

TRANSMISSIVITY VARIATIONS IN MUDSTONES

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Abstract

Many people in sub-Saharan Africa have to rely on meagre water resources within mudstones for their only water supply. Although mudstones have been extensively researched for their low permeability behaviour, little research has been undertaken to examine their ability to provide sustainable water supplies. To investigate the factors controlling the occurrence of usable ground water in mudstone environments, an area of Cretaceous mudstones in southeastern Nigeria was studied over a 3-year period. Transmissivity (T) variations in a range of mudstone environments were studied. The investigations demonstrate that within the top 40 m of mudstones, transmissivity can be sufficient to develop village water supplies ($T > 1 \text{ m}^2 \cdot \text{d}^{-1}$). Transmissivity is controlled by two factors: low-grade metamorphism; and the presence of other, subordinate, lithologies within the mudstones. Largely unaltered mudstones (early diagenetic zone), comprising mainly smectite clays, are mostly unfractured and have a low T of $< 0.1 \text{ m}^2 \cdot \text{d}^{-1}$. Mudstones that have undergone limited metamorphism (late diagenetic zone) comprise mixed layered illite/smectite clays and ground water is found in widely spaced fracture zones ($T > 1 \text{ m}^2 \cdot \text{d}^{-1}$ in large fracture zones; $T < 0.1 \text{ m}^2 \cdot \text{d}^{-1}$ away from fracture zones). Mudstones that have been further altered and approach the anchizone comprise illite clays, are pervasively fractured, and have the highest transmissivity values ($T > 4 \text{ m}^2 \cdot \text{d}^{-1}$). Dolerite intrusions in unaltered, smectitic mudstones are highly fractured with transmissivity in the range $1 < T < 60 \text{ m}^2 \cdot \text{d}^{-1}$. Thin limestone and sandstone layers can also enhance transmissivity sufficiently to provide community water supplies.

Introduction

Mudstones have largely been overlooked as a source of sustainable ground water supplies. On hydrogeology maps they are defined as non-aquifers (Struckmier & Margarat 1995) and most research has focused on their ability to retard ground water movement rather than as a source for water supply. In developed countries there is little need to use mudstones for water supply: water can be abstracted elsewhere and piped to the area of demand.

However, many of the world's poorest and most vulnerable people live in areas underlain by mudstones. In sub-Saharan Africa, approximately 70 million people live in rural communities underlain by mudstone (MacDonald & Davies 2000). Often such people have few viable alternative sources of water and so have to rely on the meagre ground water resources available within their community. Even if money were available from an external agency to pipe water into an area underlain by mudstone, experience over the past 20 years has shown that using water resources within the community is generally much more sustainable (Black 1998). These factors, combined with the current poverty focus of aid, are increasing the amount of ground water development in mudstone areas.

This paper discusses the results of three years of research into ground water occurrence and development in a mudstone area in southeastern Nigeria. Factors controlling transmissivity variations within mudstones are described and discussed. The research has provided a framework for understanding how ground water may be found and abstracted from mudstones.

Transmissivity variations were chosen as a general indicator of the presence of developable ground water resources for village supplies since hydraulic conductivity values from fractured

rocks have little meaning (Moore 1997). Using generally agreed principles for village supplies in sub-Saharan Africa (one borehole supplying 250 people with 25 litres per day), MacDonald and Davies (2000) demonstrated that transmissivity was the main factor determining borehole success or failure. If the transmissivity of the aquifer is greater than $1 \text{ m}^2 \cdot \text{d}^{-1}$, a borehole equipped with a handpump can generally meet the demand over a 6-month dry season without drawdowns becoming excessive. The quality of the ground water is a separate issue and not discussed here.

Research into the hydraulic properties of mudstones

Although mudstones have not been considered as sources of water, they have been extensively researched for other reasons: their effect on ground water flow in sedimentary basins (e.g. Remenda 2001); their importance for storing hazardous wastes (Miller et al. 2000); the effect of mudstones on hydrocarbon migration (Neuzil 1986); and the effect of clays on limiting recharge to, and contamination of, major aquifers (Desbarats et al. 2001).

There are several findings from this large body of research that are relevant to this current study. Permeability is broadly related to porosity at a laboratory scale with laboratory tests indicating hydraulic conductivity from 10^{-16} to $10^{-8} \text{ m} \cdot \text{s}^{-1}$ (e.g. Neuzil 1994). The majority of field studies of mudstone permeability indicate hydraulic conductivities two to three orders of magnitude greater than laboratory estimates for shallow depths (10^{-11} to $10^{-5} \text{ m} \cdot \text{s}^{-1}$) but declining to laboratory levels a few 10s of metres below ground surface (e.g. Sen & Abbot 1991; Gautschi 2001; van der Kamp 2001). Field studies have also indicated that shallow fractures and interbedded siltstones, sandstones and limestones can all increase field permeability (Gerber et al. 2001; Capuano & Jan 1996).

Few of the mudstone studies report the clay mineralogy, but refer to the rocks as “clay” or “fractured clay”. In this current study, more emphasis is placed on the effect of clay mineralogy, along with the presence of non-clay material, on transmissivity.

The Oju/Obi study area

An area in southeastern Nigeria was chosen as a study area to investigate the ground water potential of mudstones (Figure 1). The region covers two local government areas, Oju and Obi, which lie within Benue State. There are three different mudstone groups within Oju and Obi, ranging from soft mudstones to older, harder mudstones. Therefore the area is an excellent location for analysing ground water occurrence in different mudstone environments. The U.K. Department for International Development (DFID) had highlighted this area as a priority for aid, and in particular for improved water supply and sanitation. The British Geological Survey was commissioned to develop and undertake a programme of research into the ground water potential of the area. The knowledge and tools developed during this investigation were to be incorporated by WaterAid into a community water supply project for the area (Davies & MacDonald 1999).



Figure 1 The location of the study area: Oju/Obi.

