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An investigation of the basement complex aquifer system in Lofa County, Liberia, for the purpose of siting boreholes

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Abstract

Liberia is recovering from a 14 year civil war and only 51% of the rural population has access to safe drinking water. Little hydrogeological knowledge survives in Liberia increasing the difficult in successfully siting new boreholes. An understanding of the local hydrogeological environment is therefore needed to improve borehole site selection and increase success rates. This research provides a semi-quantitative characterisation of the hydrogeological environment of the basement aquifer in Lofa county, Liberia. Based on literature review and analysis of borehole logs, the study has developed a conceptual hydrogeological model for the local conditions, which is further characterised using 2-D geo-electric sections. Groundwater is predominantly obtained from the saprolite and underlying fractured bedrock, but specific capacities (median 281 L/hr/m; 25 and 75th percentile of 179 and 490 L/hr/m, respectively) are constrained by the limited thickness of the saturated saprolite. This study has shown that the

groundwater resources in the crystalline basement in this part of Liberia conform to the general conceptual model, enabling standard techniques used elsewhere for siting and developing groundwater to be used.

Keywords

2D electrical imaging, Regolith, Saprolite, Liberia, groundwater development

Introduction

Liberia is recovering from a devastating 14 year civil war, which has had serious consequences for both water supply and sanitation and the understanding of groundwater resources. Only 51% of the rural population has access to improved drinking water sources (WHO and UNICEF 2010), so achieving the Millennium Development Goal (MDG) of halving the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015 (MDG 7c) requires the construction of many new sustainable water points, as well as the maintenance of existing ones. A number of international NGOs are co-operating in Liberia within a programme to improve access to safe water, sanitation facilities and hygiene standards, with groundwater development a focus in rural communities. Boreholes are generally drilled using a truck mounted 10” (254mm) mud rotary drilling rig for the unconsolidated zone and a 7⅞” (200mm) Down-The-Hole (DTH) hammer drilling for hard rocks. Borehole depths commonly range from 20 to 40m with an installed plain casing and screen of 100mm diameter, and gravel packs in the screened unconsolidated zone. Each new borehole is intended to supply up to 500 people, using an Afridev hand pump. A successful borehole is defined by Action Contre le Faim (ACF), an NGO working in Liberia, , as one which achieves a minimum yield of 1000 L/h using a handpump throughout the year and is located within 500m of the community. Although this target yield may be considered high for some temperate crystalline aquifers (e.g. for Norway and Sweden - Misstear et al., 2006; Box 10.1), it is below reported median and average yields in basement complex areas of southern Zimbabwe (Wright, 1992), eastern Chad (Misstear et al., 2006 Box 10.1) and Ghana (Dapaah-Siakwan & Gyau-Boake, 2000),.

Achieving successful boreholes requires appropriate site selection based on an understanding of the hydrogeological environment. Approximately 40% of sub-Saharan Africa is underlain by Precambrian crystalline bedrock (MacDonald et al., 2005). Aquifers can develop within the weathered overburden (regolith and saprolite) and weathered or fractured bedrock (saprock) but the amount of groundwater found in the fresh bedrock is negligible (Acworth, 1987; Wright, 1992; Chilton and Foster, 1995; Taylor and Howard, 2000; MacDonald et al., 2005). However, whilst recent broad scale assessments exist (MacDonald et al., 2012), little hydrogeological research and data are available for Liberia because of past political and economic instability associated with the two civil wars in between 1989 and 2003. Most surviving data originate from pre-war times, especially the 1970s and 1980s (e.g Seitz, 1974; Beherent and Wotorson, 1974; and the data compilation of Wahl, 2007).

Away from the larger sedimentary aquifers in Africa, achieving borehole yields of above 0.5 l/s (1800 L/h) requires effective hydrogeological investigation and borehole siting (MacDonald et al., 2012). As a consequence of the limited understanding of the hydrogeological environment of Liberia, high borehole failure rates of up to 40% or higher have been common among groundwater project implementers (e.g. ACF, unpublished data, 2006). The aim of this research therefore was to develop a conceptual hydrogeological model of groundwater occurrence in Lofa county in Liberia (Figure 1) through analysis of driller's logs and geophysical investigation.

Material and methods

Study site

Lofa county is located in the northwest of Liberia bordering Guinea (north east) and Sierra Leone (west) and contains approximately 270,000 inhabitants at an average density of 27.7 people/km^2 (Government of the Republic of Liberia, 2008), see also Figure 1. Most of the population live in rural villages and small towns close to a sparse network of roads, whilst large areas of dense and inaccessible rainforest remain uninhabited. Water supplies are largely dependent on boreholes and hand dug wells, even in the county capital of Voinjama (26,600 inhabitants), since the communal pipe network was destroyed during the civil wars.

The landscape of Lofa is characterised by hilly topography, with rounded and elongated hilltops up to 300m above the surrounding terrain, and dense rainforest except when cleared (Seitz, 1974). The average terrain lies at approximately 400m above sea level (asl), with only the Wologizi mountain range rising up to 1400m. Annual precipitation ranges from 2000-3000mm (Figure 2), much less than at the coastline of Liberia (De Boer et al., 1982), with the rainy season lasting from May to October. Peak monthly rainfall occurs in July and August, with a dry period from December to April. Temperature remains relatively stable around 26°C throughout the year with daily minimum and maximum temperatures of between 10- 37°C (Reed, 1951).

Liberia is part of the West African Craton, and crystalline rocks are dominant except at the coastline where unconsolidated sediments are found (Schlüter, 2008). A geological map of the country is found in Figure 3. Lofa lies upon the Precambrian Guinean Shield (Seitz, 1974). Granitic gneiss and granite make up 85% of the lithology with lesser areas of ultramafic rocks, amphibolite, dolerite dikes, schists and iron formations (Beherent and Wotorson, 1974). Intensive weathering causes bedrock to only be exposed in road cuttings, stream channels and steep flanked Inselbergs (granitic domes) (Seitz, 1974). Thermotectonic activity around 2.7 billion years ago (Liberian Age Province) was responsible for major folding, faulting and shearing with a general north east structural trend (White, 1970). Dolerite dikes are estimated to be 1.2-2.8 billion years old in Lofa, which is much older than the Jurassic age dikes in other parts of Liberia (Grommé and Dalrymple, 1972). Lateritic soil is usually the top sequence of the weathering profile (Reed, 1951).

