Fractures in shale: the significance of igneous intrusions for groundwater flow

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Abstract: Research in Cretaceous shales from West Africa has demonstrated that significant permeability can develop within shales at shallow depths (<100 m), equivalent to a permeability of >1 m day^{-1}. Much of the variation in permeability is related to the degree of burial metamorphism, with shales that have been altered and that approach the anchizone having the highest permeability and those that are largely unaltered (early diagenetic zone) having the lowest permeability. However, further research targeting largely unaltered shales dominated by smectite clay has shown that the presence of small igneous intrusions can radically alter the hydrogeology. Twenty-four exploratory boreholes were drilled into smectite-dominated shale and nine of these boreholes were targeted to small dolerite intrusions within the shale. The dolerite was intensely fractured at the intrusion edge, with significant zeolite growth along the fracture surfaces. The permeability in the fractured dolerite was the highest measured in any shale borehole, with transmissivities of up to 60 m^2 day^{-1} measured from pumping tests. Fracturing was less where dolerite was intruded into sandstones, however, and the measured transmissivity was lower (<0.5 m^2 day^{-1}). We postulate that the low permeability and high water content of the shale enabled high pressures to develop during intrusion, facilitating the development of fractures along the intrusion contact zone.

Fractures in shale are essential for controlling fluid migration. They are often studied from the perspective of hydrocarbons as a result of the control they exert on the characteristics of reservoirs (Curtis 2002) and their impact on the coherence of cap-rocks (Shukla *et al.* 2010; Bricker *et al.* 2012). In waste management, the development of fractures within clays and shales is crucial in limiting the migration of contaminants from repositories – particularly for nuclear waste (Hanor 1993; Neuzil 1994). Shales and mudstones are more rarely considered as aquifers, although they can provide a strategic source of drinking water for dispersed rural populations (Jones *et al.* 2000).

Research within shallow shale environments shows that significant fracture permeability can develop within shales at depths <100 m, equivalent to a permeability of >1 m day^{-1} (MacDonald *et al.* 2005). Much of the variation in permeability is related to the degree of burial metamorphism the shale has undergone and the corresponding change in clay mineralogy. Shales that have been altered by burial to approach the anchizone have a clay mineralogy dominated by illite and have the highest permeability. Those that are largely unaltered (early diagenetic zone) have the lowest permeability.

These unaltered low-permeability shales are often dominated by smectite clays, within which fractures do not remain open (Neuzil 1994; MacDonald *et al.* 2005). However, the presence of igneous intrusions within low-permeability shales can radically change the hydrogeology.

To study the impact of small igneous intrusions within a smectite-dominated shale environment, we drilled and tested 24 exploratory boreholes, nine of which were targeted to small dolerite intrusions and the remainder to unaltered shale.