The water problem

Oju/Obi is a remote part of south-eastern Nigeria that experiences severe water shortages during the annual dry season. Mean annual rainfall is approximately 1600 mm. The rainy season generally lasts from May to October, leaving six months with very little rainfall. During the dry season, unprotected ponds, seepages and hollows are the primary sources of domestic water. These sources become less reliable towards the end of the dry season and many fail altogether. Consequently, women and children have to walk long distances (often greater than 10 km) to get limited supplies of generally poor quality water. Inevitably, much of the population of Oju/Obi (approximately 300 000) is badly affected by a variety of water-related illnesses, of which guinea worm, dysentery and malaria are endemic; outbreaks of cholera and typhoid are also common.

Geology

Oju/Obi is situated in the lower section of the Benue Trough, a major elongated geological rift structure infilled with Cretaceous-age fine-grained, low permeability sediments deposited within a series of basins (Ofoegbu 1985). The sediments were deposited in deep- to shallow-marine and deltaic to fluvial environments – often during periods of active tectonism. Parts of the sedimentary sequence have undergone low-grade metamorphism, and have been folded and faulted to varying degrees. Igneous rocks (mainly dolerite) have been intruded into the sediments. The environment of deposition and also the subsequent history of the rocks have a significant bearing on the water-bearing capacities of these low permeability rocks.

The lithologies and stratigraphical relationships of the sediments found in the Oju/Obi area are outlined in Table 1 (Ojoh 1990). Their distribution is shown in Figure 2.

Table 1 Stratigraphic sequence for the Oju/Obi area (adapted from Ojoh 1990).

Age	Group	Formations	Description
Maastrichtian			Post Maastrichtian NW-SE trending folding and faulting
Campanian			
Santonian			NE-SW trending elongate folds and faulting; igneous intrusions
Coniacian	Awgu Group	Awgu Shale Formation	Shaley carbonaceous mudstones with thin shelly limestones and sandstones
		Agbani Sandstone Formation	Fine to medium sandstones with siltstones and mudstones
Turonian	Eze-Aku Group	Eze-Aku Shale Formation	Shaley mudstones and siltstone with thin sandstones and limestones; can be divided into Upper (younger than Makurdi Sandstone Fm) and Lower (older than the Makurdi Sandstone Fm)
		Makurdi Sandstone Formation	Fine to coarse sandstones with siltstones and mudstone
Cenomanian			Hiatus/unconformity
Upper Albian Lower	Asu River Group	Asu River Formation	Carbonaceous shaley mudstone, limestone, sandstone and siltstone
		Metamorphosed Asu River Formation	Pyroclastics and intrusives with contact metamorphosed mudstone, shale and sandstone
Precambrian Basement			N-S trending faulting

Dolerite intrusions transect the area and are associated with both pre- and post-Turonian tectonic episodes. Although few are observed at outcrop, their presence throughout the northern part of the area is inferred from aeromagnetic maps (see Figure 2). Compressional folding began in Senonian times within the Benue Trough, forming a series of long, narrow folds parallel to the axis of the basin and producing anticlines more than 60 km long (Benkhelil 1989).

Prolonged exposure of the Cretaceous sediments to a sub-tropical climate has altered the near-surface layers to a complex fersiallitic soil and associated weathered saprolite. Within this near-surface layer, an upper zone (1-5 m thick) contains a 1-3 m zone of iron and manganese

nodules, sometimes consolidated into a ferricrete. This typically overlies several metres of weathered smectitic or illitic clays with subordinate kaolinite.

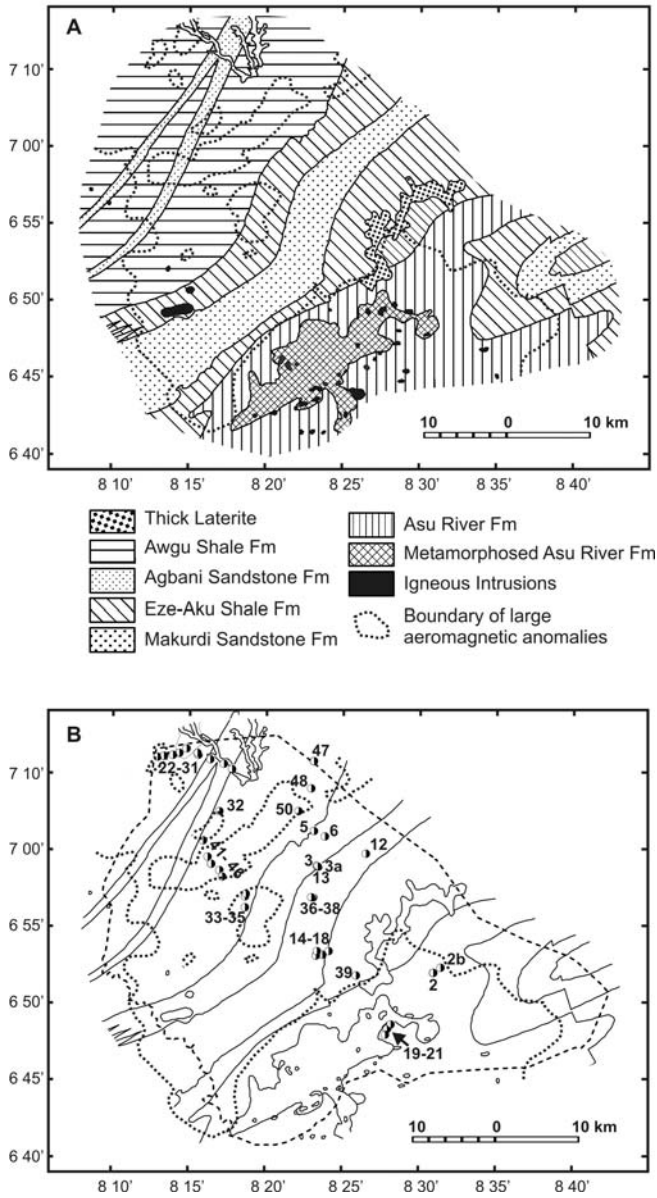


Figure 2. A: Geological map of the Oju/Obi area (based on Geological Survey of Nigeria 1957a, b) and B: Location of the exploratory boreholes (details in Table 2).

