Vingtièmes journées techniques du Comité Français d'Hydrogéologie
de l'Association Internationale des Hydrogéologues.
« Aquifères de socle : le point sur les concepts et les applications opérationnelles » La Roche-sur-Yon, juin 2015

Aquifères de socle altérés et fracturés d'Afrique : d'un concept unique à divers modèles d'aquifères
African Weathered and Fractured Basement Aquifers: From Single Concept to Diverse Aquifer Models

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I. INTRODUCTION

There is a standard accepted weathering profile for the Basement Complex Aquifer within sub-Saharan Africa. It was derived independently in the 1970s both by French workers in the region and English speaking workers. While this profile remains laudable it is now apparent that it does not necessarily fit all cases in all environments within the region. Its value as a guide for groundwater development in sub-Saharan Africa is questioned as it is believed that in some environments it can be misleading and unhelpful. The hypothesis is tested that sub-sets of the original weathering profile should be developed as a 'tool kit' applicable to all environments in which the aquifer occurs.

II. THE ANGLOPHONE EXPERIENCE

The scope of early Basement aquifer studies undertaken in former British colonial eastern and southern Africa became apparent on compilation of an archive of 'grey' information on groundwater occurrence and development for the Southern African Development Community (Davies et al., 2011). Work undertaken in South Africa, Malawi, Zambia, Tanzania and Zimbabwe underpins understanding of groundwater occurrence in Crystalline Basement aquifers within Anglophone sub-Saharan Africa. Using this experience and data acquired from a series of exploration boreholes, a conceptual model of groundwater occurrence within a typical Basement complex weathered and fractured profile was produced by hydrogeologists in Tanzania and Zambia during 1979-82 (Carl Bro et al., 1980) (Figure 1). This concept was later applied to specific studies and an assessment of national groundwater occurrence and resources in Malawi by Smith-Carrington and Chilton (1983).

In Zimbabwe, the results of water supply programmes undertaken by Hydrotechnica (1985), JICA (Sanyu, 1985) and the Primary Water Supply Unit refugee resettlement scheme (1983-6) following the 1983-4 drought, contributed to knowledge of the Basement Complex Aquifer. The results were included in the national groundwater resources assessment produced by Interconsult (1985) based upon a survey conducted by Gear (1982).

These studies formed the basis for the detailed Basement Complex Aquifer investigation that took place between 1983 and 1986. They included groundwater occurrence related to geomorphology, remotely sensed data, geophysical siting methods, collection and assessment of borehole data, geology and tectonics, and weathered and fractured zones. The project results, reported in an international conference held in Harare (Commonwealth Science Council, 1987), formed the basis of a comprehensive book on Basement Complex aquifers (Wright and Burgess, 1992) in which a standard weathering profile is presented (Figure 2).

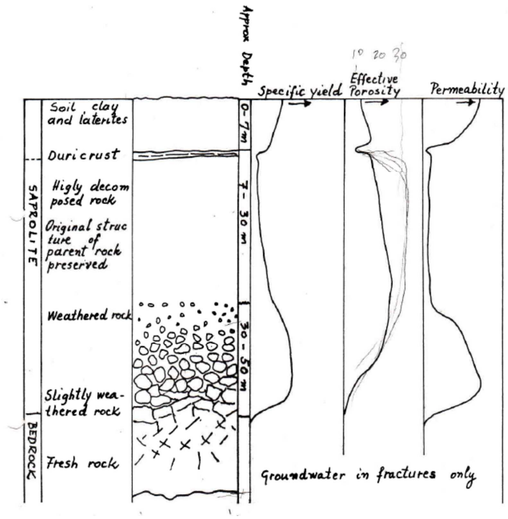

Figure 1 – Initial crystalline Basement weathering profile with hydraulic properties (Carl Bro et al., 1980).