2.2Methodology

A two stage methodology to characterise the hydrogeological environment was applied, based upon (1) the development of a semi-quantitative conceptual model of groundwater occurrence through literature review and borehole log analysis; and (2) application of 2D geo-electric profiling to characterise groundwater occurrence in key landscape positions.

Development of a conceptual hydrogeological model for Lofa county

Literature on geology and groundwater for tropical Africa (e.g. Chilton and Foster, 1995; Taylor and Howard, 2000, Foster 2012; Lapworth et al., 2013) and Liberia in particular (e.g. Seitz, 1974; Beherent and Wotorson, 1974) was reviewed to understand the likely geological sequence and groundwater occurrence in areas of crystalline bedrock in Lofa county, Liberia. Seventy-four geological logs from boreholes drilled by ACF between 2007 and 2011 in Lofa county were analysed to provide a semi-quantitative understanding – these were based on information provided by the drillers, although experienced ACF staff supervised drilling during the course of drilling campaigns. These included 55 successful boreholes, 19 unsuccessful boreholes and average discharge and drawdown data from 44 steady state pumping tests. Data on laterite, saprolite and fractured bedrock thicknesses and depth to fresh bedrock were compiled from borehole logs, together with depth to the static water table and borehole construction data. These data were analysed to understand geological variability and static water table depth in the lithological sequence.

Refinement of the conceptual model through geophysical investigation

Initial fieldwork observations revealed that exposed outcrops are scarce so structural investigations of fracture directions are difficult, although some exposures are found at the granitic domes (inselbergs) and in fluvially-eroded valley bottoms. However, it was observed that most valleys follow tectonic fault structures, and springs were also associated with fractures. Profiles for geophysical investigation were hence selected to characterise groundwater occurrence in key subsurface structures (deep weathering zones, fracture zones, weathered dykes, seasonal wetlands). Where these were associated with fracture zones, the geoelectric profiles were orientated as far as possible to intersect the fracture zones at right angles. Elevation differences across the profile were measured using the water tube level method (Critchley 1991)

Geophysical investigation was performed using 2D electrical resistivity imaging. An IRIS SYSCAL R1 SW72 with 4m electrode spacing on a Schlumberger-Wenner array was used, with RES2DINV software (Geotomo Software, 2011) used for robust inversion of the pseudosection. The 2D electrical resistivity imaging technique was used instead of the more usual electromagnetic methods to trial its utility in the region, where borehole failure rates of 40% or more were common. A topography correction was applied that shifted the surface nodes of the mesh to match the actual topography before running the inversion (Griffiths and Barker 1993, Loke and Barker 1996). The amount they are shifted is reduced exponentially with depth such that at sufficiently great depth the nodes are not shifted, as it is expected that the effect of the topography is reduced with depth (Holcombe and Jirack 1984). Loke (2000) defines this as a constant that controls the degree of damping. Here this constant has a value of 0.75.

The hydrogeological interpretation of the pseudo-sections was based on true resistivity values associated with similar lithological sequences from Kellet and Baumann (2004), Olayinka and Weller (1997) and Beauvais et al. (1999). The interpretation of some of these profiles was verified through drilling. The drilling was primarily intended to produce water supply boreholes so selected drilling sites were chosen according to both their hydrogeological potential and their suitability to the local communities. Geoelectrical sections without associated borehole logs were those not considered sufficiently promising for groundwater development to merit the time and expense of drilling water supply boreholes.

Case study of the use of the conceptual hydrogeological model in borehole siting

With a greater understanding of the aquifer structure, it is possible to select sites for borehole drilling in a more informed way. To illustrate this, a case study of the village of Halipo is presented. As well as knowledge of the aquifer, the sites for the drilling of water supply boreholes also had to be:

- close to the village;
- away from potential sites of contamination including latrines, open defecation fields, solid waste disposal sites, graves and wetlands. The latter are particularly associated with unacceptable water quality because here the water table is shallow and hence the unsaturated zone is thin (ACF, unpublished data, 2008);
- accessible for the drilling truck. Due to the truck's size, dense vegetation and rough terrain, siting was often limited to close to the access road of a village;
- acceptable to the user community.

Results and Discussion

Conceptual hydrogeological model for groundwater occurrence in areas of crystalline bedrock in Lofa county

A conceptual model based on the integration of insights from the literature and available borehole logs from Lofa county is shown in Figure 4 and described below.

Previous studies in similar environments (Acworth, 1987; Wright, 1992; Taylor & Howard, 2000; MacDonald et al, 2005; Yidana et al., 2011; Foster 2012; Lapworth et al., 2013) suggest that a downward sequence of soil, laterite, saprolite, saprock and unweathered bedrock should be expected, with groundwater associated with the saprolite and saprock/fractured bedrock – with the greatest permeability at the base of the weathered zone where the rock is fractured yet still coherent, but the greater storage in the more weathered but lower permeability material above. This was largely supported by the analysis of the borehole logs. However, we use the term "fractured bedrock" to comprise both saprock and deeper (tectonically) fractured bedrock, as differentiating them in the historic borehole logs was not possible. The mean and standard deviation for layer thicknesses were calculated. All thicknesses were found to be highly variable, with the exception of laterite thickness and depth to the water table (see Table 1 and Figure 4). The base of the saprolite and the fractured bedrock are considered to be the most permeable zones, which should be targeted to achieve a sufficient borehole yield (MacDonald et al. 2005).

The typical recorded regolith thicknesses of 10-20 m are in the range of those encountered in other basement complex areas (e.g. Jalludin and Razach, 2004) although a range of 20 to 30m is common in many sub- Sahara African areas (MacDonald et al., 2005). This may be because the combination of tropical climate, high precipitation and hilly topography give rise to high rates of colluvial and fluviatile erosion and sediment removal.