Methods

Study area

The research was undertaken in Cretaceous sediments of the Middle Benue Trough in Nigeria. The study area covers two local government areas (Oju and Obi) in Benue state (Fig. 1). Oju/Obi is a remote part of SE Nigeria and experiences severe water shortages during the annual dry season, despite a high average annual rainfall of *c.* 1600 mm (Davies & MacDonald 1999). The area has been subject to extensive groundwater investigations in an attempt to improve the stubbornly high rates of guinea worm
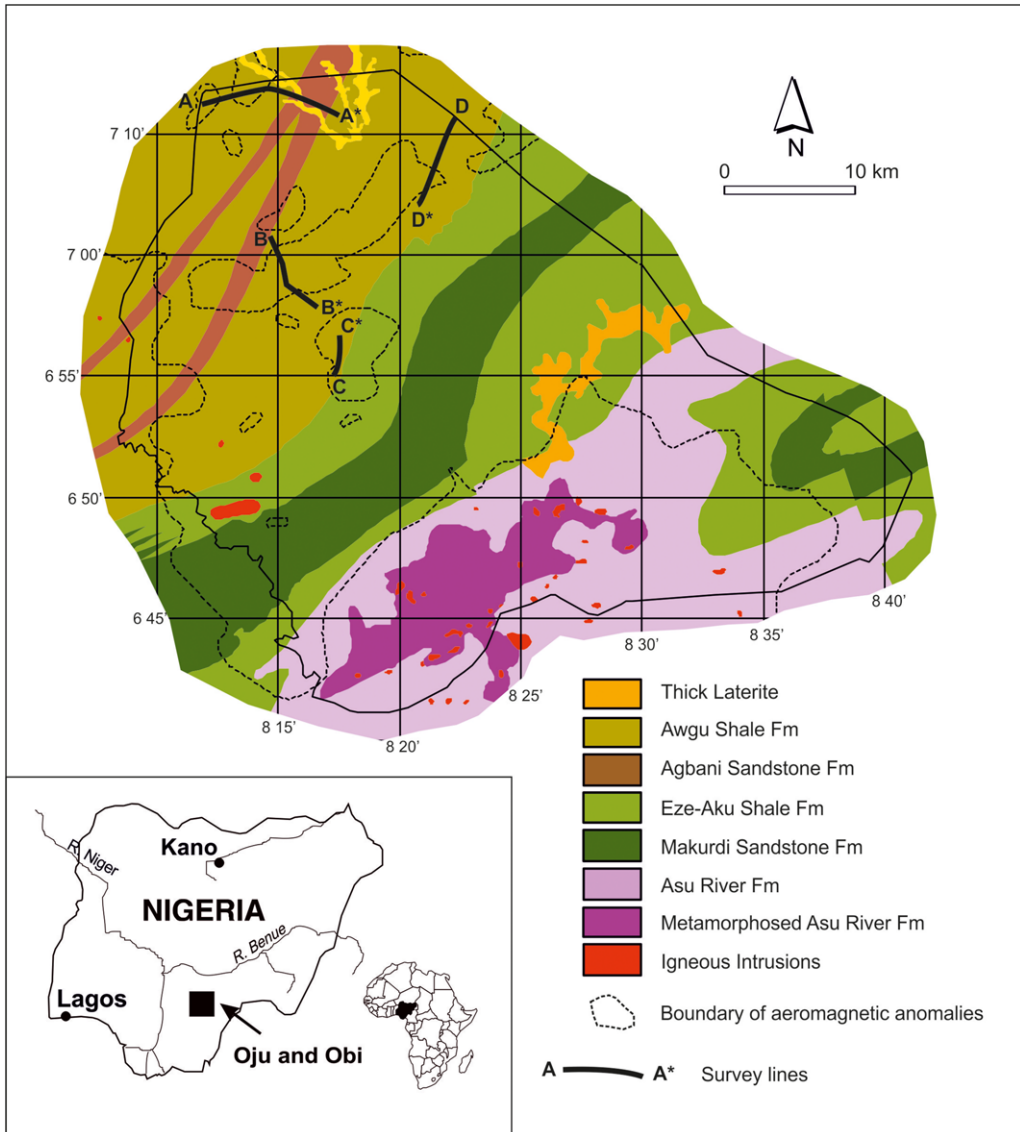
Fig. 1. Location and geology of Oju and Obi within the Benue Trough, Nigeria. The locations of the transects are also shown.

infection and low water supply coverage (MacDonald *et al.* 2001, 2005, 2008; Bonsor *et al.* 2014). Oju/Obi is situated within the lower section of the Benue Trough, a major elongated geological rift structure infilled with fine-grained, low-permeability Cretaceous sediments (Ofoegbu 1985). The sediments were deposited in deep to shallow marine and deltaic to fluviatile environments. Parts of the sedimentary sequence have undergone low-grade metamorphism (Ojoh 1990). Igneous rocks (mainly dolerite) have been intruded within the sediments.

Geophysical surveys

Smectite-dominated shale and the presence of dolerite intrusions were identified by combining frequency domain electromagnetic surveying and magnetic profiling, following a survey methodology developed by MacDonald *et al.* (2001). Four 5–10 km surveys were undertaken in areas mapped to have mainly smectite-dominated shales. The locations of the geophysical traverses are shown in Figure 1. The North Obi traverse is section A–A*,

the Ugbodum traverse is B–B*, the Adum West traverse is C–C* and the Itogo traverse is D–D*.