The ground water investigations

Test sites were selected for each geological formation on the basis of lithology and also community vulnerability – the poorest communities being prioritised. Geophysical survey methods were used to ensure that boreholes were targeted to the correct lithology. Details of the geophysical surveys and interpretation are given in MacDonald et al. (2001). Forty-three test boreholes were drilled to depths greater than 15 m, with a diameter of 170 mm. Twenty-four of the boreholes penetrated only mudstone; 11 boreholes were sited in areas where mudstone was interbedded with thin limestone and sandstone layers; and 8 boreholes were targeted to small dolerite intrusions within the mudstones. These locations are shown in Figure 2B and details given in Table 2.

Rock chip samples were taken every 0.5 m and core samples from the deepest 3 m of the borehole. Core samples were lithologically logged using standard geological techniques (Tucker 1980). 116 samples from a total of 17 boreholes were collected for quantitative <2 µm clay mineral X-ray diffraction (XRD) analysis using standard methods. In order to gain further information about the nature of the clay minerals present in the samples, modelling of the <2 µm XRD profiles was carried out using Newmod-for-Windows™ software (Reynolds & Reynolds 1996). Estimates of the smectite content of interlayered illite/smectite (I/S) were made by careful measurement of the position of the I/S 001/002 and 002/003 peaks (Moore & Reynolds 1997). Kubler Indices of white mica crystallinity were calculated from the mean of five scans over the range 7.5-10.5 °2theta at a speed of 0.5 °2theta/minute using the machine recommendations of Kisch (1991).

Table 2 Summary information from exploratory boreholes >15 m deep.

Bh ID	Location	Geological Formation	Depth (m)	Major lithology	Minor lithology	Major Fracture zones (mbgl)	Main water inflows (mbgl)	Lithology of major inflow	T (m ² .d ⁻¹)	Test type
BGS19	Oyinyi	Meta Asu River Fm	41.5	hard mudstone	thin quartzite	10-15; 26-35	14	Mudstone	6.5	C-RATE
BGS20	Oyinyi	Meta Asu River Fm	41	hard mudstone	limestone/ash	13-15; 31-34	15; 36	Limestone	27	C-RATE
BGS21	Oyinyi	Meta Asu River Fm	38.5	hard mudstone	thin quartzite	13-15	14	Mudstone	3.0	C-RATE
BGS39	Elim	Asu River Fm	40.5	compact mudstone		12-18	15	Mudstone	4.0	C-RATE
BGS2	Odubwo	Asu River Fm	63.7	compact mudstone		14-24	20	Mudstone	4.1	C-RATE
BGS2b	Odubwo	Asu River Fm	19.5	compact mudstone		12-18	12	Mudstone	3.5	C-RATE
BGS14	Edumoga	Eze-Aku Shale Fm	27.4	mudstone	silty mudstone	none	dry	-	< 0.01 ^a	-
BGS15	Edumoga	Eze-Aku Shale Fm	29.5	mudstone	silty mudstone	14-18; 26-28	15; 26	Mudstone	1.6	C-RATE
BGS16	Edumoga	Eze-Aku Shale Fm	29.5	mudstone	silty mudstone	16-20; 26-29	17	Mudstone	2.1	C-RATE
BGS17	Edumoga	Eze-Aku Shale Fm	29.5	mudstone	silty mudstone	12-29	15	Mudstone	1.4	C-RATE
BGS18	Edumoga	Eze-Aku Shale Fm	53	mudstone	silty mudstone	none	dry	-	< 0.01	-
BGS5	Ochingini	Eze-Aku Shale Fm	23.4	mudstone		none	dry	-	< 0.01	-
BGS6	Ochingini	Eze-Aku Shale Fm	19	mudstone	limestone	10; 16-19	10	Limestone	18	C-RATE
BGS3	Odaleko	Eze-Aku Shale Fm	60.7	mudstone	marl	none	dry	-	< 0.01	-
BGS3a	Odaleko	Eze-Aku Shale Fm	16	mudstone	marl	none	dry	-	< 0.01	-
BGS38	Adum East	Makurdi Sandst Fm	41.7	mudstone	sandstone	none	dry	-	< 0.01	-
BGS36	Adum East	Makurdi Sandst Fm	41.5	sandstone	mudstone	12	12; 21	Sandstone	0.8	C-RATE
BGS37	Adum East	Makurdi Sandst Fm	18.5	sandstone	mudstone	8- 12	12	Sandstone	0.8	C-RATE
BGS12	Ochingingi	Makurdi Sandst Fm	15.7	sandstone	mudstone	9-11 13-15	10	Sandstone	1.0	C-RATE
BGS13	Odaleko	Makurdi Sandst Fm	87.5	sandstone	mudstone	78 - 82	78.5	Sandstone	0.15	SLUG
BGS47	Itogo	Awgu Shale Fm	31.69	soft mudstone	alluvium	none	dry	-	< 0.01	-
BGS48	Itogo	Awgu Shale Fm	31.9	soft mudstone	alluvium	none	8	Alluvium	0.11	SLUG
BGS32	Adega	Awgu Shale Fm	32.5	soft mudstone	marl	none	dry	-	< 0.01	-
BGS22	North Obi	Awgu Shale Fm	23	soft mudstone		none	dry	-	< 0.01	-
BGS23	North Obi	Awgu Shale Fm	23.5	soft mudstone		none	dry	-	< 0.01	-
BGS24	North Obi	Awgu Shale Fm	23	soft mudstone		none	dry	-	< 0.01	-
BGS25	North Obi	Awgu Shale Fm	21.3	soft mudstone		none	dry	-	< 0.01	-
BGS26	North Obi	Awgu Shale Fm	23.4	soft mudstone	marl, silt	none	20	Mudstone	0.02	SLUG
BGS27	North Obi	Awgu Shale Fm	23.35	soft mudstone	marl, silt	none	18	Mudstone	0.08	SLUG
BGS28	North Obi	Awgu Shale Fm	23.4	soft mudstone	marl, silt	none	dry	-	< 0.01	-
BGS29	North Obi	Awgu Shale Fm	23.6	soft mudstone		none	dry	-	< 0.01	-
BGS30	North Obi	Awgu Shale Fm	23.5	soft mudstone	alluvium	none	5	Alluvium	0.36	SLUG
BGS31	North Obi	Awgu Shale Fm	15	soft mudstone	marl	none	dry	-	< 0.01	-
BGS41	Ugbodum	Awgu Shale Fm	41.5	soft mudstone	limestone	none	29.5	Limestone	0.25	SLUG
BGS43	Ugbodum	Awgu Shale Fm	31.86	soft mudstone		none	dry	-	< 0.01	-
BGS45	Ugbodum	Awgu Shale Fm	19.7	soft mudstone	thin dolerite	18-20	18	Thin dolerite	0.2	SLUG
BGS42	Ugbodum	Awgu Shale Fm	32.05	soft mudstone	thin dolerite	None	15; 18	Thin dolerite	0.8	C-RATE
BGS44	Ugbodum	Awgu Shale Fm	32	soft mudstone	thin dolerite	5-10	5	Thin dolerite	0.1	SLUG
BGS34	Adum West	Awgu Shale Fm	39.5	mudstone	dolerite	34-39	32	dolerite	4.0	C-RATE
BGS33	Adum West	Dolerite	18.5	dolerite	mudstone	15-18	16.5	dolerite	51	C-RATE
BGS35	Adum West	Dolerite	21.5	dolerite		15-21	18	dolerite	23	C-RATE
BGS50	Itogo	Dolerite	31.75	dolerite	soft mudstone	15-17	15	dolerite	2.0	C-RATE
BGS46	Ugbodum	Dolerite	32.07	dolerite	mudstone	8-10	8	dolerite	45	C-RATE