Of the 19 boreholes that failed because of insufficient yield (<1000 L/hr), 15 had a saprolite sequence thinner than 4m and only 3 had a fractured bedrock thicker than 2m, indicating the importance of the thickness of these relatively permeable zones. Although the average static water level at 7.1$\pm$ 2.4 m depth appears often to be at around the laterite/saprolite boundary where permeabilities are expected to be low due to the higher proportion of secondary clay minerals, the aquifers are considered to be unconfined with the upper zones of the water-saturated saprolite providing important groundwater storage. Based on the saturated geological sequences captured by the well screens of successful boreholes, 57% of boreholes obtained their yield solely from the saprolite, 26% from underlying fractured bedrock and 17% from a combination of both. No statistically significant relationships were observed between specific capacity (yield per unit drawdown) and either screen length, saprolite thickness or fractured bedrock thickness. In the boreholes considered as part of this study, on average only 56% of the saturated saprolite thickness was adjacent to screened parts of the borehole, but it is not clear if this is because significant pumped drawdown is expected in this low transmissivity aquifer, or simply that there is widespread poor borehole design.

The distribution of specific capacity within 44 successful boreholes in which both yield and drawdown data were available is skewed towards low values (Figure 5), with a median specific capacity of 280 L hr^{-1} m^{-1} (25 and 75th percentile of 179 and 490 L/hr/m, respectively). This is generally higher than those reported for small-diameter boreholes in weather crystalline basement aquifers in Zimbabwe, Nigeria and Malawi Chilton and Foster (1995), although less that that reported for a Cote d'Ivoire (Soro et al., 2010). Given these measured specific capacities, boreholes must have sufficient borehole depth and screened permeable zones to allow typical drawdowns of around 4 m to meet the NGO requirement that a successful borehole must achieve a minimum yield of 1000 L/h. Given that the average water saturated saprolite thickness of 6.2 m± 5.0 m within the available borehole logs, it is apparent that identifying deeper areas of weathering and/or fracturing is vital for successful borehole siting in Lofa county, although the target yield is below the median yield of 1500-2000 L/h and the average yield of 2700-12700 L/h reported in the basement complex eastern Chad (Misstear et al., 2006 Box 10.1) and Ghana (Dapaah-Siakwan & Gyau-Boake, 2000), respectively.

Examples of interpreted 2D imaging profile

26 geoelectrical profiles were surveyed, with drilling of water supply boreholes being carried out at 6 of them. Examples of selected interpreted profiles are given below to illustrate typical subsurface structures associated with promising (Figures 6a and b) and poor (Figures 6c and d) groundwater occurrence. As shown in Figure 3, all the profiles were situated on Precambrian granitic rocks. Previous resistivity profile interpretations by Olayinka and Weller (1997), Beauvais et al. (1999) and Kellet and Baumann (2004) were used to guide initial interpretations.

Figure 6a shows a SW-NE profile in a typical flat area with deep weathering of the crystalline basement. A water supply borehole was subsequently sited at 80m along the profile. The profile shows an increase in resistivity at 21m depth which drilling confirmed corresponded to the saprolite - saprock boundary (Figure 6c). The water table was expected to be below the zone of resistivities above 700 Ohm m and was confirmed at 6m during drilling. High resistivity zones (1000-3000 Ohm m) close to the surface were interpreted as the underground extent of a near-surface granite boulder at about 64m along the profile and dry ferruginous crust between 20 and 64m along the profile.

Figure 6b shows a SSE-NNW profile which extends from a shallow valley containing a wetland to the valley side beyond – a correction was applied to the inversion to remove the topography, but a 5 m change in elevation at the valley edge occurs between 140 and 160 m along the profile. The upper horizontal high resistivity zone (600- 2500 Ohm m) was associated with dry laterite and unsaturated saprolite. The aquifer is identifiable below resistivity zones of 700 Ohm m with the water table encountered at 9.2m depth during drilling at 104 m along the profile (Figure 6d). The aquifer does not extend beyond the edge of the valley bottom at 140m. A large crystalline boulder exposed at the surface is clearly detected at around 170 m along the profile. Bedrock was encountered during drilling at 20m which agrees well with the geoelectrical interpretation (Fig 6d).

Figure 6e shows a W-E geoelectric section aligned across a fracture zone. The vertical and horizontal extent of the fractured zone are interpreted as the lower resistivity areas of less than 1600 ohm-m, with localised areas of possibly saturated material. The section was located on a hill with a thin regolith sequence and common granitic outcrops (seen in the resistivity values above 3000 Ohm m). Drilling did not take place at this profile due to the uncertainty of whether the low resistivity area within the fracture zone was water bearing or rich in clay.

The Schlumberger- Wenner Array with an electrode spacing of 4m proved to be a good choice to obtain useful information on vertical and lateral structures, whilst the robust inversion, which was used instead of the common least squares inversion, avoided a “smearing” effect which would be inconsistent with the abrupt observed transitions between geological sequences (especially regolith to bedrock). It was possible to distinguish between bedrock and regolith, although fractured bedrock can be associated with a wide range of true electrical resistivity causing uncertainty. The predicted depth to bedrock on the basis of the geoelectric interpretation was within approximately 2 metres of that observed at the 3 borehole sites where drilling penetrated through the regolith.

Lithologies associated with true electrical resistivity values through validation of geoelectrical interpretations against borehole logs in Lofa county are given in Table 2, which are consistent with those given elsewhere (e.g. Aizebeokhi et al., 2010; Ritz et al., 1999). High resistivity zones in the upper regolith are either dry material, hard ferruginous crusts in the laterite or granitic boulders. Depth to the water table can be recognised if measurements take place after days of no rainfall- however, this study was conducted at the beginning of the wet season and laterite and saturated saprolite were often indistinguishable.

Case study of borehole site selection in a village

The village of Halipo (Figure 7a) has approximately 900 inhabitants, and stretches from the bottom of a valley (at around 470m m asl) to the top of a granitic dome (515m asl) over an area of approximately 70 000m^2. The current water supply for the village was a working hand dug well with an Afridev handpump, but it was sited close to a wetland and villagers believed that the water was making them ill. An old protected hand dug well was not useable since the pump was missing. It seemed unmaintained for a longer period of time and would have needed chlorination. Restoration was not an option since it was also closely sited to the wetland. Finally, 8 latrines were mapped as potential sources of contamination.