Electrical conductivity was measured using a Geonics EM34 system with 20 m separation and a transmitter frequency of 1600 Hz in both the vertical and horizontal dipole configurations. The operating range of the equipment was 0–150 mS m^{-1} with an accuracy of *c.* 10%. Smectite-dominated shales were identified by their high electrical conductivity (>60 mS m^{-1}); illite–smectite shales and sandstones were identified by their lower electrical conductivity (<50 mS m^{-1}) (MacDonald *et al.* 2001).Variations in the Earth's magnetic field were measured using a proton precession magnetometer (GEM Systems) with an operating range of 10 000–120 000 nT and a sensitivity of 0.1 nT. The presence of dolerite intrusions was identified by deflections in the Earth's magnetic field of >10 nT.

Drilling

Twenty-four exploratory boreholes were drilled in the four transects at locations identified from the interpretation of the geophysical surveys (see Fig. 1). Nine were targeted to dolerite intrusions within the shale, 11 to unaltered shale and four to the Agbani Sandstone Formation, which comprises increased sandy horizons within the shale. Rock chip samples were taken every 0.5 m and core samples were taken from targeted horizons. Exploration boreholes that encountered groundwater were developed and completed with a 125 mm plastic screen. The upper 2–3 m were grouted to stop inflow from the highly permeable shallow laterite layer.

Pumping tests

Pumping tests were undertaken in all piezometers in which groundwater was encountered. For boreholes where the yield estimated from airlifting was greater than *c.* 0.1 l s^{-1}, constant rate tests using low-yielding WHALE® pumps were undertaken. For boreholes with considerably higher yields (>0.5 l s^{-1}), a Grundfos submersible pump was used. Boreholes were pumped for five hours and the recovery data were analysed using the Theis recovery method (Kruseman & deRidder 1990). Where the yield of the borehole was estimated by airlifting to be <0.1 l s^{-1}, a modified slug test, known as the bailer test (MacDonald *et al.* 2008), was carried out. This test involved removing water over a ten-minute period and monitoring the recovery. The data were analysed numerically, accounting for the non-instantaneous removal of water (Papadopulos & Cooper 1967; Barker 1985, 1988). Pumping tests were carried out towards the end of the dry season when water levels were at their lowest and the influence of the shallow laterite aquifer was negligible (Bonsor *et al.* 2014). This combined experimental procedure enabled transmissivity values to be measured in the range 0.01–100 m^2 day^{-1}.

Results

Geophysical profiles for two of the transects are shown in Figure 2, together with a simple geological interpretation from the exploration boreholes. These profiles illustrate the different geophysical signatures between the unaltered shale and igneous intrusions within the shale. Unaltered smectite-dominated shale is clearly identified by a bulk apparent conductivity of >60 mS m^{-1} and little deflection of the magnetometer. Dolerite intrusions are identified by a lower apparent electrical conductivity (<50 mS m^{-1}) and large deflections (>10 nT) of the magnetic field over a short distance.

Summary logs for the exploratory boreholes are shown in Figure 3 for the four transects. The location of the first water strike is also noted. The Awgu Shale Formation is dominated by carbonaceous shales, rich in smectite clay minerals, with thin shelly limestone and rare thin sandstone. The Agbani Sandstone Formation consists of fine- to medium-grained sandstones, siltstones and shale. The dolerite intrusions encountered varied in thickness from <0.1 to >30 m. The dolerite generally occurs as hard, dark blue–green, fine- to medium-grained basic igneous dykes and sills. These are intruded into the mudstones, siltstones and sandstones of both the Awgu Shale and Agbani Sandstone formations. At Adum West (section C–C*), the dolerite is highly fractured and zeolite crystals (mainly mesolite) have grown on some of the fracture surfaces. At Ugbodum (section B–B*), the dolerite intrusions are thinner than those at Adum West and are mainly intruded into sandstone. The dolerite is finer grained and the occurrence of zeolite is rarer, with less evidence of fracturing from the drilling. Another dolerite sill was encountered in the Itogo traverse (section D–D*) and was observed to be medium to fine grained with zeolite growths. The control transect in North Obi encountered mostly shale with some thin limestone, sandstone and siltstone (section A–A*). No igneous intrusion was encountered by drilling, nor detected from field geophysics, in North Obi (section A–A*), despite there being some anomalies recorded in the airborne survey. The sediments at the edge of the dolerite intrusions have been altered, although rarely >1 m. The mudstones become harder and change to a light grey–white colour. At the surface, the dolerite weathers to form smectite clay (Kemp *et al.* 1998) and thick ferralitic soils develop over both the shale and the dolerite.