^a Dry boreholes have been assigned a transmissivity of < 0.01 m².d⁻¹.

Exploration boreholes that contained any ground water after drilling were developed and completed with 125 mm plastic screen. Only the upper 2 m were grouted to stop inflow from the shallow laterite layer and no gravel pack was installed; the boreholes were therefore effectively open hole. They were then test pumped to estimate the transmissivity. For boreholes where the yield estimated from airlifting was greater than approximately 0.1 l.s^{-1} , constant rate tests using low yielding electrical pumps were undertaken (pumping rate $0.1 - 0.3 \text{ l.s}^{-1}$). For boreholes with considerably higher yields, Grundfos[®] submersible pumps were used. Boreholes were pumped for 5 hours and recovery data analysed using the Theis recovery method (Kruseman & deRidder 1990). Where the yield of the borehole was estimated by airlifting to be less than 0.1 l.s^{-1} , slug tests were carried out. This involved removing water over a 10-minute period and monitoring the recovery. The data were analysed numerically using BGSPT[™] (Barker 1985; Barker & Macdonald 2000) which accounts for non-instantaneous removal of water (Papadopulos & Cooper 1967, Barker & Herbert 1989; Mace 1999). In total 27 boreholes were tested; all tests were carried out towards the end of the dry season, when water-levels are at their lowest. Figure 3 shows examples of test data for a constant rate test and a slug test. Detailed information on the data and analysis is available in MacDonald (2001).

This experimental procedure allowed transmissivity values in the range $0.01 - 100 \text{ m}^2.\text{d}^{-1}$ to be measured. Since the purpose of the research was to investigate water supply from mudstones, detailed information on transmissivity values below $0.01 \text{ m}^2.\text{d}^{-1}$ is unnecessary – transmissivities greater than $1 \text{ m}^2.\text{d}^{-1}$ are required to support a borehole with a handpump (see earlier). Boreholes with yields too low to be calculated from standard unpressurised slug tests were backfilled. To minimise data bias, dry boreholes were assigned a transmissivity value of $0.01 \text{ m}^2.\text{d}^{-1}$.

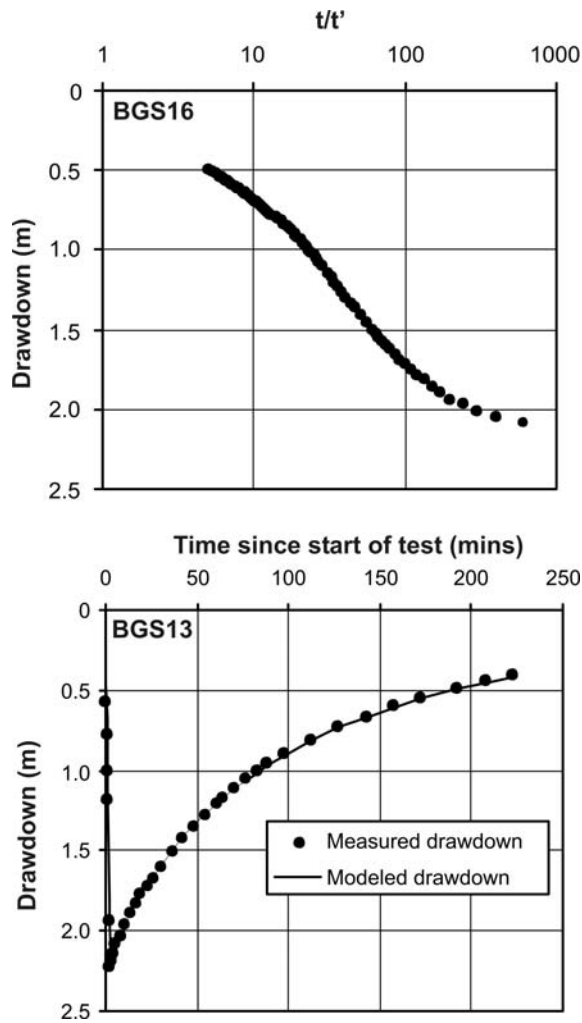


Figure 3 Examples of the pumping test data for Oju/Obi: BGS16 shows This recovery after 5 hours of pumping; BGS13 indicates drawdown and recovery for a slug test.