The synthesis of the results from the application of the improved understanding within a borehole siting strategy are compiled in Figure 7. Exposed granite bedrock was frequently found near the top of the dome with at least one preferred joint direction (strike 315°/ dip 52°), indicating a thin / non-existent regolith. Wetlands were located in the valley bottom. Seasonally varying spring outlets occurred in the fracture zones and springs had discharges of less than 0.2l/s with electrical conductivities between 28.5-103.5 µS/cm. The Kelba River flows about 400m to the east of the village but potential sites in the alluvium of the river or the small tributaries shown in Figure 7a) were not desired by villagers because of the distance from their community.

Five 2D electrical imaging profiles were conducted to investigate the thickness of regolith and the extent of fracture zones. Interpretations showed that regolith thickness increases towards the valley with a sharp boundary with the bedrock. Of the promising potential locations for drilling identified from the field and geolectrical surveys, the site selected by the community was drilled in Profile 5 at a distance of approximately 40m uphill from the wetland (Figure 7a). The depth of investigation with 2D electrical imaging at the selected drilling site was limited to approximately 15m, as the site was close to the edge of the profile. A yield test after borehole development gave around 2,100 L/h at a dynamic water level of 12.56 m below ground level (m bgl) (a drawdown of about 7m from the static water level of 5.57 m bgl) Figure 7b shows the 2D imaging profile and Figure 7c a comparison of the borehole log versus the 2D imaging prediction.

Conclusions

As the first semi-quantitative assessment of aquifer characterisation and borehole yields in the country since the civil wars, this study demonstrates that for an adequate borehole yield in Lofa county the borehole needs to intersect sufficient weathered crystalline rock and potentially deeper fractures of tectonic origin in the fresh bedrock underneath. While the solid lithologies (granite and gneiss) are relatively uniform within Lofa, the thicknesses of the weathered lithologies are highly variable. Boreholes may be vulnerable to failing during the height of the dry season owing to the generally low depth to fresh bedrock that rarely exceeds 25m. As the water table is usually found at a depth of around 7m (within the range given for Liberia by MacDonald et al. 2012), borehole site selection should seek to identify deeper pockets of weathering with a regolith thickness of at least 15-20m. However, where absent, fracture zones are the only siting option but are associated with a higher risk of unsuccessful siting.

The 2D electrical resistivity imaging proved to be highly suitable to describe watertable depth, depth to the bedrock and extent of fracture zones. It is debatable whether the method will add significant value in borehole siting compared to cheaper or less sophisticated geophysical methods such as 1D resistivity sounding and profiling or electromagnetic methods (as described by MacDonald et al., 2005 and Siemon 2010) in those areas with predictable groundwater occurrence, but provides significant insights in more complex hydrogeological conditions. However, the method has helped to confirm that the previous conceptual hydrogeological model for such environments (e.g. Acworth, 1987; Wright, 1992; Taylor and Howard, 2000; Chilton and Foster, 1995; MacDonald et al, 2005) is applicable for the local conditions, although regolith thicknesses of 10-20 m are relatively low compared to many sub- Sahara African areas. Owing to 14 years of civil war and past political and economic instability, little hydrogeological research and data are available in Liberia, with most surviving data originating from before the 1980's. This paper, associated with the activities of NGO's to provide clean drinking water for rural inhabitants, has shown that the groundwater resources in the crystalline basement in this part of Liberia conform to the general conceptual model of groundwater occurrence and the results of MacDonald et al (2012), enabling standard techniques used elsewhere for siting and developing groundwater to be used.

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References

Acworth RI (1987) The development of crystalline aquifers in a tropical environment. Quarterly Journal of Engineering Geology 20: 265-272.

Aizebeokhai AP, Olayinka, AI, Singh VS (2010). Application of 2D and 3D geoelectrical resistivity imaging for engineering site investigation in a crystalline basement terrain, southwestern Nigeria. Environ Earth Sci 61:1481-1492

Beauvais A, Ritz M, Parisot J, Dukhan M, Bantsimba, C. (1999) Analysis of poorly stratified lateritic terrains overlying granitic bedrock in West Africa using 2D electrical resistivity tomography. Earth and Planetary Letters 173: 413-424.

Beherent JC, Wotorson CS (1974) Geophysical Surveys of Liberia with tectonic and geological interpretations, U. S. Geological Survey Prof. Paper 810, Washington.

Chilton PJ, Foster, SSD (1995) Hydrogeological investigation and water-supply potential of basement aquifers in tropical Africa. Hydrogeology Journal 3(1): 36-49.

Critchley W (1991) Looking after our land, Soil and Water Conservation in Dryland Africa, Oxfam Publications, Oxford, UK

Dapaah-Siakwan S & Gyau-Boake P (2000) Hydrogeologic framework and borehole yields in Ghana. Hydrogeology J., 8; 405-416.

De Boer, E., Glay, E. and Hall C. Jr. (1982). Preliminary study for the water supply of Kolba city (Kolahun), Lofa County, Monrovia. Liberian Hydrological Service, Monrovia

Foster, S (2012) Hard-rock aquifers in tropical regions: using science to inform development and management policy, Hydrogeology Journal 20: 659–672

Geotomo Software (2011) Rapid 2-D Resistivity & IP inversion using least squares-method: Wenner (a,b,g), dipole-dipole, inline pole-pole, poledipole, equatorial dipole-dipole, offset pole-dipole, Wenner-Schlumberger, gradient and non-conventional arrays On land, aquatic and cross-borehole surveys. Geotomo Software, Penang.

Government of the Republic of Liberia (2008) National Population and housing census: Preliminary results. Liberia Institute of statistics and geo-information services, Monrovia.

Griffiths D.H. and Barker R.D.,1993. Two-dimensional resistivity imaging and modelling in areas of complex geology. Journal of Applied Geophysics, 29, 211-226.

Grommé S, Dalrymple GB (1972) K-Ar ages and paleomagnetism of dikes in Liberia. American Geophysical Union 53 (10): 1130

Holcombe, J. and Jirack, G., 1984. 3-D terrain corrections in resistivity surveys. Geophysics, 49, 439-452.

