Deoxygenated gas occurrences in the Lambeth Group of central London

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Abstract: Deoxygenated gas poses a serious and life-threatening hazard (confined space hypoxia) for engineering projects in London, particularly those in the Upnor Formation of the Lambeth Group. We review its causes and postulate that it is induced by dewatering or positive pressure tunnelling bringing air into contact with these sediments, causing oxidation. Subsequent resaturation results in pockets of deoxygenated gas. Drawdown of the Lower Aquifer during the industrial growth of London brought air into contact with Lambeth Group sediments on a regional scale. Its recharge has trapped and compressed deoxygenated gas beneath overlying impermeable clays. Historically, the mineral glauconite has been blamed for these hazards, but it lacks potency as a reducing agent and remains unaltered in many oxidised Lambeth Group sediments. Pyrite and organic carbon are both plausible but a more potent agent is green rust, which readily and rapidly oxidises on contact with air, and which is only briefly observed in fresh core samples. This research identifies two key ground engineering hazards: the misidentification of risk by reliance on observations of glauconite; and the likelihood of encountering pressurised deoxygenated gas within Lambeth Group sediments in underground projects following short- or long-term changes in ground water level.

Confined space hypoxia (Zugibe et al., 1987), caused by deoxygenated gas, is well-known within the water and sewerage industry and past tragedies have led to increasingly stringent Health and Safety legislation for working in confined conditions underground (Confined Spaces Regulations, 2009). Nevertheless, even with good compliance, hypoxic ground conditions can occur and rapidly lead to unconsciousness and even death. It is therefore imperative for the correct quantification of risk that the conditions under which confined space hypoxia occurs are as well understood as possible.

This paper highlights a specific type of confined space hypoxia that occurs within Lambeth Group sediments in central London (Figures 1 and 2), in which deoxygenated but otherwise normal air is encountered underground, often under an excess pressure and occasionally with elevated carbon dioxide.
1 Background

One of the earliest well-recorded incidents of deoxygenated gas in London tunnelling occurred during construction of the London Underground Limited (LUL) Victoria Line (Morgan and Bartlett, 1969; Clark, 1970), however, the cause of this loss of oxygen was never identified.

In 1984 an oxygen-deficient atmosphere was found at the start of each day shift (E. Woods and A. Miller, pers. comm.) during construction of the Effra Storm Relief Sewer, south London. The 1.83 m internal diameter tunnel was driven beneath Brockwell Park, Dulwich, as a day-works only contract, with the ventilation switched off at the end of each day shift. Oxygen deficiency was encountered at the start of each day shift (with levels restored only after a period of ventilation) through the Streatham Fault Zone (Figure 3), which juxtaposes the London Clay Formation and Lambeth Group sediments, particularly the Upnor Formation, and as a result the ventilation capacity was increased for the remainder of the tunnel drive.

The most serious incident to date took place in August 1988, when two fatalities occurred during construction of a Thames Water Ring Main (TWRM) shaft at Stoke Newington, north London. The shaft was 46.5 m deep with an 11.9 m internal diameter and had been completed 26 months previously. An engineer and assistant were both asphyxiated within the confined space of a sealed section of pipework extending from a high integrity valve into a closed tunnel heading within the Upnor Formation. It was concluded at the subsequent Crown Court trial (CNPlus, 1991) that glauconite, within the soil groundmass, was the probable cause of the hypoxia.

Within the same TWRM contract, poor air quality was subsequently encountered during the tunnel drive from Coppermills to this shaft. Internal correspondence from the Resident Engineer (P. Hemmings, pers. comm.) noted that air in this section, through the Upnor Formation, contained as little as 11% O2. A number of construction engineers (E. Woods, G. Howells and A. Miller, pers. comm.), working on this section, gave accounts of gas escaping through the final invert of the shaft at Coppermills, visible as bubbles rising vertically through water ponded on the shaft floor. The oxygen-depleted gas was encountered in the section of tunnel in which the invert and base slab were constructed within the Upnor Formation (Figure 4), a section recorded as ‘dry’ in piezometer data collected. The oxygen deficiency was mitigated through air quality monitoring and adequate ventilation.
A ‘near miss’ incident occurred during construction of a cross-passage (C. Warren and E. Woods, *pers. comm.*) between two completed running tunnels of the Channel Tunnel Rail Link (CTRL) beneath Hackney Wick in north London. Another incident took place during caisson sinking of the TWRM shaft at Honor Oak, south London (Newman and Wong, 2011). In both these incidents, an oxygen deficient atmosphere was recorded during construction in the Upnor Formation after a period of dewatering and drawdown from the underlying chalk.