The slug test and This recovery methods applied above assume homogeneous and porous media – despite ground water flow in the rocks tested being primarily through fractures. Several key publications, however, have illustrated that fractured aquifers can be adequately analysed using these techniques, provided the borehole penetrates a representative sample of the aquifer, flow through the fractures is laminar and the time taken for water to diffuse from the matrix to the borehole is short (e.g. Snow 1968). Barker & Black (1983) and Black (1985) took this further to demonstrate that, as a worst case scenario, errors in the value of

derived transmissivity using homogeneous approaches are unlikely to exceed a factor of 2. In media where transmissivity can vary by 4 or 5 orders of magnitude this error can be considered admissible. Further modelling (MacDonald 2001) indicated that these errors are only introduced if the time of diffusion across a matrix block, $b^2 S_s / K_m$, was more than 0.01 day (where b is the maximum distance to a fracture, S_s is the specific storage of the matrix and K_m is the hydraulic conductivity of the matrix).

Results

Representative borehole logs for each of the different units are shown in Figure 4. Detailed logs for each borehole are available in MacDonald (2001). Transmissivity measurements from the longest reliable dry season pumping test are shown in Table 2.

To test for systematic patterns in transmissivity, geometric means from the different hydrogeological units are compared in Table 3. For the purpose of the analysis, mudstone units within the Makurdi Sandstone Formation have been designated as the Eze-Aku Shale Formation. Also boreholes that penetrated very thin dolerite sills (< 1 m) within the Awgu Shale Formation have been distinguished from boreholes penetrating larger dolerite intrusions.

Table 3 Summary of transmissivity data for the hydrogeological units in Oju/Obi.

	No of tests	Transmissivity ($\text{m}^2 \cdot \text{d}^{-1}$)		
		Minimum ^a	maximum	geometric mean
Metamorphosed Asu River Formation	3	3.0	27	7.9
Asu River Formation	3	2.5	4	3.3
Eze-Aku Shale Formation	10	< 0.01	18	0.1
Makurdi Sandstone Formation	5	0.1	1	0.37
Awgu Shale Formation	11	< 0.01	0.25	0.02
Agbani Sandstone	3	< 0.01	0.4	0.06
Thin dolerite in Awgu Shale	3	0.06	0.8	0.17
Dolerite	5	2.0	51	13

^a Dry boreholes have been assigned a transmissivity of < 0.01 $\text{m}^2 \cdot \text{d}^{-1}$.

Highest transmissivity values are found within the Metamorphosed Asu River Formation, the Asu River Formation and the larger dolerite intrusions. Lowest transmissivity values are found within the Awgu Shale Formation. Large variations in transmissivity are found within the Eze-Aku Shale Formation.

The detailed geological logs of the boreholes provide a first indication of why some boreholes have higher yields than others. For example, fractures at a depth of 12-35 m within both the Metamorphosed Asu River Formation and unmetamorphosed strata from the same formation are responsible for the high transmissivity measurements (see Table 2). The lack of open fractures within the Awgu Shale results in the very low transmissivity values. The geological logs show that the large range of measurements in the Eze-Aku Shale Formation is due to the presence of fractures in the mudstone, or thin bands of limestone. Boreholes that penetrate fracture zones have higher transmissivity than those with little evidence of fracturing. Where competent limestone is present (and fractured) transmissivity can be high; where limestone is absent, transmissivity is low.

However, the geological logs alone give little indication as to why some mudstone units are fractured (and therefore permeable) and some are not. In the following sections, the effect of two factors on transmissivity are discussed – low-grade metamorphism and the presence of other lithologies (such as thin sandstone layers or dolerite intrusions).

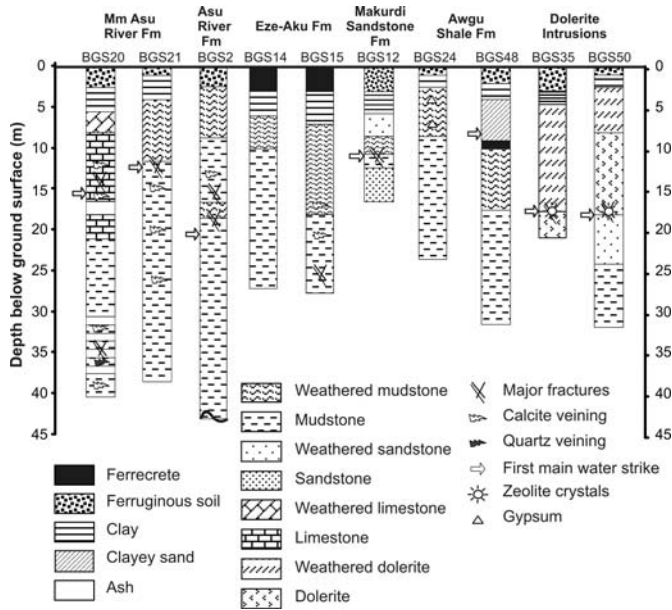


Figure 4 Representative borehole logs for each hydrogeological unit in Oju/Obi.

Factors controlling transmissivity variations

Diagenesis and low-grade metamorphism

The reaction series smectite \rightarrow I/S \rightarrow illite \rightarrow muscovite is indicative of irreversible, prograde transformation from diagenesis to low-grade metamorphism (Merriman & Peacor 1999). Such changes are coupled with the expulsion of water and a regular pattern of increasing crystal size and crystal perfection which occurs from late diagenesis through to the epizone at temperatures up to 300 °C. Temperature is the main driving force for these reactions but strain energy from tectonic stress may also be important. The classic study of Hower et al. (1976) from the US Gulf Coast first showed that smectite was replaced by I/S with an increasing proportion of illite layers as a function of increasing burial depth. While the presence of this reaction series is widely accepted, the nature and extent of the intermediate I/S remains controversial (Merriman & Peacor 1999). The maturity chart shown

in Figure 5 illustrates the expected clay mineralogy and physical properties of mudstones at various stages of diagenesis and low-grade metamorphism.