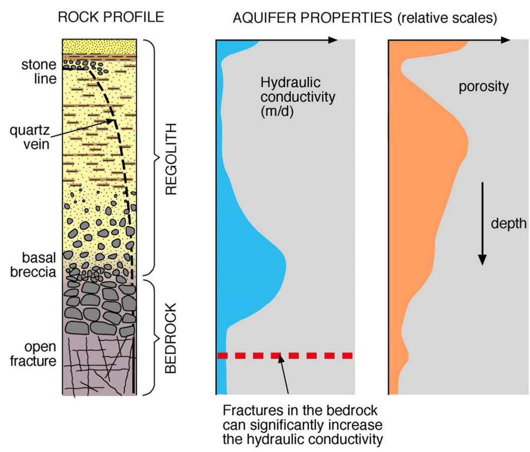

Figure 2 – Standard weathering profile (Wright, 1992).

III. THE FRANCOPHONE EXPERIENCE

Within Francophone sub-Saharan Africa, similar concepts of weathering patterns related to groundwater occurrence were developed by soil scientists during the 1970s, 1980s and 1990s (Nahon, 1991; Tardy, 1997); landforms developed within tropical areas were reported by geomorphologists (Trichart, 1972; Migon, 2006); and the occurrence of groundwater by hydrogeologists such as Grillot and Dussarrat (1992). The development of groundwater within Basement Complex rocks has been undertaken by French hydrogeologists in numerous parts of western and Central Africa including studies in Benin, Cote d'Ivoire, Chad, Mali, Niger, Senegal, Togo, and Madagascar, as reviewed by BRGM (1987) and summarised by Guiraud (1988) (Figure 3). Later research undertaken by French geomorphologists on Basement Complex terrains is reviewed by Godard (2001) while recent and ongoing studies of Basement Complex hydrogeology by French experts in India are described by Lachassagne et al. (2014). The Indian experience has resulted in the formulation of a conceptual model of groundwater occurrence in weathered and fractured basement that is similar to that presented by Guiraud (1988) (Figure 4).

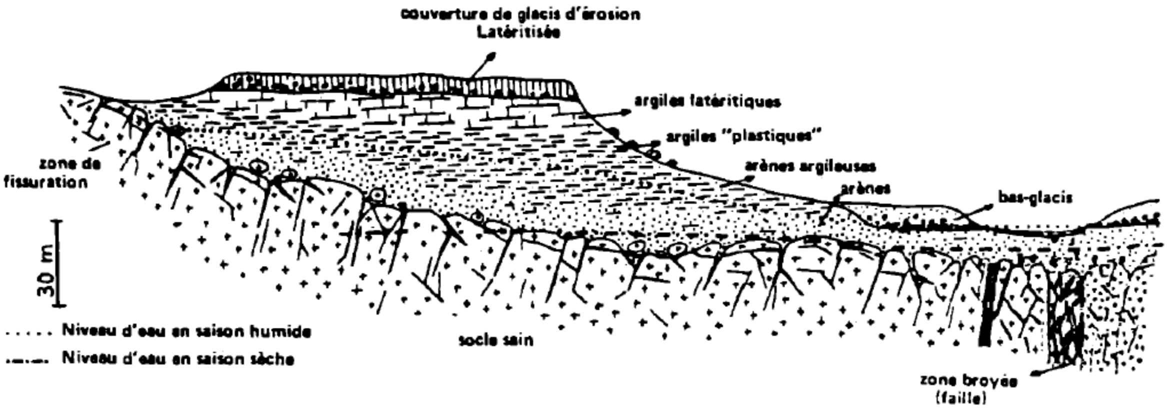

Figure 3 - Weathering profile showing water tables in granite formation (Guiraud, 1988)