Significant oxygen depletion was also recorded within a number of borehole monitoring installations during separate ground investigations for two large tunnelling schemes in north London: Thames Water’s North London Flood Relief Sewer (NLFRS); and the TWRM northern extension tunnel.

During borehole investigations for the section of the NLFRS between Victoria Park and Stoke Newington (Figure 5), samples of gas were taken from borehole installations within the Upnor Formation. Laboratory analyses found that the gas contained up to 98% N₂, less than 1·2% O₂, and elevated levels of CO₂. Rates of gas emission from each borehole were between 1·6 and 5·0 m s⁻¹, indicating an over-pressured gas source. Monitoring of the NLFRS site investigation boreholes was undertaken over a 12-month period. The oxygen levels within these installations (also entirely within the Upnor Formation) were consistently below 1% during this time (Figure 6), with CO₂ levels between 1 and 2%. Lewis and Harris (1998) proposed a link between these gas levels and barometric pressure but we find no evidence to support such a link in these data.

Almost the entire 2·82 m internal diameter NLFRS tunnel was driven through the Upnor Formation; given the results of the borehole investigations, clearly defined underground entry procedures and an increased capacity ventilation system were enforced so that no injuries were caused by poor air quality during construction, but gas was frequently heard passing through the tunnel lining (Lewis and Harris, 1998, G. Howells and V. Yuan, *pers. comm.*).

During site investigation for the extension of the TWRM between Stoke Newington and Thames Water’s New River Head (NRH) site in north-central London (Figure 7; Newman *et al.*, 2010), measurements of gas from within borehole monitoring installations in the Upnor Formation indicated up to 2·4% CO₂ and less than 1% O₂ in some of the boreholes. Nitrogen was not
measured. Monitoring of the TWRM boreholes was also undertaken over a 12-month period. The oxygen levels (Figure 8) are more variable than the NLFRS data, often with a sharp decrease from a concentration between 12 and 15% to one below 5%, remaining stable at that level thereafter. Again, however, there is no clear link between the gas levels and barometric pressure.

The 2.85 m internal diameter Stoke Newington to New River Head tunnel was also constructed predominantly within mostly dry Upnor Formation, the interpreted piezometric levels indicating that the stratum lay above the Lower Aquifer.

A similar incident was experienced during ground investigation for the Crossrail scheme in London’s docklands area, whereby Borehole IOD30R (refer to Figure 2 for location) encountered air escaping from the borehole upon its intersection with the Upnor Formation (U. Lawrence, *pers. comm.*). Subsequent gas monitoring of this indicated significantly low levels of O₂ and slightly elevated CO₂ but no obvious associated effects from changes in barometric pressure.

At each of these locations, deoxygenated gas was encountered within the Upnor Formation.

However, deoxygenated gas has also been recorded in sandy sections of the Woolwich Formation Laminated Beds at borehole investigations undertaken for proposed residential developments in Romford and Little Ilford, Essex, in 2005 and 2008 respectively (P. Gawne *pers. comm.*), as well as in Thames Water’s Tideway Tunnel scheme investigation along a section of the Victoria Embankment (Temple) and in Tower Hamlets in 2009. In these cases the deoxygenated gas was also accompanied by elevated levels of CO₂.

At Romford, pockets of air containing severely depleted levels of O₂, at 0.1%, and CO₂ levels as high as 2.6%, were recorded during subsequent monitoring of standpipe installations. At Tower Hamlets, 8.7% O₂ and 0.6% CO₂ were recorded. At both locations drillers recorded ‘blowing sand’ during borehole excavation and distinct voids were observed in rotary core samples recovered. These are presumed to represent gas migration pathways; material surrounding the voids was noted to be patchily oxidised, although the origin of the gas is unclear at this stage.

### 2 Causal Mechanisms: Physical Processes

The Upnor Formation is normally considered hydraulically connected with the Chalk via the Thanet Sand Formation, forming the Lower Aquifer of London’s water table (Simpson *et al.* 1989). In its natural state, prior to any significant human influence, the Lower Aquifer was
under artesian pressure (Figure 9), confined throughout much of London by the Lower Mottled Beds above.

