding in sedimentary and igneous rocks, or foliation, schistosity and cleavage in metamorphic rocks.

When rocks are folded, dilational openings and longitudinal joints sometimes form along the hinge lines of the folds due to flexural slip and strain compensation. Since water usually flow the path of least resistance (but under the influence of gravity) these hinge lines could act as conduits for groundwater flow.

CONCLUSION

This review considered published works on the effects of geological structures on groundwater occurrences and flow in crystalline basement aquifers. Groundwater is water that exists in the pore spaces and fractures of geologic materials beneath the Earth's surface. Most of these structures especially lineaments such as joints, fractures and faults, acts as a reservoir for the accumulation of water.

In crystalline rocks, fracture zones and fracture crossing points are generally the ideal sites where groundwater may occur. The best sites for location of water boreholes are the highly weathered areas and areas of high fracture density with cross-cutting lineaments. These locations are where groundwater occurrence is most promising (Obiefuna *et al.*, 2010). In addition, Edet *et al.*, (1994) has earlier stated, high lineaments frequency are obtained in areas where basement rocks outcrop are closer to the surface (thin overburden aquifer, low groundwater potential) whereas low lineament frequencies are characteristic of areas with deeply buried basement rocks (thick overburden aquifer, high groundwater potential).

Faults, joints and folds act as barriers to the flow of groundwater if filled with impermeable material such as silts and clays. These factors have a strong influence on the aquifer yields through boreholes, static water levels, flow and hence distribution of groundwater. Therefore, the amount of water available in a tectonic region of crystalline basement rocks would be influenced.

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