Jalludin M, Razach M (2004) Assessment of hydraulic properties of sedimentary and volcanic aquifer systems under arid conditions in the Republic of Djibouti (Horn of Africa). Hydrogeology Journal, 12; 159-170

Kellett R, Bauman P (2004) Mapping groundwater in regolith and fractured bedrock using ground geophysics: a case study from Malawi, SE Africa. Canadian Society of Exploration Geophysicists, February 2004: 24-33

Lapworth, D. J.; MacDonald, A. M.; Tijani, M.N.; Darling WG, Gooddy DC, Bonsor HC, Araguas-Araguas LJ (2013). Residence times of shallow groundwater in West Africa: implications for hydrogeology and resilience to future changes in climate. Hydrogeol. J. 21(3): 673-686

Loke, M.H., (2000) Topographic modelling in electrical imaging inversion, EAGE 62nd Conference and Technical Exhibition — Glasgow, Scotland, 29 May - 2 June 2000. Proceedings of the 62nd European Association of Geoscientists and Engineers (EAGE) Conference & Technical Exhibition, Glasgow, Glasgow; Session DO2

Loke M.H. and Barker R.D.,1996. Rapid least-squares inversion of apparent resistivity pseudosections using a quasi-Newton method. Geophysical Prospecting, 44, 131-152.

MacDonald AM, Bonsor HC, Dochartaigh BEO and Taylor RG (2012). Quantitative maps of groundwater resources in Africa. Environ. Res. Lett. 7: 024009

MacDonald A, Davies J, Calow R, Chilton J (2005) Developing Groundwater: A guide for rural water supply, Practical Action Publishing Ltd, Warwickshire.

Misstear B, Banks D, Clark L (2006). Water Wells and Boreholes. J Wiley and Sons, Chichester, UK

Olayinka AI, Weller A (1997) The inversion of geoelectrical data for hydrogeological applications in crystalline basement areas of Nigeria. Journal of Applied Geophysics 37: 103-115

Reed WE (1951) Reconnaissance: Soil Survey of Liberia. Agriculture Information Bulletin, 66: 1-29.

Ritz, M; Parisot, JC; Diouf, S; Beauvais A, Dione F, Niang M (1999). Electrical imaging of lateritic weathering mantles over granitic and metamorphic basement of eastern Senegal, West Africa. J Applied Geophys 41(4): 335-344

Schlüter T (2008) Geological Atlas of Africa, 2nd ed., Springer, Berlin Heidelberg.

Seitz JF (1974) Geology of the Voinjama Quadrangle, Liberia, U. S. Geological Survey Open-File Report 74-301.

Siemon, P (2010) Electromagnetic methods- frequency domain. Cited in: Kirsch R (2010). Groundwater geophysics: A tool for hydrogeology. 2nd ed., Springer, Berlin Heidelberg, p.155-178.

Soro S, Soro N, Ahoussi KE, Lasm T, Kouame FK, Soro TD, Biemi J (2010) Assessment of the hydraulic properties of fractured aquifers in crystalline and metamorphic formations in the region of Lacs (Central Côte d'Ivoire). Estudios Geológicos, 66(2): 227-242

Taylor R, Howard K (2000) A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: Evidence from Uganda. Hydrogeology Journal 8: 279-294.

Wahl RR (2007). Geological, geophysical and mineral localities map of Liberia- A digital compilation. USGS Open-File Report 2007-1258.

White, RW (1970). Reconnaissance mapping of weathered crystalline rocks in Liberia, Mining and Metallurgy Society Liberia Bulletin 4: 96-102.

WHO and UNICEF (2010). Progress on Sanitation and drinking water, 2010 update. World Health Organization, Geneva.

Wright EP (1992). The hydrogeology of crystalline basement aquifers in Africa. Geological Society Special Publication 66: 1-27.

Yidana SM, Ganyaglo S, Banoeng-Yakubo B, Akabzaa T (2011) A conceptual framework of groundwater flow in crystalline aquifers in Southeastern Ghana, Journal of African Earth Sciences 59: 185-194.