The clay mineralogy of representative mudstone boreholes in Oju/Obi is shown in Table 4. To exclude the effects of tropical weathering, which can result in the alteration of a clay assemblage (e.g. Vicente et al. 1997), only the deepest, unweathered, samples from each borehole are considered.

Metapelitic zone	Clay composition	%illite in I/S	Kubler Index	TEM mean illite size (Å)	Typical pelitic lithologies
Early diagenetic zone	smectite	60-80	1.0		shale/ mudstone
Late diagenetic zone	I/S	90	0.42	220	cleaved/ pencillet mudstone
Low anchizone	illite	95	0.30	380	slate
High anchizone		>99	0.25	520	roofing slate
Epizone	muscovite				(phyllite)

Figure 5 Metapelitic zones and indicators of smectite-I/S-illite-muscovite progress (after Merriman & Peacor 1999).

The youngest mudstones, from the Awgu Shale Formation, have not undergone any significant burial and are still largely composed of unaltered smectite clay with minor kaolinite and traces of presumably detrital illite. The older Eze-Aku Group mudstones have been subjected to deeper burial and show a degree of fissility. NEWMOD-modelling of their I/S-dominated clay mineralogy suggests that the proportion of illite layers in the I/S increases with increasing burial (Table 4). These analyses are consistent with an earlier study of burial metamorphism in the Benue Trough (Akande & Erdtmann 1998).

Table 4 Clay mineralogy and low-grade metamorphism indicators for representative boreholes in Oju/Obi.

Exploratory Borehole	depth of sample (m)	Composition of clay (%)				smectite in I/S (%)	Kubler Index (2 θ)
		kaolinite	illite	smectite	I/S		
Awgu Shale Formation							
BGS27	19.5	35	3	62	0	100	
BGS31	5.25	23	1	76	0	100	
BGS32	10.5	31	2	67	0	100	
Eze-Aku Shale Formation							
Upper BGS3a	14.5	25	5	0	70	35	-
BGS4	7.5	12	2	0	86	40	-
BGS6	9.5	14	6	0	-	36	-
Lower BGS15	9.5	6	3	0	91	29	-
BGS16	9.5	1	6	0	93	25	-
BGS18	9.5	12	6	0	82	32	-
Asu River Formation							
BGS2b	17	16	84	0	0	-	0.53
Akande et al. (1998) ^a			illite clay			-	0.56
Metamorphosed Asu River Formation							
BGS19	8.5	38	49	13	0	-	0.18
BGS21	4.5	30	65	5	0	-	0.37

^aAkande et al. (1998) analysed samples from nine different boreholes within the Benue Trough, 50 km from Oju/Obi

The clay mineralogy of the oldest mudstones, from the Asu River Group, is dominated by illite with minor kaolinite. The Kubler index of white mica crystallinity provides a measure of the crystal-size and order of illite crystals, and can be used as a useful indicator of the degree of low-grade metamorphism (Merriman & Peacor 1999). Kubler indices of *c.*0.5 for the Asu River Formation indicate late diagenetic grades while lower values of 0.37 and 0.18 indicate higher-grade anchizonal and epizonal metamorphism respectively for the Metamorphosed Asu River Formation (Table 4).

Figure 6 and Table 5 show the transmissivity values measured in boreholes penetrating the upper 20-40 m of mudstone, related to degree of low-grade metamorphism. Only boreholes that struck water within mudstone are included – all limestone, sandstone and dolerite boreholes have been omitted. It is clear that as metamorphism increases and the smectite content reduces, transmissivity increases. For unaltered, smectite-rich mudstones, transmissivity is consistently low. As metamorphism proceeds to the early/late diagenetic zone boundary, higher transmissivity values are possible since large fracture zones remain open; the variance remains high however, since transmissivity is still low away from the large fractured zones. Where metamorphism has proceeded well into, and beyond, the late diagenetic zone, the mudstones are sufficiently competent for widespread small fractures to remain open and transmissivity can be consistently high.

Table 5 Transmissivity and metamorphic indicators for the mudstone units in Oju/Obi. Boreholes in bold are those with measurements of clay mineralogy and metamorphic indicators.

<i>Mudstone unit</i>	<i>Boreholes</i>	<i>Transmissivity ($m^2.d^{-1}$)</i>		<i>Metamorphic indicators</i> (see table 4)
		<i>Geometric mean</i>	<i>Range</i>	
Metamorphosed Asu River Fm	BGS19, BGS21	4.4	3.0 - 6.5	Kubler Index = 0.18 - 0.37
Asu River Fm	BGS2, BGS2b ; BGS39	3.3	2.5 - 4.0	Kubler Index = 0.53 - 0.56
Eze-Aku Shale Fm				
Lower	BGS14, BGS15, BGS16, BGS17, BGS18	0.54	< 0.01 - 2.0	%smectite in I/S = 28.7%
Upper	BGS3, BGS3a , BGS5	0.01	< 0.01	%smectite in I/S = 37%
Awgu Shale Formation	BGS22, BGS23, BGS24, BGS25, BGS26, BGS27, BGS28, BGS29, BGS31, BGS32	0.013	< 0.01 - 0.08	%smectite in I/S = 0%

The metamorphic model provides a major step towards understanding variations in transmissivity between different mudstone formations. Mudstones must be fractured to enhance their permeability sufficiently to be of use as an aquifer. Immature mudstones, that

have not achieved late diagenetic grade metamorphism, still have a high component of smectite clay. Smectite-rich clays are plastic, easily deformed, and do not fracture easily. Any fractures that might be develop within the smectite can be quickly healed, either due to additional deformation or water absorption and swelling. Therefore, unaltered mudstones have little ability to transmit ground water.