Over-abstraction of the Lower Aquifer began in the early 1800s at rates rising steadily from approximately $9 \times 10^6$ m$^3$ a$^{-1}$ to a peak of $8.3 \times 10^7$ m$^3$ a$^{-1}$ by 1940 (Hurst and Wilkinson, 1986). This led to a significant lowering of the groundwater table and the formation of a large cone of depression beneath west central London, first recognised in 1820 and extensively developed by 1850 (Marsh and Davies, 1983). From 1940, the rate of abstraction from the Lower Aquifer reduced significantly with the destruction of a large number of abstraction wells during World War II and the control of abstraction by the 1945 Water Act (Wilkinson, 1985). Escalating costs, the increasing depth of abstraction required, and economic decline limited the number of new wells constructed. Nonetheless, over-abstraction continued until by 1965 the groundwater table had lowered by more than 70 m (lower surface in Figure 9) in the centre of the cone of depression (Simpson et al. 1989). This was the lowest level on record and equated to $1.03 \times 10^9$ m$^3$ of water abstracted from more than $1.2 \times 10^{10}$ m$^3$ of the Lower Aquifer (Flavin and Joseph, 1983) over an area in excess of 200 km$^2$ (Marsh and Davies, 1983). The centre of the cone of depression was located close to Charing Cross and Trafalgar Square but a significant area of drawdown occurred within the Lee Valley, near Thames Water’s Abbey Mills Pumping Station site.

Since 1965, the rate of groundwater abstraction from the Lower Aquifer decreased by between 30 and 50%, from $6.2 \times 10^7$ m$^3$ a$^{-1}$ in 1965 to $4.3 \times 10^7$ m$^3$ a$^{-1}$ by 1982 (Wilkinson, 1985). This was allied with the demise of heavy industry, the largest consumer of groundwater, and resulted in a rise in the Lower Aquifer groundwater table. Estimates of the rate of rise vary, from $1.5$ m a$^{-1}$ (Simpson et al. 1989) to $2.5$ m a$^{-1}$ (Lucas and Robinson, 1995), to a more recent estimate of $3.0$ m a$^{-1}$ (Jones, 2007). The greatest recovery is within the central London cone of depression, which had risen 20 m by 1988 (approximately midway between the 1965 and the pre-abstraction levels in Figure 9). By 1994, the cone of depression had also significantly reduced in geographical extent, becoming confined to an area between Hammersmith and central London, mainly north of the River Thames. Most of the change between lowest recorded levels and highest rate of recovery encompasses an area between Hammersmith in west London and the section of the north bank of the River Thames between Chelsea and Victoria Embankments. By the late 1980s, the continued rise in groundwater level was recognised as a risk to deep tunnels and basements by changing the ground engineering properties and potentially causing
flooding. In response, the GARDIT (General Aquifer Research Development and Investigation Team) strategy was launched in 1998 to control the rising groundwater by abstraction of 70 Ml per day ($2.56 \times 10^4$ m$^3$ a$^{-1}$) on a schedule up to 2004. However, Thames Water and Environment Agency groundwater modelling demonstrated in 2000 that this rate was too high (Jones, 2007) and should be reduced to 50 Ml per day ($1.83 \times 10^7$ m$^3$ a$^{-1}$). Continued monitoring demonstrates the success of GARDIT, with groundwater levels now broadly stable throughout central London (Jones, 2007).

The drawdown of the Lower Aquifer is believed (Flavin and Joseph, 1983) to have caused large volumes of permeable saturated Lambeth Group sediments to drain, and air to enter the sediments through 'windows' in the overlying London Clay or via large borehole adits, leading in places to sediment oxidation and the production of deoxygenated air. The GARDIT-controlled incomplete recharge of the Lower Aquifer would then have trapped this deoxygenated air under pressure below impermeable Lambeth Group sediments, in particular the Lower Mottled Beds.

The lithologies encountered within the Upnor Formation and adjacent strata are geographically variable but have a broadly consistent stratigraphic sequence (Figure 1). The base of the Upnor Formation is frequently demarcated by a rounded fine to coarse flint gravel, set within a more typical green, clayey, fine to medium sand, with variable quantities of the mineral glauconite (Page and Skipper, 2000). The main body of the Upnor Formation often consists of a grey-green, silty, fine to medium sand to sandy clay, with some fine to medium (occasionally coarse) black flint gravel, commonly containing a variable abundance of the mineral glauconite. In some locations, particularly to the north and east of London and as encountered during the NLFRS and TWRM northern extension, distinct thin to medium interlaminated brown clay and fine sand dominates the unit.