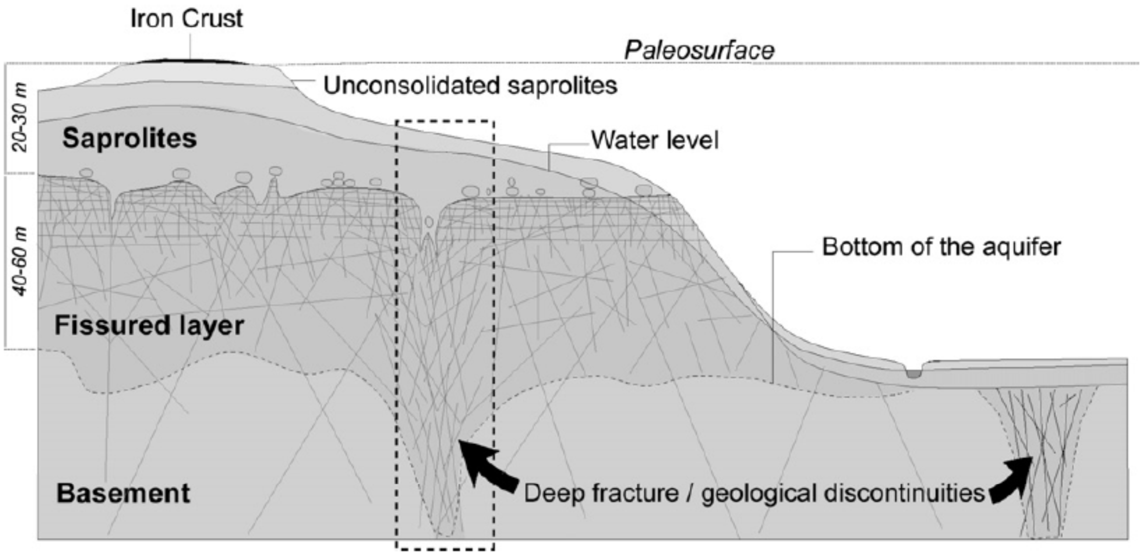

Figure 4 - Idealised weathering profile in Crystalline Basement (Lachassagne et al., 2014)

IV. APPLICABILITY OF THE MODEL

The conceptual model has, since the 1980s, been applied to development of groundwater in Crystalline Basement in areas of sub-Saharan Africa such as Uganda, Nigeria and South Africa.

The basic elements of the conceptual model include aspects of both geomorphology and hydrogeology:

- Landforms – surface and subsurface, drainage, geology, soils, erosion surfaces
- Weathering – climate, physical and chemical processes, weathering profile elements (soil, saprolite, saprock and bedrock) revealed in generic weathering profiles and cross-sections within a series of climatic and tectonic settings.
- Groundwater flow patterns – zones of enhanced flow as recognised during drilling and water level monitoring.

The controls on weathering include both subsurface chemical and biological weathering related to temperature, rainfall and groundwater throughflow as well as the susceptibility of minerals to alteration. Weathering can in places continue to clay-grade material so excluding recharge to the granular weathering products below.

The wide distribution of lithologies that comprise the Precambrian Crystalline Basement were identified by Key (1992):

- Cratonic rocks - Ancient Metamorphic and igneous masses gneisses and schists.
- Mobile belts – Metamorphic belts wrapped around cratons – greenstones belts, metasediments, schists.
- Major intrusions – later intrusions within cratonic and metamorphic belts Granite, gabbro, microgranite.
- Dyke swarms – Dolerite dykes of various ages.
- Metasediments – Proterozoic formations.
- Igneous intrusives: Granites, gneisses, microgranites, rhyolites.

This wide variety of geological environments observed throughout the region questions whether the original conceptual models are still adequate. Recent detailed hydrogeological surveys show that the lithological nature and hydraulic features of the weathering layers are dependent on a wide range of processes that vary from place to place:

- Present and past climatic environments – variations in rainfall, temperature, evaporation.
- Base rock lithology – mineral composition, grain-size, degree of metamorphism.
- Rates of mineral breakdown and dissolution due to chemical and biological action.
- Local tectonics – cratonic stability, rifting, folding, continental break-up and drift.
- Geomorphological modes of erosion/deflation due to drainage and oscillation of sea levels during glacial events.
- Age of weathering and how the nature of weathering has been affected by major changes in atmospheric composition as caused by large volcanic eruptions and lava outpourings.

V. EXPERIENCE

Experience in the Anglophone countries alone indicates a wide range of depths occur to the various interfaces within the weathering profile and that a wide range of lithological types are present. Within crystalline terrains, depth to the base of the main weathering profile elements: soil, saprolite, saprock and bedrock have been recognised within large numbers of borehole logs within crystalline Basement aquifers in Tanzania, Malawi and Zimbabwe. Mean values are tabulated for comparison. Recognition of similar weathering profiles within consolidated Precambrian sediments is difficult as illustrated using data from the Voltaian Basin in Ghana.

