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Hydrogeological Investigations of the Ouagadougou Area (Burkina Faso) Using a Combination of Geological and Geophysical Methods

Hydrogeologische Untersuchungen im Gebiet von Ouagadougou (Burkina Faso) mittels einer Kombination geologischer und geophysikalischer Methoden

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Content

1. Introduction

As other Sahelian countries, Burkina Faso has serious problems of water resources (drinking water and water for agriculture). Since the independence of the state in 1960 some dams have been constructed in order to supply big cities like Ouagadougou and others with drinking water. However, there is still an increased water problem due to the growing population and decrease of rainfall; for example in Ouagadougou, only 40 % of the population has access to drinking water.

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The central problem is lack of systematic prospection, effective (water) management, and protection of groundwater (S. Mandouh, 2002). This study gives a methodical contribution for groundwater exploration using geological and geophysical techniques, applied in a selected area.

2. Geology of Burkina Faso and the area of investigation

Most parts (> 80 %) of Burkina Faso are occupied by Archean and Proterozoic rocks (A. Blanchot & J. Marcellin, 1972, A. Kim et al., 2004). These formations are known as Precambrian D (Ante-Birrimian; Archean, > 2,6 Ga), and Precambrian C (Birrimian; Early Proterozoic, about 2,2 Ga).

The basement is covered discordantly along the N and NW border by Precambrian A sediments of the Taoudeni basin and on the SE by those of Voltaien basin (Precambrian A to Eocambrian). At the extreme NW, in the plain of Gondo, Tertiary and Quaternary continental deposits (Continental Terminal) superpose directly the Precambrian A formations (A. Blanchot &. J. Marcellin, 1972, A. Kim et al., 2004).

The current area of the investigation is the region around the capital Ouagadougou and regions situated SSE (Koubri) and ESE (Mogtedo). The study is aimed at addressing:

- the shortage of water supply for the relatively highly populated area of Ouagadougou and its surroundings with about 3.8 Mio. of inhabitants,
- the increasing need of drinking water and water for agriculture, which is affected by the decreasing rainfall,
- the contamination problems due to human activities.

The basement of this area is composed of Precambrian D (basic amphibole bearing migmatites, granite consisting biotite and amphibole) intruded by post-tectonic Precambrian C tonalitic batholithes. The brittle deformation is represented by a system of faults and joints following the two principal directions: N 60°W and N 80°W.

The basement is covered by thick weathered, lateritic materials. Generally this cover has a thickness of 10–30 m. It shows three horizons, each of them with a specific mineralogy. A detailed analysis is given in section 4 “Weathering profile and position of aquifers”.

The morphology is weak and only at a few locations the basement rock is outcropping in the plain. There are some hills with maximum elevation of 200 m above the plain. These hills are also covered by laterite, but there is no information about the thickness of the laterite in the high positions and the basement rocks within the hills.

Regionally there are two aquifers in the plain region:

- aquifer A, above the clay saprolite,
- aquifer B, within the debris material zone (fractured parents rocks) which communicate with the water bearing joint system at the top of the fractured basement.

The geological investigation program includes:

- collection and compilation of geological data,
- aerial photo interpretation,
- geological field investigation,
- petrographic and petrophysical rock investigation,
- X-ray diffraction analyses of the lateritic cover,
- geophysical field investigation and borehole measurements.

3. Geologic investigation – lineament analysis

Field studies and aerial photo interpretation were applied for lineament analysis. The reliability of photo interpretation depends on the recognition and assessment of factors like topography, drainage pattern, erosion relief, vegetation, land use, outcrops and tectonic lineaments.

In the investigated area the most prominent mapped subjects are lineaments representing tectonic features (faults, joints and fractures) within the Precambrian basement. But mostly the basement is covered by the lateritic cover. The lineaments are noticed in photos by alignment of cracks like fractures and vegetation.

Photo interpretation was conducted in the southern part of Ouagadougou and the northern part of Koubri. Nearly 95 % of the basement rocks are covered by weathered materials, in average 30 m thick. Nevertheless the lineaments could be traced, where the main directions of the tectonic elements being N 50°E and E 30°S and a third along E 80°S direction (Fig. 1).