Interpretation of the presence of fractures within the boreholes from drilling records and analyses
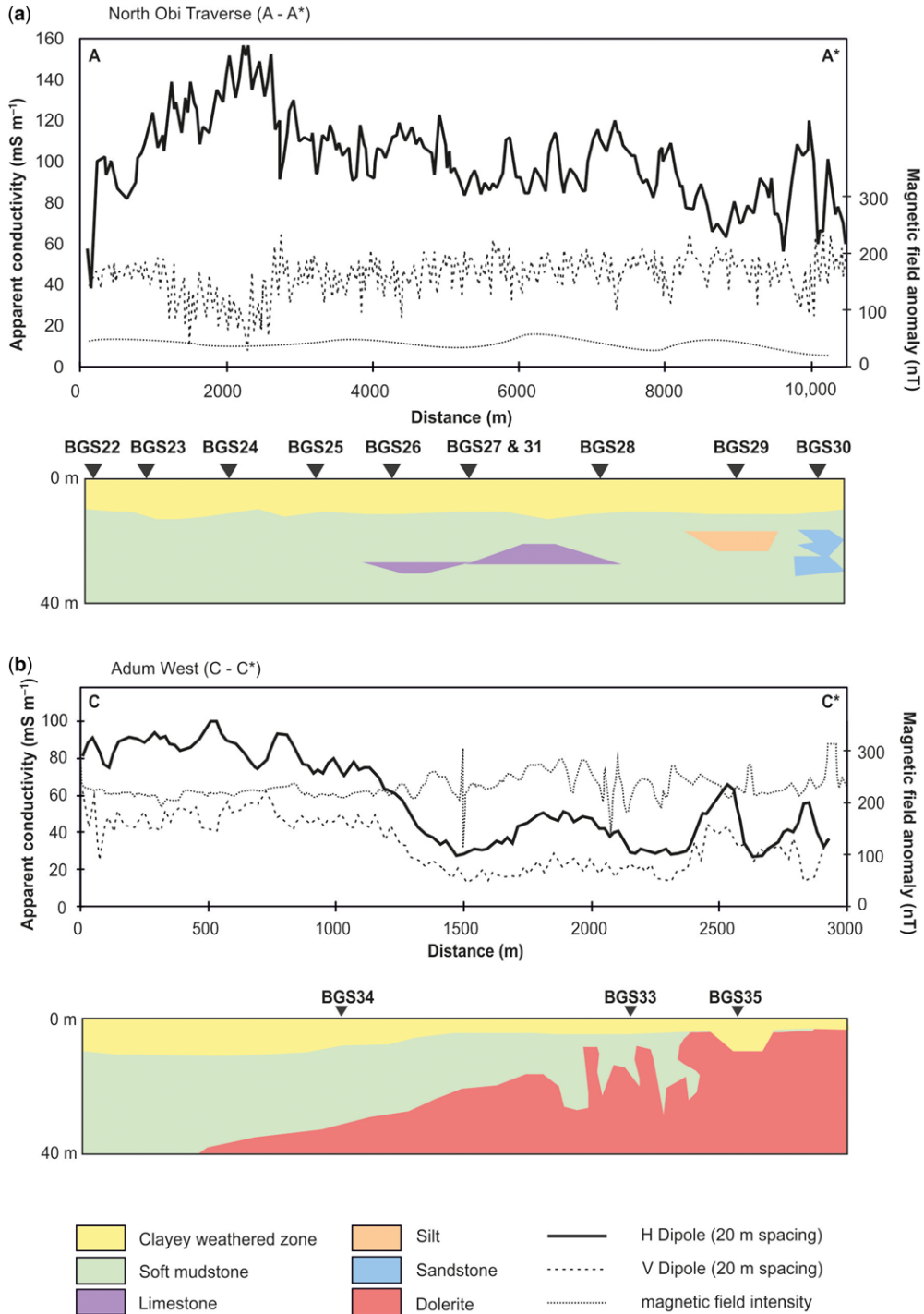
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Fig. 2. Geophysical profiles for two transects: (**a**) the North Obi traverse (A–A*) and (**b**) the Adum West traverse (C–C*). The apparent conductivity measured