The resulting emergence of terrestrial conditions over the area of what is now south east England resulted in the formation of the Lower Mottled Beds (Page and Skipper, 2000). These deposits display characteristically very strong pedogenetic effects, typified by the vivid red, orange and purple hues that are associated with oxidation and other pedogenetic processes within soil horizons (Ellison, 1983). Inspection of numerous borehole core samples and underground excavations across the London area demonstrates that these pedogenetic processes have affected the top of what were formerly Upnor Formation sediments, in particular the gravel that frequently defines the top of this unit (Ellison et al., 1994; Ellison et al., 2004). The lithologies in this zone are distinct from the unaltered material below, comprising an assortment of colours (red, brown, grey and white) of weathered, subrounded, fine to coarse flint set within a light blue-grey mottled orange-brown clay matrix. The effects of pedogenesis diminish with depth,
leading to a gradational contact with the unaltered material below, and where permeable they are in hydraulic continuity with the Upnor Formation and the Lower Aquifer.

## 3 Causal Mechanisms: Chemical Processes

Recharge of the aquifer is a plausible mechanism for the excess gas pressure encountered, as previously deoxygenated air became trapped beneath the Mid-Lambeth Hiatus by impermeable clay-rich layers of the upper parts of the Lambeth Group and the London Clay Formation, but what geochemical reactions are responsible for the reduction of the air trapped in these sediments?

Within the construction industry, glauconite is regarded as the reducing agent responsible for loss of oxygen in confined spaces (CNPlus, 1991). Strictly, glauconite is a compositionally-variable series within the mica group and the name is used for all green clay pellets with a glauconitic component (Huggett and Knox, 2006). It has been described (Harder, 1980) as forming within the mildly reducing conditions of cooler (<13°C) deeper marine environments, associated with muddy marine sediments at the interface between reducing and oxidising zones in relatively calm environments with slow sedimentation rates and/or interrupted deposition by precipitation of Fe-hydroxides from Fe, Al, Si and K solutions under reducing conditions. However, the palaeontology and ichnofacies (Skipper, 1999) of the Upnor Formation indicate that it was formed under subtropical shallow marine conditions. Under the binocular microscope, glauconite varies in colour from very pale bluish green to greenish yellow to dark green when fresh. However, when oxidised, it breaks down into iron oxides, displaying a typically brownish yellow or reddish brown colour (Pettijohn et al. 1987).

During recent borehole investigations for Thames Water’s Tideway Thames Tunnel scheme, two boreholes (SR2071 and SA1066D) intersected high pressure ground gas (Newman and Hadlow, 2011). Both boreholes were constructed using cable percussion techniques; the first borehole was obtained from a jack-up rig in the River Thames adjacent to Cadogen Pier, Chelsea Embankment; the second from Whitehall Gardens on the Victoria Embankment. In both boreholes, pressurised ground gas was encountered at the point of intersection with the gravelly Lower Mottled Beds, at 50·9 m below river bed level and 56·0 m below ground level respectively. In the case of borehole SR2071, gravel material was ejected to surface, whilst from SA1066D (Figure 9), gas was recorded venting from the borehole casing for a period of eight months until sealed with a permanent cap. A number of return visits were made to this borehole to collect gas samples for laboratory analysis; between 21 August and 15 October 2009 the recorded oxygen content was never more than 3·4% (by volume) and usually less than 2%, with
no apparent relationship with barometric pressure. CO₂ was recorded at 600 to 900 ppmv, which at two to three times normal atmospheric concentration is not considered unusual.

Flow rate observations were not possible until two weeks after gas was first encountered, so the initial rate is uncertain. Assuming an exponential gas release model (Table 1) the initial rate is estimated to have been 120 litres/hour, rapidly declining over a two-week period to a background level determined from long term monitoring of between 7 and 22 litres/hour. This implies that up to 15,500 litres of gas was initially released from a disturbed zone of approximately 2 m radius around the borehole and that up to 500,000 litres was released in total over a 2½ year period. The soil matrix permeability, \( \approx 10^{-6} \text{ m s}^{-1} \), inferred from the background rate indicates that a fine silt and clay matrix controls gas migration through this layer.