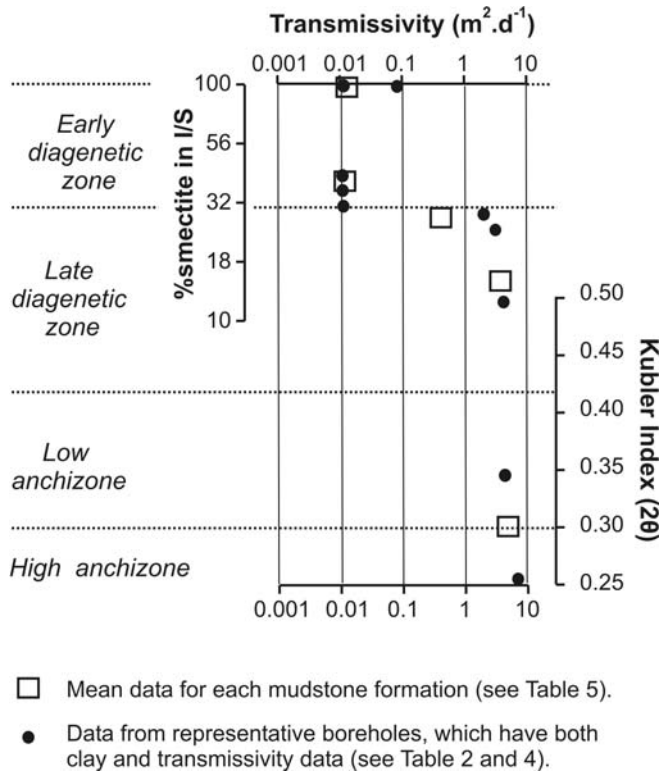


Figure 6 Transmissivity related to degree of low-grade metamorphism of mudstones in Oju/Obi using %smectite and Kubler Index as indicators.

Where mudstones have been buried and subjected to anchizonal metamorphism, illite dominates the clay mineralogy. Illite has a much higher negative charge than smectite, and therefore binds interlayer ions more closely. Illite does not swell, and often has large crystals ($>100 \text{ \AA}$). This makes illitic/micaceous mudstones stable and resistant to weathering (hence the durability of roofing slate). Any fractures at shallow depths within the mudstone will generally remain open. This is clearly observed in the Asu River Group where fractures are

widespread. The brittleness of illite-dominated mudstones ensure that they are easily fractured. Tectonic stresses, erosional unloading or even the reactivation of hydrofractures could easily give rise to stresses that create the fractures (Singhal & Gupta 1999).

In Late Diagenetic Zone mudstones, the proportion of illite and smectite layers within I/S is crucial to the development of secondary permeability. Where illite dominates, fractures are likely to remain open and enhance the permeability of the mudstone. However, if mudstones are less mature and high-smectite I/S clays dominate, secondary permeability is unlikely to develop. The exploratory boreholes in the Eze-Aku Shale Formation showed that permeability was greatly enhanced by large fault zones, giving transmissivity values of 1 to 3 $\text{m}^2.\text{d}^{-1}$. However, boreholes that did not penetrate large fracture zones had low transmissivity (akin to those in the Awgu Shale).

Variations in transmissivity data from Oju/Obi are therefore explained by considering the extent of low-grade metamorphism. This conceptual model may apply to other mudstone areas.

The presence of thin sandstone and limestone layers

The presence of interbedded non-mudstone lithologies, ranging from one millimetre to several metres thick, has an important effect on the hydrogeology of mudstone environments. Three test sites were located in areas that had significant sandstone or limestone beds interlayered within the mudstone: Ochingini, Odaleko Adiko and Adum East, all within the Eze-Aku Group. Two others penetrated thin alluvium layers: Itogo and the north Obi traverse.

Laboratory estimates of hydraulic conductivity and porosity for the sandstone boreholes indicate that fracture flow dominates (MacDonald 2001). Careful examination of core samples indicates thin fractures in many of the sandstone boreholes at about 8 – 20 m. Pumping tests in these boreholes indicated transmissivity ranging from 0.1 to 1 m².d⁻¹ for 5 boreholes (Table 3). Similar shallow fractures have been found subsequently by WaterAid when constructing hand-dug wells.

Thin limestone layers were also found to contain significant ground water in Oju/Obi where fractured. A good example is Ochingini (BGS6) where a thin (< 0.3 m) limestone layer is present within a soft smectite mudstone. A five-hour pumping test indicated transmissivity of about 18 m².d⁻¹. Cores from the limestone indicated pervasive fracturing.

Thin sandstone and limestone layers therefore have a significant impact on the local hydrogeological conditions in mudstones. In soft, unaltered mudstones, searching for thin sandstone or limestone layers may be the only reasonable option for ground water supplies to rural communities. Fortunately such interlayers are common in mudstones that have been deposited in deltaic or shallow sea environments. Even deep marine mudstone can contain coarser material and limestone because of turbidites (Reading 1996).

The sustainability of supplies from deeply buried thin sandstone or limestone layers, cannot be assessed from the short pumping tests used in this study to estimate transmissivity. Much longer tests, ground water dating methods, or long term monitoring of pumping yields and water levels are required. Several studies have indicated that recharge through thick clay layers is possible: Rushton (1986) demonstrated that vertical seepage through clay layers was the main mechanism for recharge in thin alluvial aquifers in India; similar mechanisms were

also found through the London Clay to the Lower Greensand in southern England (Egerton 1994).

Dykes and sills

Some of the most productive boreholes in Oju/Obi penetrated dolerite intrusions found within the soft, smectitic mudstones of the Awgu Shales Formation. Often, dykes and sills are avoided as they rarely contain ground water and often act as impermeable barriers to ground water flow (e.g. Bromley et al. 1994). On the rare occasions that the presence of dykes and sills has been found to increase borehole yields, the main factor has been increased fracturing in the host rocks due to contact metamorphism (Ventriss et al. 1982).