using the Geonics EM34 system (1600 Hz transmitter and 20 m coil separation) and the total magnetic field intensity clearly identify the presence of shallow igneous intrusions within the shale.
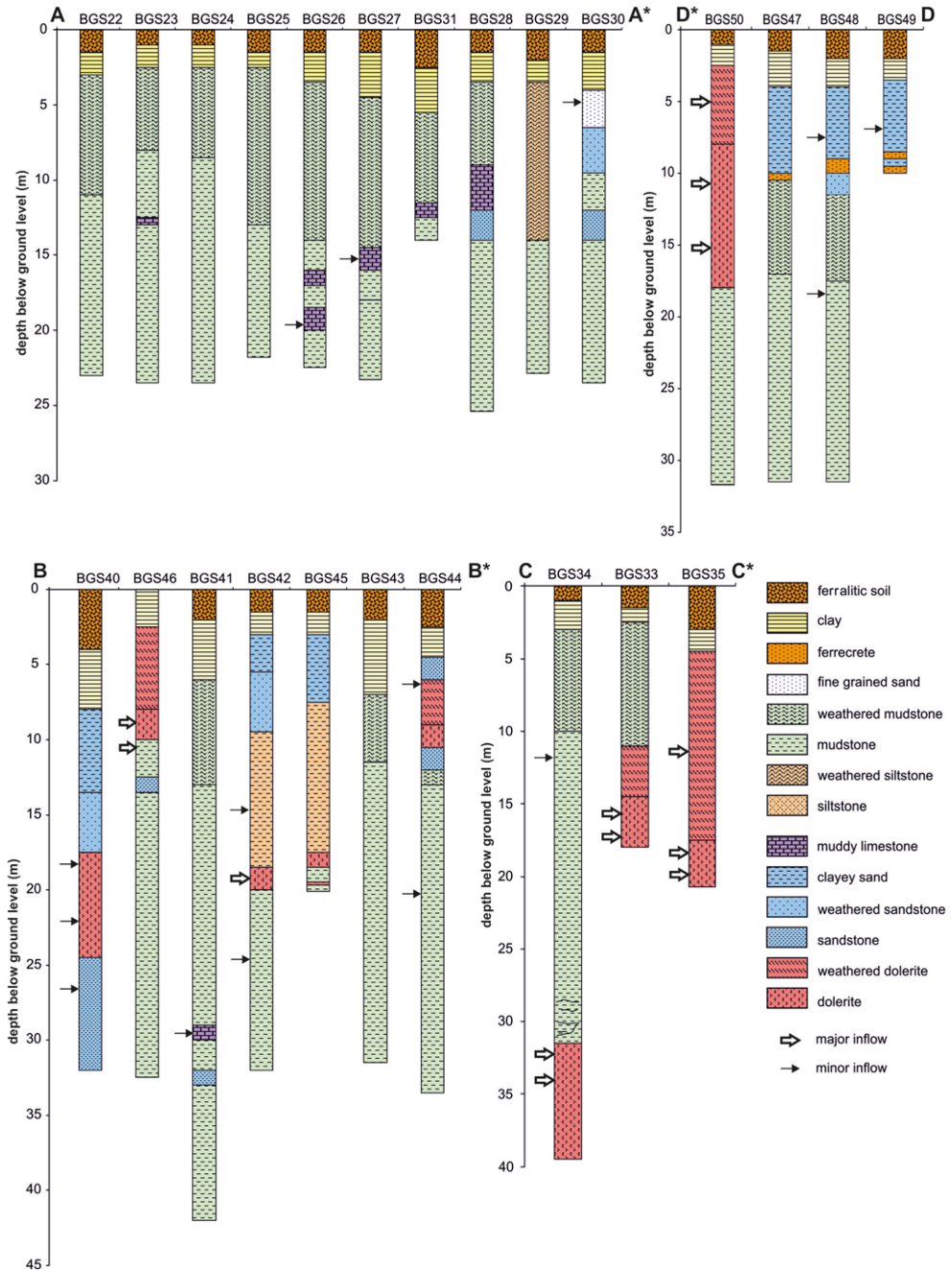
Fig. 3. Lithological logs for exploratory boreholes in the Benue Trough. The location of the transects are shown in Figure 1.