The vegetation cover is made up of trees which are well spaced and resistant to the dry season.

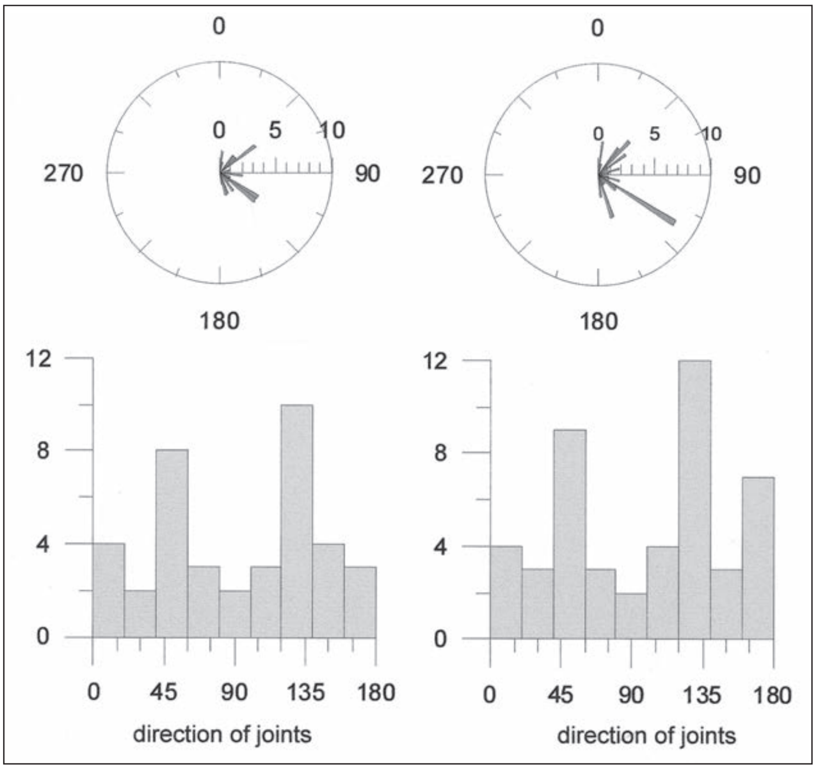

Fig. 1: ROSE diagram (upper part) and histogram (lower part) derived from outcrop joint analysis in two areas (Ouagadougou – left, Mogtedo – right).
Kluftrichtungsdiagramm (obere Darstellung) und Histogramm (luntere Darstellung), abgeleitet aus Kluftanalysen (outcrop) in zwei Untersuchungsgebieten (Ouagadougou – linke Darstellung, Mogtedo – rechte Darstellung).

Field investigation of the joint system on the outcrops revealed joints ± parallel to the surface (regularly spaced, 3–5 cm) and two systems of steeply dipping joint swarms. In Ouagadougou and Mogtedo areas, the directions of the latter cluster around the main directions can be correlated well with the directions of the photo lineaments. Altogether they show a good confidence with the main directions known from the literature: NE–SW and WNW–ESE (A. Blanchot & J. Marcellin, 1972, W. P. Sunday, 1991, A. Kim et al., 2004). At the surface all joints are sealed and do not allow water to infiltrate.

4. Weathering profile and position of aquifers

In Ouagadougou region, as shown in fig. 2, three weathering horizons overlie the basement rocks, consisting mainly tonalitic composition or subordinately basic migmatite:

- laterite horizon, forming the top soil and also the top of some hills in the region,
- clay saprolite horizon which is rich in clay minerals,
- debris materials zone formed by fragments and minerals of the parent rock within a matrix of dispersed clay material.