Both boreholes SR2071 and SA1066D lie within the (1964) central cone of depression in the Lower Aquifer. Whatever the chemical process, it is clear that a large volume of Upnor Formation could have been oxidised as a result of this cone of depression. However, the subsequent water table recovery was also greatest here and we propose that the rise in the groundwater table since 1965 has trapped and compressed N₂-rich, O₂-depleted gas against the underside of the overlying impermeable clays of the Lower Mottled Beds.

As much as 14 km of drilling samples have been recovered to date during the ground investigation for Tideway Thames Tunnel. In a number of instances, examples of apparently fresh (unoxidised) glauconite have been observed within pedogenetically altered sediments belonging to the Lower Mottled Beds (Figure 10), which have been subject to intense weathering, and/or within core samples of the Upnor Formation left exposed to free air over a number of months. This implies that the oxidation of glauconite is not a rapid process and that its decomposition above the water table might not make it the primary culprit in the production of trapped hypoxic gas.

Obvious alternative reducing agents are organic carbon and pyrite. Organic carbon in the form of driftwood fragments is present throughout the Group, often as dispersed small particles but sometimes in large concentrations. Oxidation of organic carbon primarily results in the production of CO₂. Pyrite is common in the Laminated Beds of the Woolwich Formation and in the Upper Mottled Beds Sand Channel of the Reading Formation, usually as disseminated fine sand grade material or rarely as gravel-sized lumps. Its oxidation leads to acidified groundwater
that reacts with any carbonate, ultimately releasing CO$_2$. The oxidation of both organic carbon and pyrite should therefore be associated with elevated CO$_2$ levels. Elevated CO$_2$ levels are sometimes associated with incidents of confined space hypoxia, such as at Thames Water NRH and at Romford, where organic carbon was also noted to be present, but usually the hypoxic gas is 'normal' air with reduced oxygen. Geochemical tests in the Upnor Formation (Table 2), in which many of the incidents occurred, show that pyrite is extremely rare and organic carbon present at very low levels (<1%), typically in the form of isolated wood fragments.

Fresh core samples from the Upnor Formation and Lower Mottled Beds are frequently observed to have a transient bright bluish green colour (Figure 11) that on exposure to air rapidly changes over a period of minutes to hours to a dull grey-green colour and then, over a few hours or days, to a yellow-orange colour. These changes are characteristic of the oxidation of green rust minerals (Christiansen et al. 2009; Taylor and McKenzie, 1980), a reaction that is both much more rapid than glauconite oxidation and one which consumes much more oxygen, weight for weight.

Green rust is a family of mixed Fe(II) and Fe(III) layered double hydroxides with a pyroaurite-like structure consisting of alternating positively charged Fe(II)/Fe(III), brucite-like, hydroxide layers and hydrated interlayers composed of anions and water molecules (Nagata, et al. 2009; Christiansen et al. 2009; O’Loughlin et al. 2007). It is characteristically bluish-green in colour (Trolard and Bourrie, 2006; Legrand et al. 2004), forming in environments close to the Fe(II)/Fe(III) transition zone, in conditions without much oxygen. It forms as free colloidal-size particles within natural groundwater, under weakly acidic to alkaline conditions, and possesses a ratio of Fe(II) to Fe(III) of 2:1 (Zegeye et al. 2005). Although chemically distinct, it plays a similar role to that of ferric brown rust in forming a stain or coating on mineral grains in the sediment.

Green rust is suspected to be a very common mineral, widely distributed in soils and sediments at a depth of a few metres within certain marine environments and in waterlogged anoxic gley soils (Genin et al. 2005). Dissimilatory iron(III)-reducing bacteria (DIRB), in particular _Shewanella putrefaciens_ (O’Loughlin et al. 2007), are metabolically most active in these environments (Parmar et al. 2001) and form green rust through the bioreduction of Fe(III) oxides and oxyhydroxides.
Green rust crystals are very small, typically about 10 nm across and 3 nm thick, and so possess a relatively high surface area that makes them particularly susceptible to oxidation. The Fe(II) ions oxidise to Fe(III) ions, transforming the green rust to iron oxihydroxides and iron oxides, i.e., the commonly observed brown rust, such as goethite, lepidocrocite and magnetite (Nagata et al. 2009; Trolard and Bourrie, 2006; O’Loughlin et al. 2007). Ferrihydrite usually forms only as an intermediate product but may be observed when oxidation is so rapid that alteration to goethite and lepidocrocite does not occur (Refait et al. 2003).