Figure captions

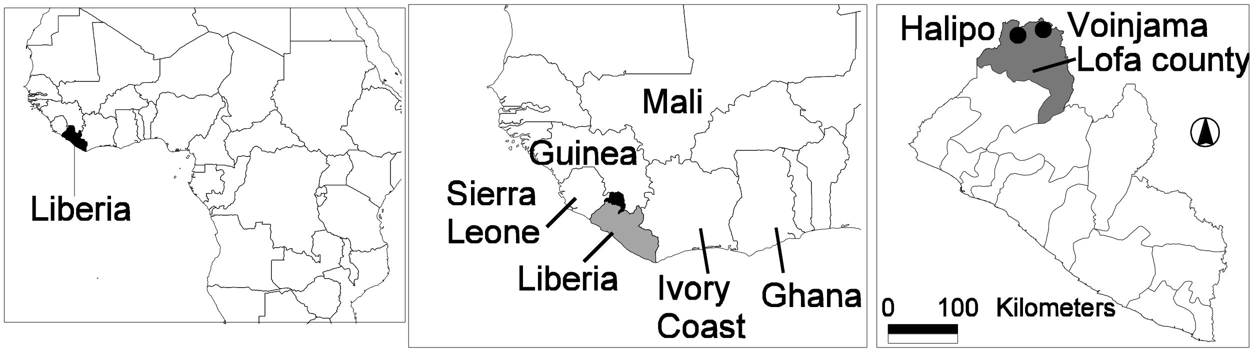

Fig 1 Location of Liberia and Lofa county

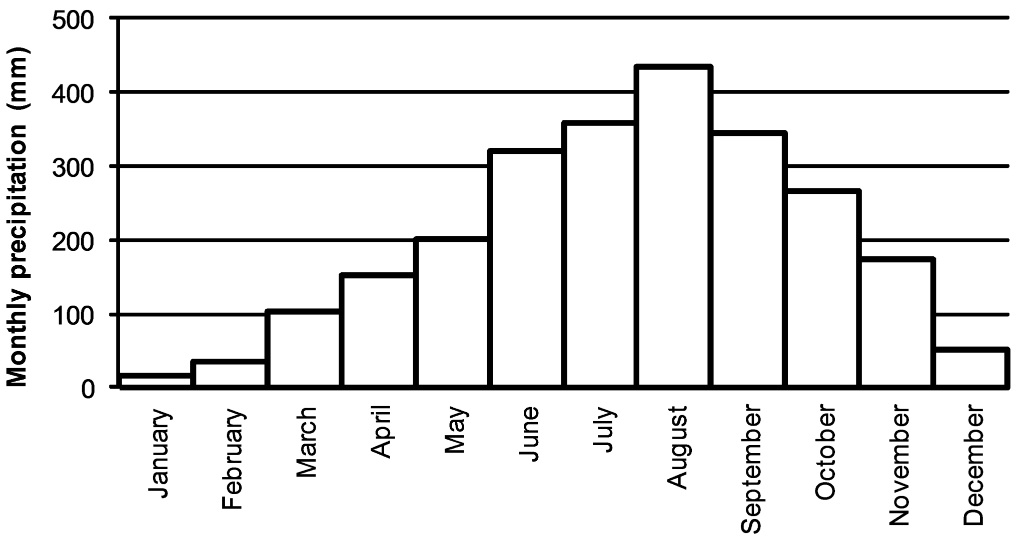

Fig 2 Mean monthly precipitation for Voinjama for 1953-73 and 1978-80 (from previously unpublished data by De Boer et al. 1982)

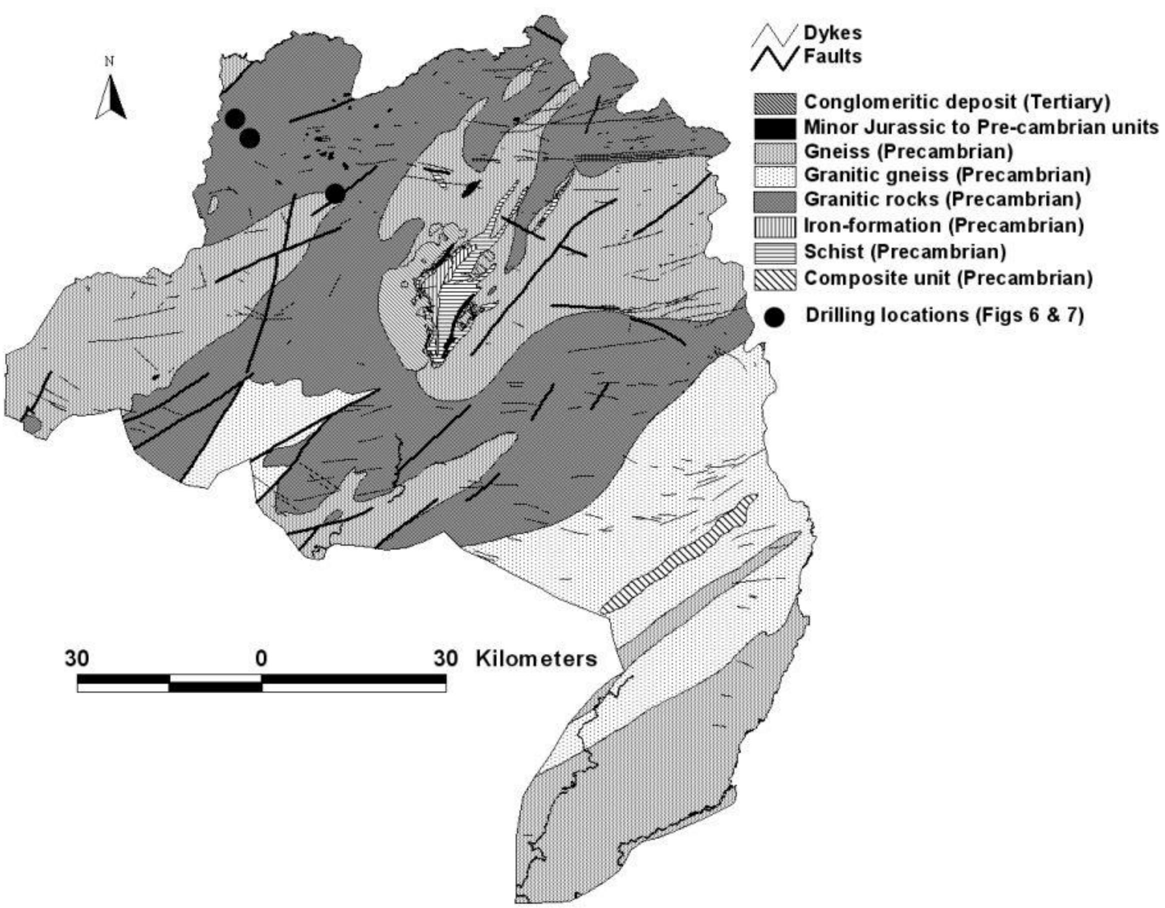

Fig 3 Geological map of Lofa County, Liberia (from Wahl, 2007) showing approximate locations of drilled boreholes illustrated in Figures 6 and 7.