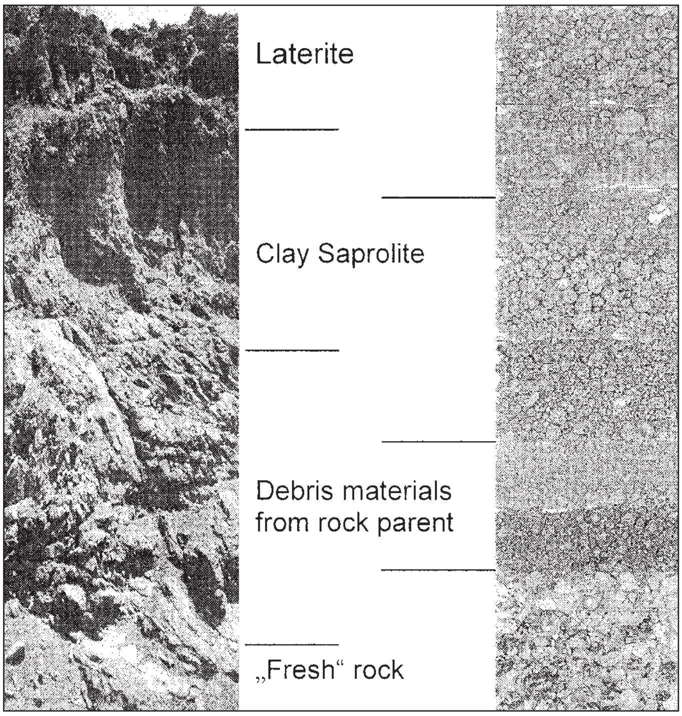

Fig. 2: Weathering profile: left – outcrop (Koubri area) of "fresh" basement rocks covered by weathered materials; right – cutting log of the borehole 2 (Mogtedo area) exploring the weathered materials. Verwitterungsprofile: Die linke Darstellung zeigt den Aufschluss im Gebiet Koubri mit einer Überlagerung des Basements durch Verwitterungsprodukte. Die rechte Darstellung stellt ein „Cutting log" des Bohrlochs 2 (Gebiet Mogtedo) dar, das die Verwitterungszone durchteuft.

In order to characterize the layers of the cover sequence complete lithologic profiles were sampled from three boreholes; X-ray diffraction (XRD) and petrophysical analysis (magnetic susceptibility measurement) were performed. Table 1 summarizes the mineral phases determined by XRD measurements.

Tab. 1: Qualitative mineral content (identified by XRD analysis) and magnetic susceptibility of the individual samples from the layers of borehole 2 (Mogtedo) and the position of the aquifers. Abbreviations for minerals: go = goethite, he = hematite, ill = illite, ka = kaolinite, sm = smectite, m-l = mixed layers, qz = quartz, ort = orthoclase, pla = plagioclase, am = amphibole, bio = biotite. From 34 m to 43 m the fresh rock basement was drilled.
Mineralbestand (qualitativ) nach XRD-Analyse und magnetischer Suszeptibilitätsmessung an Einzelproben der Horizonte in Bohrung 2 (Mogtedo) sowie Position der Aquifere. Abkürzungen für Minerale: go = Goethit, he = Hämatit, ill = Illit, ka = Kaolinit, sm = Smectit, m-l = mixed layers, qz = Quarz, ort = Orthoklas, pla = Plagioklas, am = Amphibol, bio = Biotit. Von 34–43 m wurde unverwittertes Grundgebirge erbohrt.

Horizon	Layer	Depth [m]	Iron minerals		Clay minerals				Primary rock minerals					Susceptibility	Aquifer system
			go	he	ka	ill	sm	m-l	qz	ort	pla	am	bio		
1	1	0–6	+	+	+				+					21	Upper aquifer A
	2	6–11	+	+	+				+					7	
2	3	11–15	+	+	+	+		+	+					12	Impermeable
	4	15–20	+		+	+	+		+	+				21	
	5	20–26			+	+	+	+	+	+	+			19	
3	6	26–30			+		+	+	+	+	+	+		25	Lower aquifer B
	7	30–34			+	+	+		+	+	+	+	+	17	

The diagnostic minerals of the three soil horizons are:

– 1^{st} horizon (layers 1, 2) laterite: rich in iron minerals (goethite, hematite),
– 2^{nd} horizon (layers 3–5) clay saprolite: clay minerals (illite, smectite, mixed layers),
– 3^{rd} horizon (layers 6–7) debris materials: clay minerals and mineral components from "fresh" parent rock.