of the chip and core samples showed that fractures are present mostly within the dolerite and occasionally within the baked margins surrounding the intrusions.

Transmissivity and water strike data for the tests are shown in Table 1 and summarized for the different formations in Figure 4. Dry boreholes were assigned a transmissivity of <0.01 m^2 day^{-1}

Table 1. *Summary information for piezometers, lithology, fracture zones and measured transmissivity*

Piezometer	Traverse	Major lithology	Minor lithology	Lithology of major inflow	Depth to fracture zones (m)	Depth* to water strike (m)	Transmissivity (m² day⁻¹)
BGS22	A, North Obi	Soft shale			None	Dry	<0.01
BGS23	A, North Obi	Soft shale	Limestone		None	Dry	<0.01
BGS24	A, North Obi	Soft shale			None	Dry	<0.01
BGS25	A, North Obi	Soft shale			None	Dry	<0.01
BGS26	A, North Obi	Soft shale	Limestone	Limestone	None	20	0.024
BGS27	A, North Obi	Soft shale	Limestone	Limestone	None	15	0.08
BGS28	A, North Obi	Soft shale	Limestone, sandstone		None	Dry	<0.01
BGS29	A, North Obi	Soft shale	Siltstone		None	Dry	<0.01
BGS30	A, North Obi	Soft shale	Sandstone		None	5	<0.01
BGS31	A, North Obi	Soft shale			None	Dry	<0.01
BGS33	C, Adum West	Dolerite	Soft shale	Dolerite	15–18	16.5	57
BGS34	C, Adum West	Dolerite	Soft shale	Dolerite	34–39	32	3.8
BGS35	C, Adum West	Dolerite	Soft shale	Dolerite	15–21	18	23
BGS40	B, Ugbodum	Sandstone	Dolerite	Dolerite		17, 26	0.15
BGS41	B, Ugbodum	Soft shale	Limestone	Limestone	None	29.5	0.25
BGS42	B, Ugbodum	Sandstone	Soft shale, siltstone	Dolerite	None	15, **18**, 24	0.8
BGS43	B, Ugbodum	Shale			None	Dry	<0.01
BGS44	B, Ugbodum	Soft shale	Dolerite, sandstone	Dolerite	5–10	5	0.1
BGS45	B, Ugbodum	Sandstone	Siltstone, dolerite	Dolerite	18–20	18	0.19
BGS46	B, Ugbodum	Soft shale	Dolerite	Dolerite	8, 10	**8**, 9, 10	59
BGS47	D, Itogo	Sandstone	Soft shale		None	Dry	<0.01
BGS48	D, Itogo	Sandstone	Soft shale	Sandstone	None	8, 19	<0.01
BGS49	D, Itogo	Sandstone		Sandstone	None	7	0.04
BGS50	D, Itogo	Dolerite	Soft shale	Dolerite	15–17	5, 11, **15**	3.6

*If more than one water strike, the most significant is given in bold.
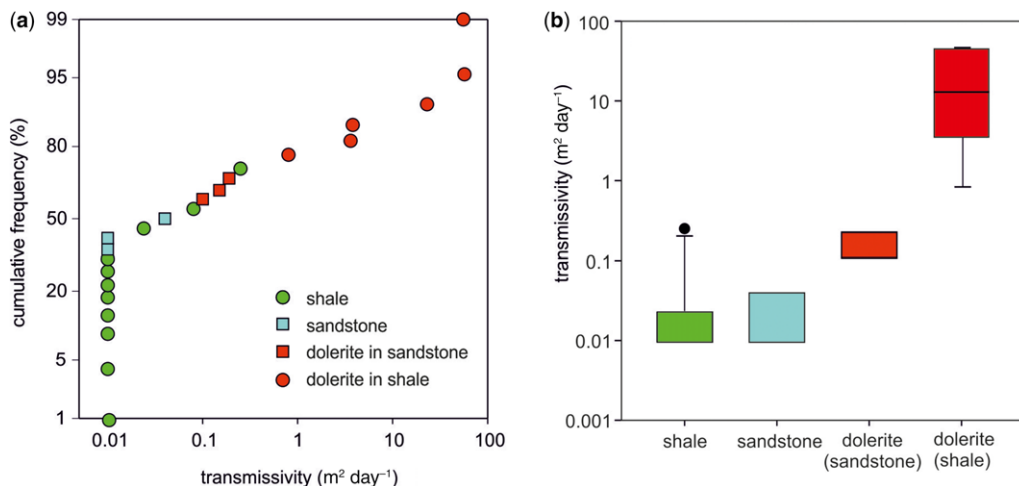
Fig. 4. Transmissivity data from pumping tests from boreholes encountering shale, fine-grained sandstone and dolerite intrusions in the Benue Trough. (**a**) Cumulative frequency plot. (**b**) Box plot.