Some simple calculations demonstrate the potency of green rust with respect to glauconite and other possible reducing agents. Oxidation of 1 kg average glauconite (Bentor and Kastner, 1965) consumes just $6.5 \times 10^{-4}$ kg O$_2$. Assuming a gas pressure of 500 kPa (slightly above hydrostatic conditions at 40 m depth), 35% average porosity (this study), dry conditions and normal air composition (21% O$_2$), each cubic metre of Upnor Formation sediments has up to 2.35 kg free (gaseous) O$_2$ before reduction. The total mass of material in 1 m$^3$ of Upnor Formation is 1690 kg, assuming a particle density of 2600 kg m$^{-3}$ and 35% porosity. Each cubic metre therefore requires up to 3615 kg, i.e., 213.9 wt% (Table 3), of glauconite to fully reduce this oxygen. Such calculations demonstrate that glauconite cannot be solely or even principally responsible for the loss of oxygen in underground confined air spaces.

Organic carbon and pyrite are both very powerful reducing agents, respectively requiring just 0.88 kg and 4.4 kg per cubic metre of ground. Both are present in the ground in sufficient quantity but are concentrated into widely dispersed particles with very low reactive areas. Their potency is thus much reduced by permeability and surface area to volume constraints. In addition, there is no evidence from incidences within the Upnor Formation of elevated CO$_2$ or acidified groundwater that are expected by-products from the oxidation of these materials.

Although green rust has a very wide compositional range, measurements by Feder et al. (2005) indicate that in a typical ground profile, the average composition is 27% Fe(OH)$_2$, 62% Fe(OH)$_3$ and 11% Mg(OH)$_2$, so that 105.3 kg is required per cubic metre of ground, and leaves no characteristic oxidation by-products. Green rust forms as a coating on quartz grains (much like the normal rust that turns sand grains red). These grains are typically silt to sand size, so assuming spherical grains with an average diameter of 0.1 mm and a green rust density of 3670 kg m$^{-3}$, 6.2 wt% green rust would form a 1.2 µm thick coating on each quartz grain, giving green rust a remarkably large reactive area. These factors make green rust a strong candidate for primary chemical cause of deoxygenated ground gas in Upnor Formation sediments.
4 Green Rust Detection and Analysis

We hypothesise that the extremely wide distribution of green rust minerals on the surface of sediment grain, coupled with its extreme reactivity and reduction potential, its absence in all but the freshest of core samples make green rust the most likely chemical cause of deoxygenated gas in central London. Furthermore, the absence of green rust and the presence of brown rust in Upnor Formation sediments from cores taken within the lower aquifer cone of depression, indicate that large volumes of sediment in central London may have been oxidised in the last ~150 years, leaving behind a nitrogen-rich hypoxic gas, now pressurised by recharge of that aquifer.

A full programme of laboratory testing on borehole samples recovered during the ground investigation phase of the Tideway Thames Tunnel project is underway to identify the mineralogy of reduced and oxidised soil samples. So rapid is the oxidation of green rust that its recovery from field samples for testing is extremely difficult. Samples recovered to date do contain glauconite and goethite (a possible oxidation product of green rust) but green rust itself has not yet been observed, other than briefly by eye during sample recovery. Part of the reason for this may be sample retrieval and preparation. At present the procedure is that immediately following recovery from the ground and while still within a protective, rigid plastic lining, the 100 mm diameter core is cut into 100 mm length samples at predetermined intervals within the stratigraphic sequence. Liquid wax is poured onto the open ends of the cut core to form an impenetrable barrier against potential oxidising effects and then wrapped in a layer of cling film. Plastic caps are placed on both ends and then the whole sample is wrapped in a second layer of cling film, labelled and placed within a clear plastic soil sample bag sealed with tape. This procedure is undertaken as rapidly as possible to minimise exposure of the soil sample to oxidation. Nonetheless, when the sample is unwrapped in a specially designed anaerobic chamber (glove box) a measurable increase in oxygen levels is recorded, implying that the waxing and wrapping technique is not entirely effective in preventing oxygen from becoming trapped in the wrapping of the sample. To overcome this issue, future core samples will be vacuum packed immediately upon core recovery and then frozen in dry ice.