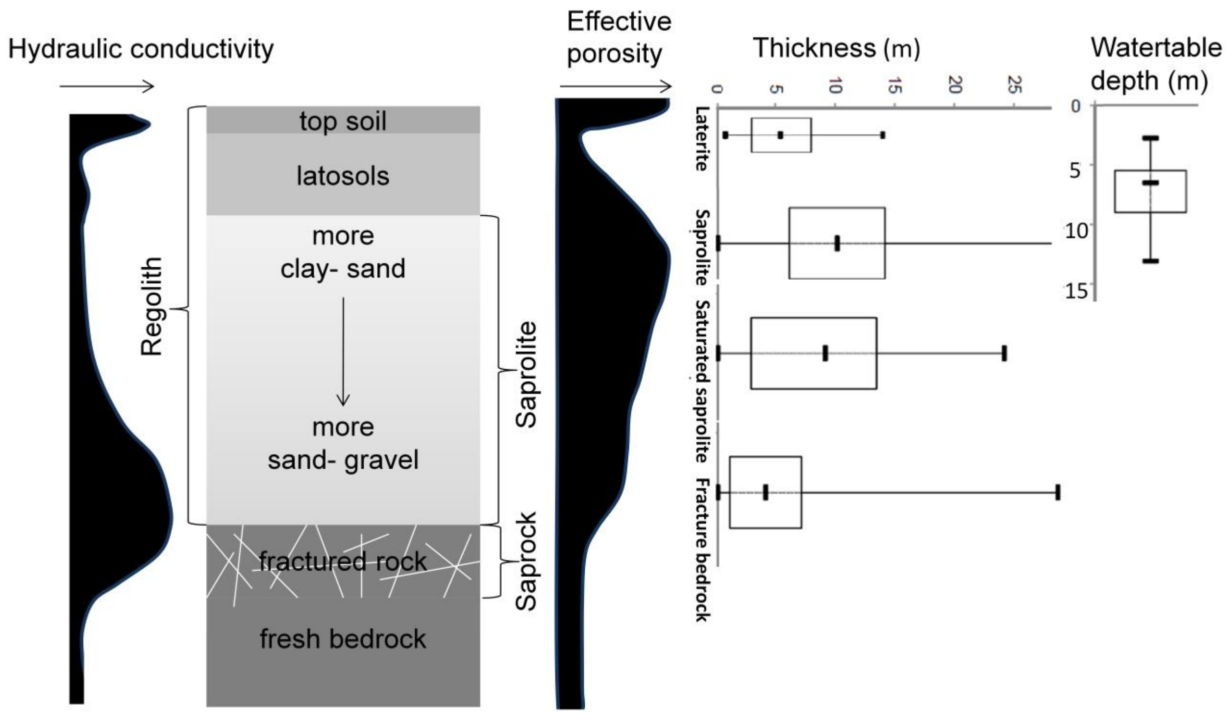

Fig 4 Conceptual hydrogeological model for groundwater occurrence in weathered basement in Lofa county (modified after: Chilton and Foster 1995) with boxplots (median, minimum, maximum, 25% quartile, 75% quartile) of lithological sequence thicknesses and water table depth obtained from drillers' logs for successful boreholes.

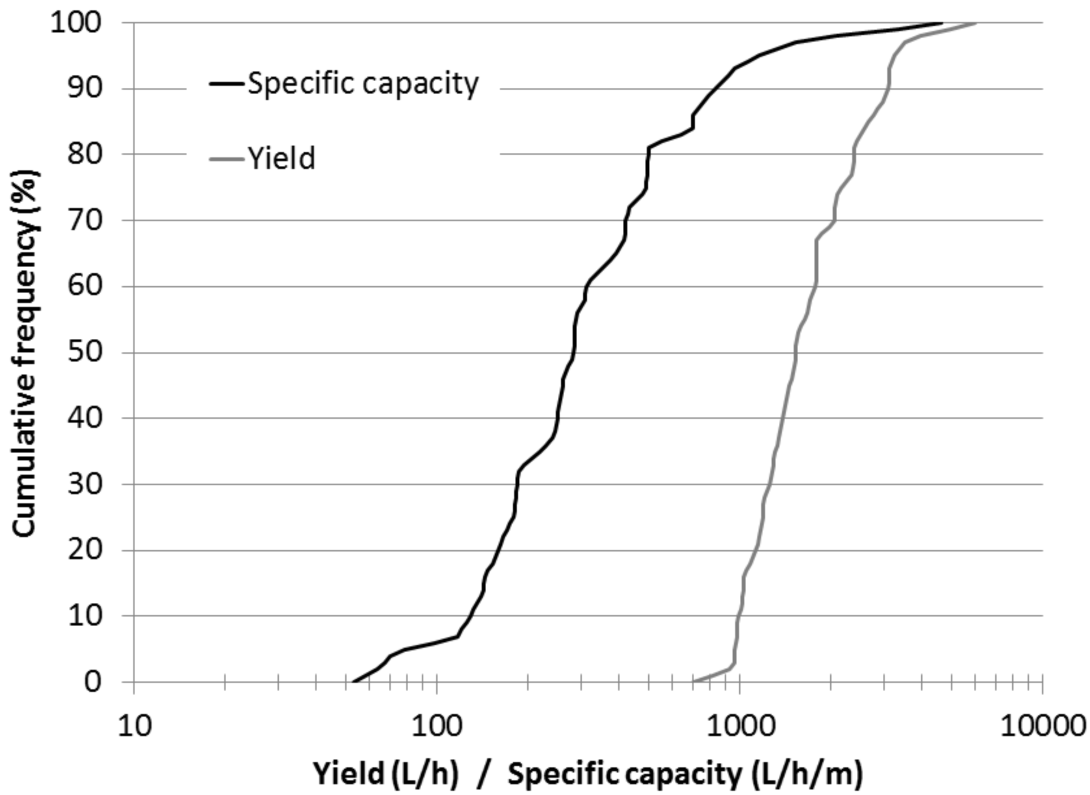

Fig 5 Cumulative frequency plot of specific capacity and yield within 44 successful boreholes in Lofa county