V.1. Experience in Tanzania

The development of weathering profiles within fractured and weathered Crystalline Basement in south west Tanzania, adjacent to the main Lake Tanganyika Rift Valley, is illustrated using data from Iringa District (1). These and data from adjacent Mbeya and Ruvuma districts (Carl Bro et al., 1982) were used to develop the basic weathering profile aquifer model (Carl Bro et al., 1980). These are compared with borehole data obtained from granite and gneiss inselberg terrains of the ancient Tanzania Craton in Tabora (2) ; and the block faulted metamorphic banded ironstones, phyllites and meta-quartzites of the Greenschist Belt, at the southern end of the Murchison Rift, in Nzega (3) (Davies and Ó Dochartaigh, 2002).

Elevation (masl)	(Area) Geology	No. Bhs	Soil Base (m)	Saprolite Base (m)	Saprock Base (m)	Mean Bh Depth (m)	Yield (l/s)
700-1000	(1) Granite and gneiss	12	2.9	15.3	35.3	47.4	2.9
1000-1800	(1) Granite and gneiss	46	4.5	19.1	42.4	66.7	1.26
1100-1300	(2) Granite and gneiss	25	7.5	24.1	41.1	47.7	1.17
1100-1300	(3) Green-schist Belt	28	6.1	22.4	34.3	43.3	1.0

Table 1. Mean weathering profile element depths, mean borehole yields and depths within elevation ranges in basement areas of south-western (1) and central (2,3) Tanzania.

V.2. Experience in Malawi

Significant quantities of borehole data are available to define the distribution of weathering profile elements within weathered basement sequences below high level plains of the African and Post African surfaces (1) as well as the near rift fractured basement terrains along the Malawi rift associated with the inselberg and high relief areas associated with the Post African/Pleistocene erosion surfaces (2) (Atkins, 2011). Extensive well documented data are available from the Namwera/Mangochi area of SW Malawi that allow better definition of weathering profile elements beneath the African/Post African surfaces (1000-1500masl), (3) and eroded inselberg, rift valley side dominated Post African/Pleistocene erosion surfaces (500-1000masl) (4) of SE Malawi (GITEC, 2006).

Elevation (masl)	(Area) Geology	No. Bhs	Soil Base (m)	Saprolite Base (m)	Saprock Base (m)	Mean Bh Depth (m)	Yield (l/s)
500-1500	(1) WB Granite/ gneiss	867	5.7	18.8	34.6	41.6	0.82
500-1500	(2) FB Granite/ gneiss	248	7.0	16.5	33.2	41.1	0.66
1000-1500	(3) Granite/ gneiss	112	5.2	20.8	38.3	49.4	0.7
500-1000	(4) Granite/ gneiss	705	4.4	20.3	37.7	50.7	0.67

Table 2. Mean weathering profile element depths, mean borehole yields and depths with elevation ranges in basement areas of central (1,2) and south-eastern (3,4) Malawi.

V.3. Experience in Zimbabwe

Sufficient borehole derived information have been collected to illustrate groundwater occurrence within weathering profiles developed in the highland areas underlain by weathered and fractured granite and gneiss of the undulating African/Post African surface (1000-1500 masl) of the Zimbabwe Craton (1); and the inselberg terrains of the escarpment zone underlain by fractured and weathered granite/schist and gneiss of the Post African/Pleistocene surface (500-1000 masl) of the Limpopo Belt (2). The groundwater resources of weathered and fractured basement in Zimbabwe is discussed by Davies and Burgess (2013).

Elevation (masl)	Geology	No. Bhs	Soil Base (m)	Saprolite Base (m)	Saprock Base (m)	Mean Bh Depth (m)	Yield (l/s)
1000-1500	(1) Granite	156	1.6	17.1	33.4	42.0	0.82
1000-1500	(1) Gneiss	19	2.2	17.4	41.9	53.5	1.16
500-1000	(2) Granite	156	1.8	17.0	29.4	44.5	0.67
500-1000	(2) Gneiss	190	1.5	18.7	33.1	44.7	0.64
500-1000	(2) Schist	16	2.4	13.4	34.5	46.3	5.0

Table 3. Mean weathering profile element depths, mean borehole yields and depths with elevation ranges in basement areas of central (1) and southern (2) Zimbabwe.