(i.e. below the detection limit for the experimental set-up). The data showed a clear difference in the transmissivity data measured from boreholes that encountered dolerite. Boreholes that encountered only unaltered sedimentary rocks generally had a transmissivity $<0.1 \text{ m}^2 \text{ day}^{-1}$. Where dolerite was encountered, the transmissivity was $>0.1 \text{ m}^2 \text{ day}^{-1}$ and, for dolerite within shale, it was mostly in the range $1–100 \text{ m}^2 \text{ day}^{-1}$. Figure 5 shows representative recovery curves from bailer tests for boreholes that encountered shale or dolerite.

Discussion

A clear pattern emerges from the data: boreholes that penetrate dolerite intrusions within the shale have considerably greater transmissivity than boreholes that encounter only smectite-dominated shale, or thin sandstone and limestone layers within the shale (Fig. 4). Thick dolerite intrusions (such as at Adum West or Itogo) contain significant groundwater and generally have a transmissivity $>5 \text{ m}^2 \text{ day}^{-1}$. These thicker intrusions are the most productive aquifers within the region. Boreholes that encounter only unaltered shale have negligible transmissivity ($<0.01 \text{ m}^2 \text{ day}^{-1}$), which is occasionally enhanced to up to $0.5 \text{ m}^2 \text{ day}^{-1}$ by the presence of thin sandstone units and limestones. Thinner dolerite intrusions ($<10 \text{ m}$) also increased the measured transmissivity from pumping tests, but not to the same extent as the larger intrusions, and there is some indication that intrusions within sand-dominated layers had less impact on the transmissivity.

The geological logs of the Adum West and Itogo transects contain interesting information about

the fracturing of the larger dolerite intrusions and shale. Most groundwater is not found in the metamorphosed and disturbed rock next to intrusions, as found previously in most studies of dolerite intrusions within the Karoo sediments of South Africa (Bell & Maud 2000; Woodford & Chevallier 2002). The groundwater is encountered in fractures within the dolerite. The dolerite is highly fractured, with significant void spaces that allow the growth of several millimetre-long mesolite crystals within the fractures. For example, at two boreholes, BGS33 and BGS35, the dolerite was highly fractured and contained much mesolite (Fig. 6 shows a photograph of a core sample from BGS 35); transmissivity values $>20 \text{ m}^2 \text{ day}^{-1}$ were determined at these two boreholes. At another borehole, BGS34, the dolerite
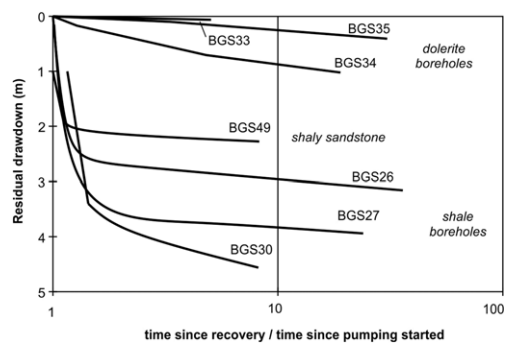

Fig. 5. Recovery curves from bailer tests in different boreholes in the study area. The bailer test is a modified slug test involving pumping for ten minutes at rates between 0.15 and 0.31 s^{-1} and monitoring the recovery (MacDonald et al. 2008).

was encountered at 31 m depth; there was little zeolite present and the transmissivity was 4 m^2 day^{-1}. Subsequent modelling of the geophysical data showed that an extensive dolerite sill was present in the area, which was further intruded by dolerite dykes (MacDonald et al. 2001).