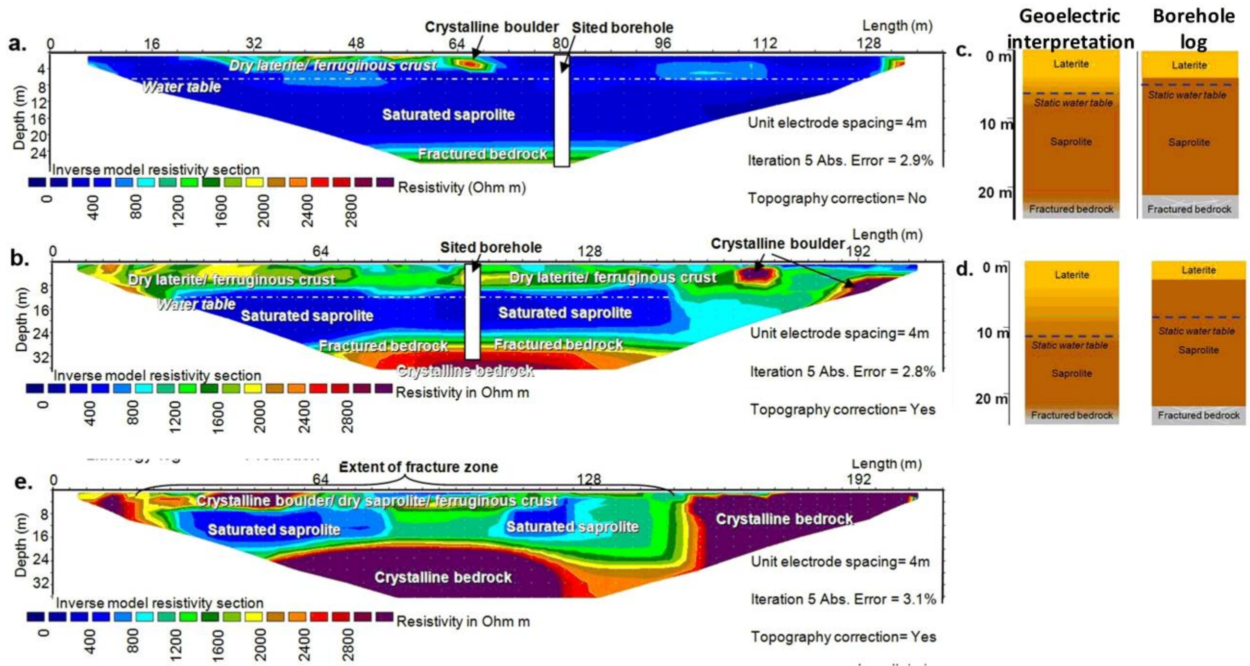

Fig 6 Examples of 2D electrical resistivity imaging pseudo-sections and interpretations for (a and c) flat area with deep weathering [Lat 8.36111°; Long 10.19952°]; (b and d) dambo with valley bottom sediments [Lat 8.37787°; Long 10.25864°], and (e) fracture zone [Lat 8.29024°; Long 10.07607°]. Approximate location is shown in Figure 3.

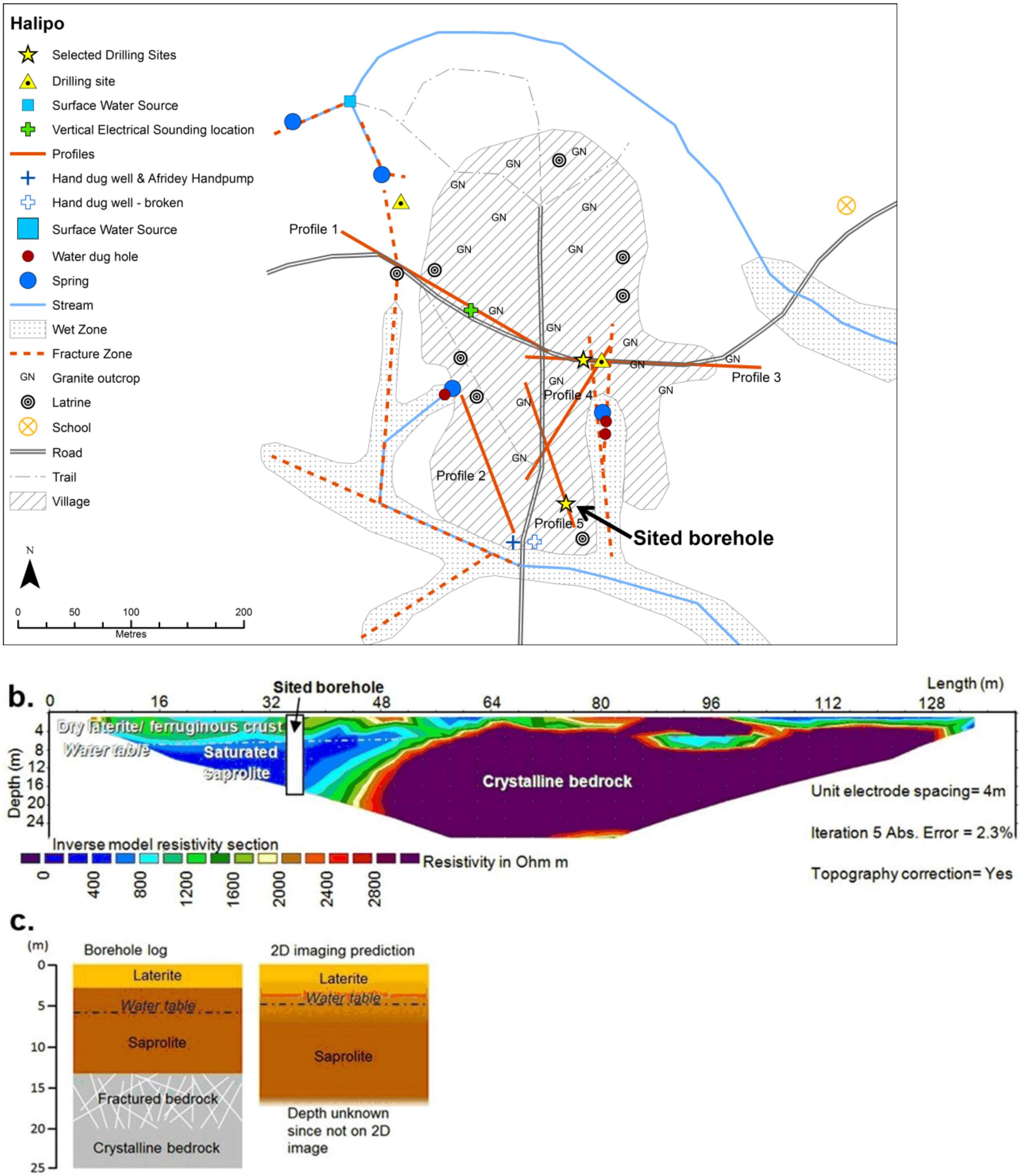

Fig 7 Case study of borehole site selection or the village of Halipo (Lat 8.28929°; Long 10.07765°) in Kolahun district with (a) hydrogeological mapping, (b) Profile 5 geoelectric section and (c) comparison of geoelectrical interpretation and borehole log. Approximate location is shown in Figure 3.