Kaoline occurs in all layers. Fe-rich minerals (goethite and hematite) are concentrated at the top of the profile. Other clay minerals (illite, smectite and mixed layer) are missing in layer 1 and 2 but are concentrated in layer 3–7. In general, the deeper the profile the more mineral components of the parent rocks occur. From top to bottom the succession of these minerals reflects the decreasing resistance against chemical weathering: quartz – orthoclase – plagioclase – amphibole – biotite.

Generally the thickness and composition of such soils depends on the lithology of the basement rock and the climate conditions of soil formation. Horizons 1–3 were formed in-situ during weathering. As indicated by their mineralogical composition, this succession was formed under a tropical/subtropical humid climate and a good drainage of the soil (W. Vortisch & R. Butz-Braun, 1992).

The 1^{st} horizon is laterite according to its mineralogical composition. Laterite is formed mostly in the sub-tropical and tropical regions. Lateritization is a chemical process whereby atmospheric and groundwater processes interact through exposed rock surfaces and fractures in the bedrock to decompose the primary rock minerals and form more stable mineral phases in the weathering profile with hydroxides of iron

(H. Füchtbauer, 1988, W. Vortisch & R. Butz-Braun, 1992). In West Africa they were formed during special Eocene and Pliocene climatic conditions with high drainage and high temperature favouring the accumulation of iron minerals and the formation of hardened crusts. The altitude of the crusts varies between 100 and 300 m (A. Blanchot & J. Marcellin, 1972, W. P. Sunday, 1991, T. Lavaud et al., 2004).

The magnetic susceptibility of the soil materials is mainly influenced by the minerals described above:

- In the upper layers the magnetic susceptibility is mainly influenced by iron minerals. The value of magnetic susceptibility decreases with the depth corresponding to the decrease of the iron containing minerals.
- In the medium layers this value is lowered by clay minerals.
- In low layers, there is an increase of magnetic susceptibility again mainly due to the presence of dark mafic minerals (amphibole, biotite), plagioclase and only a small amount of clay minerals.

The mineralogical composition of the soil horizons determines the hydraulic properties:

- The upper part forms the shallow aquifer or superficial aquifer.
- The medium part, characterized by the high content of clay minerals, forms an impermeable zone separating the two main aquifers.
- The lower part (debris horizon) is made up of primary minerals and fragments of the rock basement. It forms the deep aquifer which is also connected with the water circulating in the uppermost fractured zone of the basement rocks.

These results give fundamentals for zonation of the profiles based on indication from the geophysical measurements (magnetic and nuclear logs).

5. Geophysical field investigations

Applied geophysics offers different methods for the investigation of fractured zones, particularly fractured reservoirs. The methods are based on different effects on physical rock properties. One of the most important methods is electrical method based on the conductivity effect of water filled fractures. Various well logging techniques use electrical resistivity methods for the characterization of fractured reservoirs (S. M. Luthi & P. Souhaite, 1990, O. Faivre, 1993, S. Mares et al., 1994, V. Vasvári, 2001).

The decision to apply geoelectric methods for this study was made taking into account the following two aspects:

- The electric effect is connected with the presence of water in the fractured zone.
- Geoelectric methods can be realized very economical.

Field measurements of the resistivity can be done on the surface as profiling, sounding, and multi-electrode measurement, or in the borehole with different conventional or focusing arrays of electrodes.

For the field measurements on the surface profiling and vertical sounding were applied. In the following section an example of vertical sounding is discussed. For the measurement a SCHLUMBERGER array with AB/2 up to 100 m was used. Figure 3 shows an example of the resistivity-depth-curve.