Other exploratory boreholes targeting dolerite also encountered intrusions within sandstone. Here the dolerite was much less fractured and zeolite was rare. Pumping tests from these boreholes indicated that, although the aquifer properties were enhanced (up to 0.5 m^2 day^{-1}), the transmissivity was not as high as that recorded in the intrusions with soft, smectite-rich shale.

Why are the dolerite intrusions so fractured in Oju and Obi? The most likely reason is the high-porosity, low-permeability, swelling nature of the host rock, the Awgu Shales. At the time of intrusion the mudstones had undergone little change since deposition and therefore had a high porosity and contained large quantities of interstitial water. As the dolerite was intruded and the sills and dykes developed, the interstitial water reacted, leading to high pressures (Jamtveit et al. 2004), which were unable to dissipate quickly due to the low permeability of the mudstone and the plastic, self-healing nature of the smectite clay. The resulting high pressures and rapid cooling may have caused the extensive fracturing observed within the edges of the intrusions. Circulating fluids may subsequently have given rise to zeolite growth on the fracture surfaces. This hypothesis is supported by data from the boreholes that encountered dolerite intruded into sandstone, which encountered little fracturing or zeolite growth. In this situation, the higher permeability of the

sandstone would not have allowed high pressures to build. A study in the dolerite dykes of the Karoo in South Africa identified similar chilled margins of dolerite dykes as potential fluid pathways, with the extent of fracturing associated with the hydraulic properties of the host rock (Senger et al. 2015).

Within the context of water supply, the presence of dolerite intrusions within low-permeability shale provides targets for viable groundwater supplies. This is particularly important as shale environments are often the most difficult areas in which to find groundwater (MacDonald & Calow 2009) and are associated with persistent low water coverage and poor health (MacDonald et al. 2005). Dolerite intrusions are also relatively simple to find using geophysical methods (Woodford & Chevallier 2002). Because the fracturing mechanism is not associated with weathering and unloading, dolerite intrusions are also likely to provide significant fluid pathways at depth within a sedimentary sequence. In this example, the intrusions were more significant than the presence of sandstone, limestone or siltstone. Therefore the occurrence of dolerite intrusions must also be carefully considered when relying on argillaceous environments to restrict fluid migration.

Conclusions

Detailed research into the hydrogeology of low-permeability Cretaceous shales in West Africa has shown that the presence of dolerite intrusions can significantly enhance permeability and facilitate groundwater flow. Exploration boreholes that targeted dolerite intrusions within smectite-dominated host rock have transmissivities of up to 60 m^2 day^{-1}. Where dolerite was intruded into sandstones, however, fracturing was less and the measured transmissivity was lower (<0.5 m^2 day^{-1}). Where no dolerite intrusion was present, the transmissivity was generally <0.01 m^2 day^{-1}. The dolerite intrusions within the shale were intensely fractured at the intrusion edge, with significant zeolite growth along fracture surfaces. We postulate that the low permeability and high water content of the shale enabled high pressures to develop during intrusion, facilitating the development of fractures along the intrusion contact zone.

This research has two major implications: (1) dolerite intrusions may offer a promising target for rural water supply in smectite-dominated shale environments; and (2) when considering shale environments for their ability to restrict fluid flow, and therefore as targets for waste repositories, careful consideration is required of the possibility of encountering igneous intrusions within the sequence.
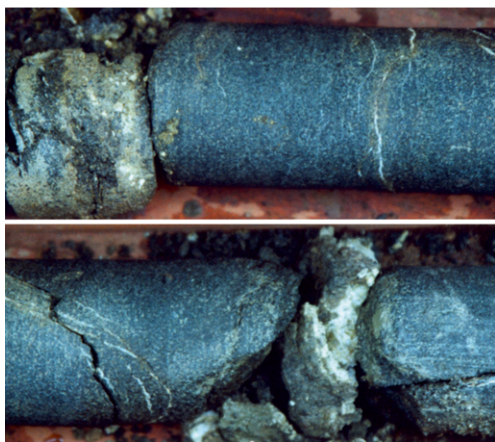

Fig. 6. Core from BGS 35 at 17–17.5 m depth. This zone is the main water inflow to the borehole and consists of fractured dolerite with significant zeolite associated with the fractures. The width of the core is 75 mm.

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