At present the XRD (X-ray diffraction) and FTIR (Fourier Transform Infrared) analyses cannot be undertaken in an oxygen free environment, with the result that all samples are oxidised during testing. In future, samples will be mixed with glycerol, which acts a barrier against oxidation (Hansen, 1989) without unduly affecting the analyses. Normal powder X-ray diffraction techniques dehydrate the green rust before testing, XRD-PSD (Position-Sensitive Detector) is capable of ’real time' analysis and is being used alongside infrared spectroscopy to characterise
the reactants and reaction rates of the samples on exposure to air. It is hoped that these measures will allow quantitative identification of green rust in the recovered core samples.

5 Conclusions

This study has identified two key hazards for geotechnical engineering in Lambeth Group (particularly Upnor Formation) sediments in London: the misidentification of the risk of confined space hypoxia by reliance on observations of glauconite; and the likelihood of encountering pressurised deoxygenated, nitrogen-rich gas following short- or long-term changes in ground water level.

Glaucinite should no longer be considered the most important predictor for confined space hypoxia and the absence of glauconite should not be taken to imply a lower risk of its incidence. Lambeth Group geology is complex and different factors appear to be important in different locations/stratigraphic depths but our research to date strongly suggests that other minerals, such as green rust, pyrite and organic carbon, have a much more important role in the occurrence of confined space hypoxia. While pyrite and organic carbon are relatively easy to identify and may leave a characteristic signature following oxidation, to date green rust has proved particularly difficult to identify, even in samples collected specifically for this research project. In very fresh samples (such as while drilling or boring) green rust can be identified by its characteristic teal (blue/green) colour, but its rapid oxidation requires that such observations be made within the first few minutes of sample extraction.

Current and past dewatering pose significant risks, potentially causing the build up of deoxygenated gas under pressure following a rise in water level. The limited gas flow data collected to date indicates that the permeability of gas in Upnor Formation sediments is similar to that of water, i.e., $\approx 10^{-6}$ m s$^{-1}$. Under these conditions, a single borehole would take almost a year to relieve the gas pressure in soil out to a 30 m radius, and thus it is most likely impractical to relieve any excess gas pressure encountered within an engineering project. While this may not be an immediate concern for pressure-balancing tunnel boring machines (TBMs), oxygen-poor gas may readily seep through some concrete tunnel linings, particularly during the first year of installation (Pihlajavaara, 1991), posing a hazard to personnel during fitting out or inspection work. Indeed, the high forward ground pressures induced by pressure-balancing TBMs may exacerbate this problem.

Further research into this hazard is urgently required to identify structural and lithological controls on the migration and trapping of hypoxic gas and to develop a rapid, reliable and quantitative technique for the identification of green rust in fresh or properly preserved samples.
The authors welcome contact from drillers, engineers, geologists and anyone else with experience of encountering hypoxic conditions, pressurised anoxic gas, or elevation CO₂ levels on site. Confidentiality will be respected.

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References


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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Belle Tout</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. The geological succession for London, with details of variations within the Lambeth Group. Deoxygenated gas incidences are primarily known from the Upnor Formation but are also known from the Laminated Beds.
Figure 2. Location map of ground gas incidences during construction.
Figure 3. Schematic geological section along the Effra storm relief sewer.
Figure 4. Schematic geological section between Coppermills and Stoke Newington.
Figure 5. Schematic geological section between Stoke Newington and Abbey Mills. Refer to Figure 4 for key.
Figure 6. Monitored gas levels in North London Flood Relief Sewer borehole 278D
Figure 7. Schematic geological section between Stoke Newington and New River Head (from Newman et al., 2010). Refer to Figure 4 for key.
Figure 8. Monitored gas levels in TW New River Head borehole 773A.
Figure 9. Piezometric levels across London 1800 to 1994.
Figure 10. Gas production from borehole SA1066D.
Figure 11.