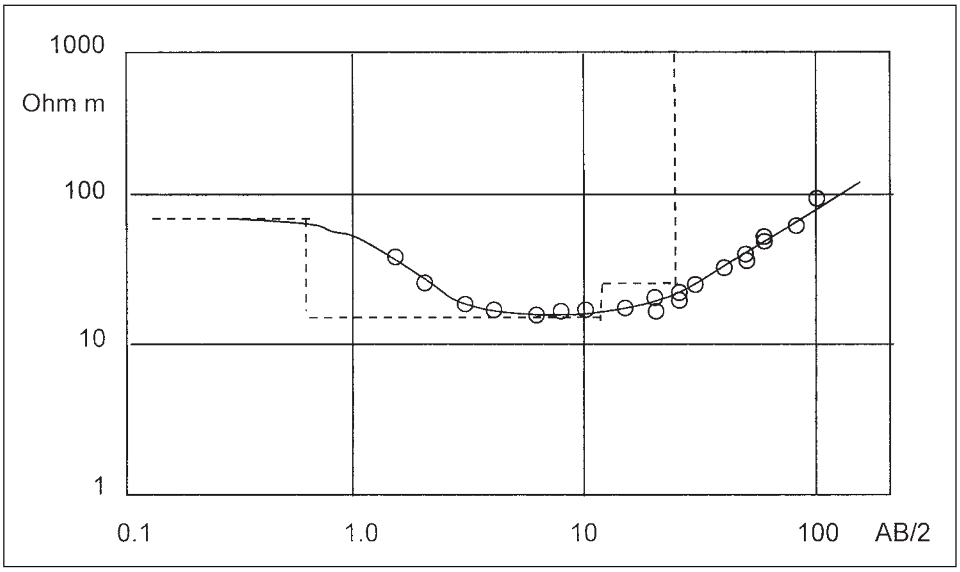

Fig. 3: Result of a geoelectrical sounding; the x-axis shows the spacing AB/2 in m (from 0.1 to 100 m on the scale), the y-axis the apparent resistivity in Ohm m (from 1 to 1000 Ohm m on the scale). Table 2 gives the result of the iteration process.
Ergebnis einer geoelektrischen Sondierung. Die x-Achse zeigt das spacing AB/2 in m (von 0,1 bis 100 m), die y-Achse zeigt den scheinbaren spezifischen Widerstand in Ohm m (von 1 bis 1000 Ohm m). Tabelle 2 enthält die Ergebnisse der iterativen Berechnung.

Table 2 shows the derived geoelectric underground model.

Tab. 2: Underground model, derived from fig. 3.
Untergrundmodell, abgeleitet aus Fig. 3.

Depth [m]	Specific electrical resistivity [Ohm m]
0–1	42
1–12	14
12–29	37
29	1300

This method of processing gives a general model with four layers:

– 1st layer: high to medium resistivity,
– 2nd layer: low resistivity,
– 3rd layer: medium resistivity,
– 4th layer: extremely high resistivity.

This four-layer resistivity model fits very well with the result from vertical electrical sounding in the Kano State (northern Nigeria; J. M. Reynolds, 1997). However, it should be noted that the investigated layer in Nigeria consists of unconsolidated weathered products, while the two uppermost layers in the investigation area in Burkina Faso are comprised of laterite.

The measurement of formation resistivity in a borehole is fundamental to determine the lithologic profile and thus the fractured zone, but also to estimate reservoir properties (for example porosity). The equipment is a rugged, portable, hand-operated downhole logger which measures the resistance point-by-point. It consists of a cable (100 m) with a probe with four electrodes (two potential electrodes M, N and two current electrodes A, B in a distance of 20 cm).

The graphic demonstration given in fig. 4 shows from left to right:

– the resistivity curve,
– the temperature curve,
– the porosity estimate from formation factor.

The resistivity curve shows three main parts:

29–32.5 m: low resistivity, probably fracture,
32.5–36 m: increasing resistivity, transition zone,
36–40 m: high resistivity, probably non fractured zone.

Compared with the surface measurement the resistivity log gives a more detailed picture of the 4th layer (and the transition to the 3rd layer). The combination gives the complete vertical resistivity profile.

The porosities are derived with ARCHIE's equation and can be interpreted as follows:

There is an intrinsic porosity of the rock substance which corresponds to about 10 % "electrical porosity"; in the upper part there is additionally a fracture porosity of about 8 %. This is the dominant and connected part of the hydraulic effective porosity. The plateau in the temperature curve confirms 29–32.5 m as the hydraulic active part of the profile.