V.4. Experience in Ghana

Near surface weathering in Protoeozoic age meta-sandstones, mudstones, siltstones and conglomerates of Voltaian basin is dominated by iron-rich lateritic duricrusts. These ancient, weakly fractured and well cemented metasediments have low primary and secondary permeabilities. Weathered regolith thicknesses were recorded during borehole drilling in the Afram Plains area of the southern Voltaian Basin (Table 4). Regolith thicknesses were not recorded during drilling in similar formations within the Northern region (Table 5). Recognition of the ferrecrete duricrust cap and underlying regolith are important as this layer often inhibits active recharge in the generally flat plain areas of Northern Region and the Afram plains where low borehole yields often failing after 2-3 years of hand pump abstraction. These aquifers have been described in the Hydrogeological Assessment Project of the Northern Regions of Ghana Atlas (Carrier et al., 2009).

Elevation masl	Geology	No. Bhs	Regolith Base (m)	Mean Bh Depth (m)	Yield (l/s)
99 - 242	Voltaian Basin Sediments	122	9.2	34.2	2.42
99 - 116	Non-fractured Shale and Sandstone	8	2	31.9	1.47
121 - 220	Massive Conglomerate and Sandstone	54	12.3	36.7	2.23
160 - 242	Quartzitic Sandstone and Conglomerate	21	12.8	34.6	1.24
113 - 216	Feldspathic Sandstone, Siltstone and Mudstone	39	4.3	30.8	3.4

Table 4. Mean regolith depths, borehole yields and depths within elevation ranges in the Voltaian aquifers of the Afram Plains, Ghana (Davies and Cobbing, 2002).

Geological Formation	Lithologies	No. Bhs	Elevation (masl)	Mean Bh Depth (m)	Yield (l/s)
Afram	Mudstones, siltstones	95	87-161	58	1.0
Anyaboni	Sandstones	104	108-248	50.3	4.4
Bimbila	Mudstones, siltstones, sandstones	1208	104-260	54.1	1.3
Bunya	Siltstones, Sandstones	630	110-260	49.1	2.5
Chereponi	Sandstones	186	104-213	50.8	1.3
Darebe	Tuffs	86	80-210	56.5	2.7
Panabako	Sandstones	469	130-450	55.3	1.3
Tamale	Sandstones	55	150-190	60.9	2.5
Obosum	Mudstones, siltstones	913	70-200	60.3	1.0

*Table 5. Mean borehole yields and depths within elevation ranges in the Voltaian Basin formations of Northern Region, Ghana (*Carrier et al., 2009*).*

VI. DISCUSSION AND CONCLUSION

Experience in a variety of geological settings, both in granitic and gneissic rocks, indicates considerable range in depth of weathering. The soil in Zimbabwe is notably thin and in Tanzania it is highly variable. The depth to the base of the saprolite is also thin in Zimbabwe but is highly consistent in Malawi where it is between 19 and 21 m depth. Depth to the base of the saprock is least in Malawi and is highly variable in Zimbabwe. By contrast the regolith base in the Voltaian metasediments in Ghana is shallow but yield s can be higher than it is in the granites and gneisses in the Zimbabwe, Tanzania and Malawi region. In addition some weathering continues to clay grade material excluding recharge.

The evidence collectively suggest that the original standard conceptual model of the weathering profile in Basement aquifers does not fully encompass the wide range of profiles that occur. There is considerable variety in sub-Saharan Africa and there is a need to identify the different profile types that occur as sub-sets of the original model. Variation extends to climate, past climate and morphology. This range of settings suggests that the one conceptual model as a 'catch-all' is now potentially misleading as it is not necessarily universal for all situations.

The hypothesis that the traditional basement complex aquifer profile needs to include sub-sets if it is to continue to contribute to groundwater development programmes appears to be correct. Work on identifying the least number of sub-sets that are most appropriate will continue to tax hydrogeologists, but it is work that needs to be concluded at an early opportunity to help workers best develop the scarce groundwater resources available in the Basement Complex aquifers.

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