Sediments of the Lower Mottled Beds illustrating pedogenic alteration and unoxidised glauconite.
Figure 12. Green rust (bluish surface colour) in fresh core samples.
### Table 1  Gas Release Model for SA1066D.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Rate of Gas Release</td>
<td>120 litres / hour</td>
</tr>
<tr>
<td>Background Rate of Gas Release</td>
<td>$14.3 \pm 7.3$ litres / hour</td>
</tr>
<tr>
<td>Total Volume of Gas released from Disturbed Zone</td>
<td>$13.9 \pm 1.5$ m$^3$</td>
</tr>
<tr>
<td>Thickness of Soil Layer containing Gas</td>
<td>2.5 to 4.0 m</td>
</tr>
<tr>
<td>Porosity of Soil Layer</td>
<td>35 to 50%</td>
</tr>
<tr>
<td>Radius of Disturbed Zone</td>
<td>$1.8 \pm 0.3$ m</td>
</tr>
<tr>
<td>Soil Permeability with respect to Gas Flow</td>
<td>$2.3 \pm 1.5 \times 10^{-6}$m$^{-1}$</td>
</tr>
<tr>
<td>Gas Composition</td>
<td>$97.6 \pm 0.5%$ N$_2$, $2.4 \pm 0.7%$ O$_2$, $730 \pm 160$ ppm CO$_2$</td>
</tr>
</tbody>
</table>
Table 2  X-Ray Diffraction Analysis of Lambeth Group Sediments.

<table>
<thead>
<tr>
<th>Component</th>
<th>Glauconite$^1$</th>
<th>Glauconite$^2$</th>
<th>Kaolinite</th>
<th>Smectite</th>
<th>Quartz</th>
<th>Goethite</th>
<th>Pyrite$^3$</th>
<th>Carbonate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Mottled Beds</td>
<td>0.9 ± 3.0</td>
<td>12.5 ± 12.5</td>
<td>7.1 ± 5.5</td>
<td>35.6 ± 26.2</td>
<td>27.3 ± 25.6</td>
<td>4.0 ± 3.9</td>
<td>0.2 ± 0.6</td>
<td>0.3 ± 0.7</td>
</tr>
<tr>
<td>LMB Gravels</td>
<td>15.9 ± 17.4</td>
<td>19.7 ± 17.8</td>
<td>1.4 ± 2.2</td>
<td>21.3 ± 16.7</td>
<td>47.3 ± 25.8</td>
<td>3.2 ± 4.6</td>
<td>0.1 ± 0.5</td>
<td>0.7 ± 1.2</td>
</tr>
<tr>
<td>Upnor Formation</td>
<td>9.1 ± 6.5</td>
<td>15.9 ± 8.4</td>
<td>1.2 ± 1.8</td>
<td>12.5 ± 8.5</td>
<td>61.0 ± 14.8</td>
<td>0.3 ± 1.0</td>
<td>0.1 ± 0.4</td>
<td>1.1 ± 1.8</td>
</tr>
<tr>
<td>Thanet Sands</td>
<td>2.3 ± 2.3</td>
<td>5.4 ± 5.3</td>
<td>0.5 ± 1.0</td>
<td>2.8 ± 5.3</td>
<td>81.6 ± 12.5</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.3 ± 1.2</td>
</tr>
</tbody>
</table>

$^1$Point-Count data (vol. %); $^2$XRD: includes illite and mica; $^3$includes gypsum. ± is one standard deviation.
<table>
<thead>
<tr>
<th>Compound</th>
<th>Reducing Potential</th>
<th>Mass Fraction</th>
<th>Grain Size</th>
<th>Reactive Area $^1$</th>
<th>Required Mass Fraction $^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glaucnite</td>
<td>0·00065 kg kg$^{-1}$</td>
<td>15·9 ± 8·4 wt%</td>
<td>0·5 mm</td>
<td>1220 m$^2$</td>
<td>213·9 wt%</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0·80 kg kg$^{-1}$</td>
<td>0·1 ± 0·4 wt%</td>
<td>0·1 mm</td>
<td>20 m$^2$</td>
<td>0·2 wt%</td>
</tr>
<tr>
<td>Organic Carbon</td>
<td>2·67 kg kg$^{-1}$</td>
<td>&lt;0·1 wt%</td>
<td>3 mm</td>
<td>&lt;3 m$^2$</td>
<td>0·1 wt%</td>
</tr>
<tr>
<td>Green Rust</td>
<td>0·022 kg kg$^{-1}$</td>
<td>unknown</td>
<td>0·1 mm$^a$</td>
<td>23,340 m$^2$</td>
<td>6·2 wt%</td>
</tr>
</tbody>
</table>

$^1$ grain area per m$^3$ of soil; $^2$ to reduce 2·35 kg O$_2$ per m$^3$ of soil; $^a$ average size of quartz grains coated by green crust.