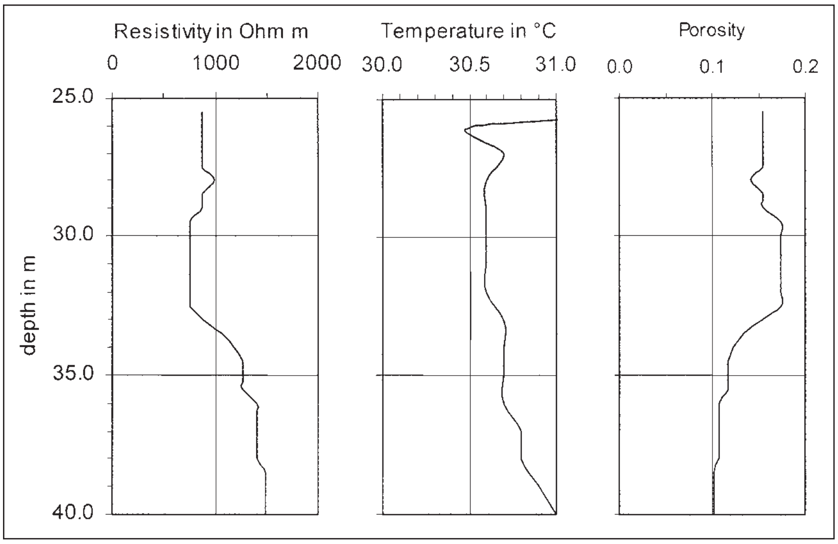

Fig. 4: Resistivity log, temperature log and porosity log (derived from formation factor). Well Ouagadougou-Kossodo-1: altitude = 304 m, well diameter = 10", total depth = 40 m, completed depth = 40 m, static water table = 25.6 m, water resistivity (Rw) = 42 Ohm m.
Widerstandslog, Temperaturlog und Porositätslog (berechnet aus dem Formationsfaktor). Bohrung Ouagadougou-Kossodo-1: Höhe = 304 m, Bohrlochdurchmesser = 10", Bohrtiefe = 40 m, Tiefe/ausgebaut = 40 m, statischer Wasserspiegel = 25,6 m, Wasserwiderstand (Rw) = 42 Ohm m.

6. Results and conclusions

The investigation of the area around Ouagadougou in Burkina Faso results in a detailed knowledge of the hydrogeological situation of the study area and the development of an interdisciplinary approach for exploring groundwater resources in the Sahel zone.

The aquifers in Ouagadougou are situated at the top of fractured igneous rocks and the top layers of the lateritic cover:

– The superficial aquifers (A) situated in the laterite horizon is porous due to alteration/leaching processes.
– The lower aquifer (B) is formed by unconsolidated angular debris with a small amount of dispersed clay material at the top of the fractured basement rocks.

The fracturing has a tectonic origin and follows two main tectonic directions as detected by aerial photo interpretation and structural field investigations.

Aquifer B produces water of better quality because it is sealed by the saprolite clay horizon against pollution from the surface. This sealing is also responsible for the confined hydraulic conditions.

Aquifer A is controlled very strongly by the variation of annual rainfall and is not protected against contamination from the surface. Therefore aquifer B is of high importance for the stable water supply of the region.

The methods used consist of the combination of geological, hydrogeological and geophysical methods. The configuration of the applied geophysical methods is simple, it may be handled by one to three people and the investment for such instrumentation is relatively low. Therefore the designed approach could become standard for groundwater exploration in countries with comparable geology and climate. The synthesis of all results gives a geologic-hydraulic and geophysical model as a basis for water exploration and water well construction.

Summary

Groundwater exploration is still a fundamental problem in Sahelian countries, where aquifers are mostly related to fractures within crystalline rocks. A combination of investigation methods could help to characterize the aquifer systems and to build a model which could be used for efficient aquifer investigations in similar areas. Such a model for the Ouagadougou area was developed from a combination of geology, hydrogeology, petrophysics and geophysics.

The aquifers in Ouagadougou are situated at the top of fractured igneous rocks and their weathered lateritic cover:

– The upper aquifer (A) formed by laterite is porous due to the alteration process.
– The lower aquifer (B) is formed by unconsolidated angular debris with a small amount of dispersed clay material and the top of the fractured basement rocks. The fracturing has a tectonic origin and follows the main tectonic directions as detected by aerial photo interpretation and field investigation.

Aquifer A is controlled very strongly by the variation of annual rainfall and is not protected against contamination from the surface. Therefore aquifer B is of high importance for the stable water supply of the region. Aquifer B produces the higher water quality.