In Oju/Obi, a clear pattern emerges: boreholes that penetrate thick dolerite intrusions (see Table 2) yield significant quantities of ground water (geometric mean transmissivity for 5 boreholes, $13 \text{ m}^2 \cdot \text{d}^{-1}$). Where thinner intrusions (less than 0.5 m thick) are encountered within the smectite mudstone, transmissivity was slightly enhanced, relative to the mudstone (geometric mean transmissivity for 3 boreholes, $0.17 \text{ m}^2 \cdot \text{d}^{-1}$), but rarely sufficient to support a borehole equipped with a handpump.

The geological logs of the exploratory boreholes contain interesting information about the dolerite (Figure 4). The majority of ground water was not found in the metamorphosed and disturbed mudstone next to the intrusions but within the dolerite, primarily at the contact zone with the host rock. Exploratory boreholes that targeted thick intrusions found that the edges of the dolerite intrusions were characterised by a large number of open fractures. Many of the fractures were lined with millimetre-long zeolite (mesolite) crystals, suggesting precipitation from low temperature, hydrothermal fluids. The other exploratory boreholes targeting

dolerite encountered much thinner intrusions – some only a few centimetres across. Geological cores indicated that fracturing within thin dolerite intrusions was poorly developed and there was little corresponding zeolite growth within the fractures.

Therefore the presence of large dolerite intrusions, which can be highly fractured within mudstone environments, are excellent targets for village water supplies – particularly in soft smectite mudstones where other usable ground water resources are sparse. Transmissivity alone, however, cannot give reliable information on sustainability – particularly where the inflow to the borehole is from isolated fractures within intrusions with 10s of metres of mudstone between the ground surface and the fractures. The pumping tests within the intrusions were too short (5 hours) to indicate barrier effects. Three exploratory boreholes targeting the thick intrusions were completed as production boreholes and equipped with a handpump. The boreholes continue to be a reliable source after 4 years of pumping. Further and more widespread monitoring will help to give more information on sustainability.

Summary and conclusions

The study of the hydrogeology of the Oju/Obi area has provided an excellent opportunity to examine the hydrogeology of mudstone environments. The research has demonstrated that transmissivity in the upper 40 m can be sufficient to sustain boreholes with handpumps (success is based on supplying 250 people 25 litres per day). Two aspects are particularly

important in controlling the transmissivity: low-grade metamorphism and the presence of subordinate lithologies, particularly dolerite intrusions (Figure 7).

The results of this research are being used by WaterAid in Oju /Obi to develop village water supplies. Simple guidelines have allowed more than 100 successful village water supplies to be developed in an area that was thought not to contain any significant extractable ground water. The illite dominated mudstones are distinguished using electromagnetic techniques (MacDonald et al. 2001). Dolerite intrusions within smectite mudstones continue to be targeted using magnetic profiling. Sandstone layers are being developed using hand-dug wells after being identified with electromagnetic methods.

Continued research of mudstone environments is central to helping provide safe reliable water supplies to many of the poorest communities in Africa. Although this research has demonstrated successful boreholes can be drilled in mudstone environments, careful monitoring and further research is necessary to ensure sustainability and reliability.

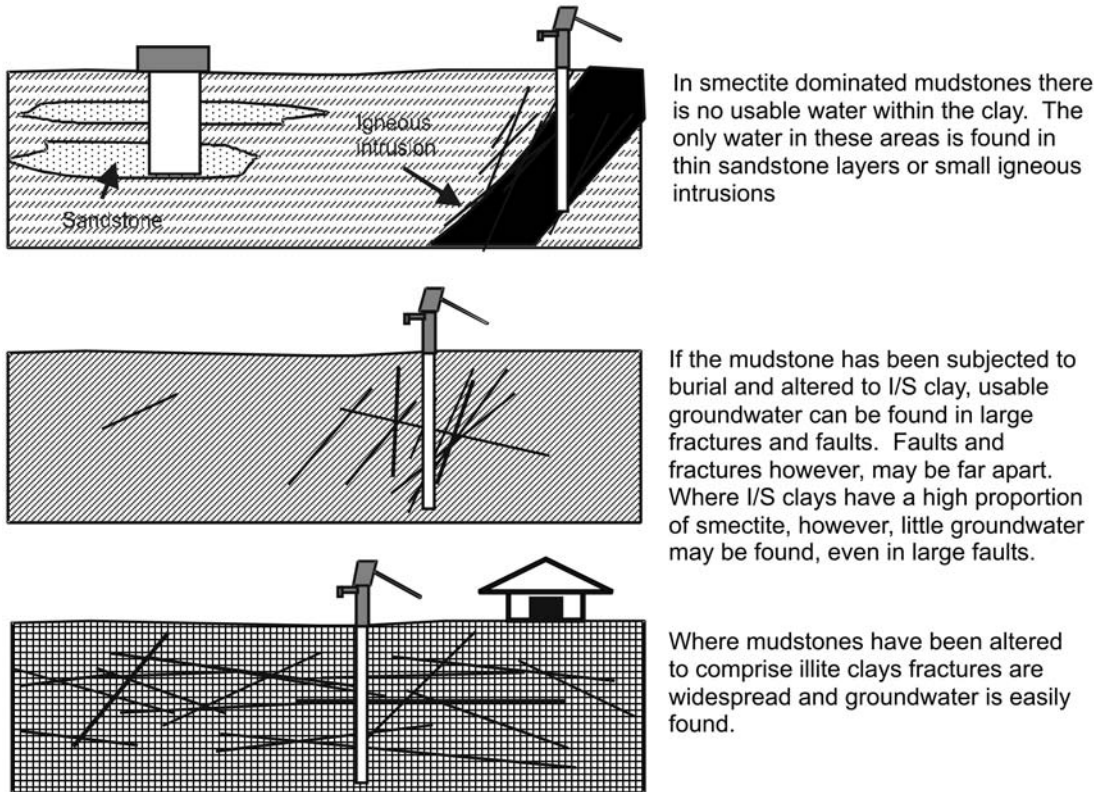


Figure 7 Schematic representation of the main factors affecting ground water occurrence in mudstone environments.

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