With the field studies and the laboratory investigations on rock samples, a detailed characterization of the aquifer systems was possible. Four series of typical horizons including the basement rock have been distinguished.

X-ray diffraction and magnetic susceptibility measurements result in a complete weathering profile in these areas; it is made up of three parts, each characterized by its mineralogical composition and its magnetic susceptibility. These results give fundamentals for a zonation of profiles based on indication from geophysical measurements (magnetic and nuclear logs).

The lineament analysis at outcrops results in a ROSE diagram of the dominant fracture systems of the region. Additionally the aerial photo interpretation delivers the orientation of the tectonic lineaments. Combination of both methods allowed recognizing two main directions in investigated area:

– The principal dominant direction is N 50°E.
– A second clear visible direction is E 30°S.

The vertical profile was investigated by geoelectrical measurements from the surface (vertical electrical sounding) and from boreholes. They confirm clearly the 4-layer model. Fractured zones are indicated by low resistivity. The borehole measurement allows a porosity estimate. The derived porosity of aquifer B has two components: intrinsic porosity and fracture porosity which is connected to the hydraulic effective porosity. The temperature logs confirm this zone as the hydraulic active part of the profile.

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Zusammenfassung

Die Grundwassererkundung ist ein großes Problem in der Sahel Zone. Durch Kombination von Methoden der Geologie, Hydrogeologie, Petrophysik und Geophysik wurde für das Gebiet um Ouagadougou/Burkina Faso ein Modell zur Grundwassererkundung entwickelt.

Die Aquifere in diesem Bereich werden von porösen Lateriten (Aquifer A) und von kantigem, geringfügig von Ton durchsetztem kantigem Gesteinsdetritus gebildet, der sich unmittelbar über dem aus geklüfteten magmatischen Gesteinen bestehenden präkambrischen Basement (Aquifer B) befindet. Die Mächtigkeit der lateritischen Verwitterungsbildungen beträgt im Durchschnitt zwischen 10 und 30 m.

Strukturaufnahmen an Aufschlüssen und Luftbildauswertungen zeigen, dass das Kluft-/Störungssystem durch zwei Hauptrichtungen (N 50°E, E 30°S) dominiert wird. Röntgendiffraktometer- und petrophysikalische Gesteinsuntersuchungen ermöglichen eine detaillierte Gliederung des Verwitterungsprofils und Charakterisierung beider Aquifere. Aquifer B besitzt eine größere Bedeutung als Aquifer A. Er ist hydraulisch gespannt und durch die Überlagerung einer saprolitischen Tonzone vor Obertagseinflüssen und Kontamination geschützt.

Mit geoelektrischen Feldmessungen (geoelektrische Tiefensondierungen, Widerstandsmessungen in Bohrungen) konnte das 4-Schichten-Modell verifiziert werden. Aus Laboruntersuchungen abgeleitete Zusammenhänge zwischen Formationsfaktor und Porosität ermöglichten schließlich eine Porositätsabschätzung für den Aquifer B. Es zeigt sich, dass die Porosität aus zwei Anteilen (Matrix- und Kluftporosität) zusammengesetzt ist, wobei nur der kluftgebundene Anteil von ca. 10 % hydraulisch wirksam ist.

Mit den geoelektrischen Bohrlochmessungen und den Oberflächenmessungen ist die Ableitung eines geologisch-geoelektrischen Modells möglich.

Die durchgeführten Untersuchungen haben hinsichtlich der optimalen Positionierung von Bohrungen zum Erfolg geführt. In ihrer Abfolge von einer tektonischen Übersichtsanalyse, mineralogisch/petrologischen Bearbeitung von Verwitterungsprofilen, über geoelektrische Profilmessungen bis zu Sondierungen stellen sie zugleich eine auf geologisch/klimatologisch vergleichbare Gebiete anwendbare Methodik mit realisierbarem Aufwand dar.

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Keywords: groundwater exploration, Burkina Faso, geophysical methods, well logging, weathering profile

Schlüsselwörter: Grundwasserexploration, Burkina Faso, geophysikalische Verfahren, Bohrlochmessungen, Verwitterungsprofile