Subsurface engineering and water resources of Greater London

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Outline

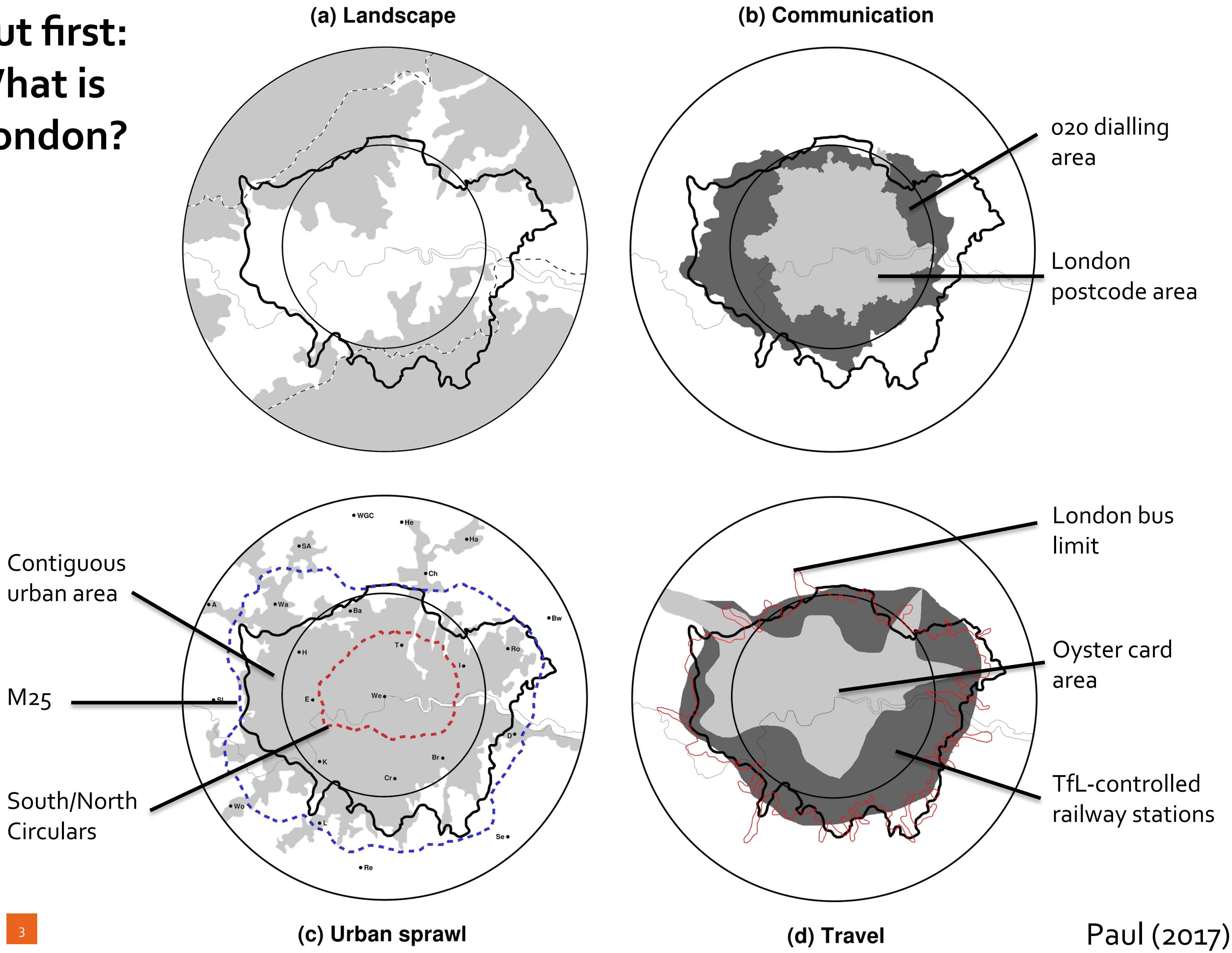
Part 1

- Geology of the London Basin – a primer
- Construction calamities and engineering solutions
- How stratigraphy and structure have shaped the Underground map

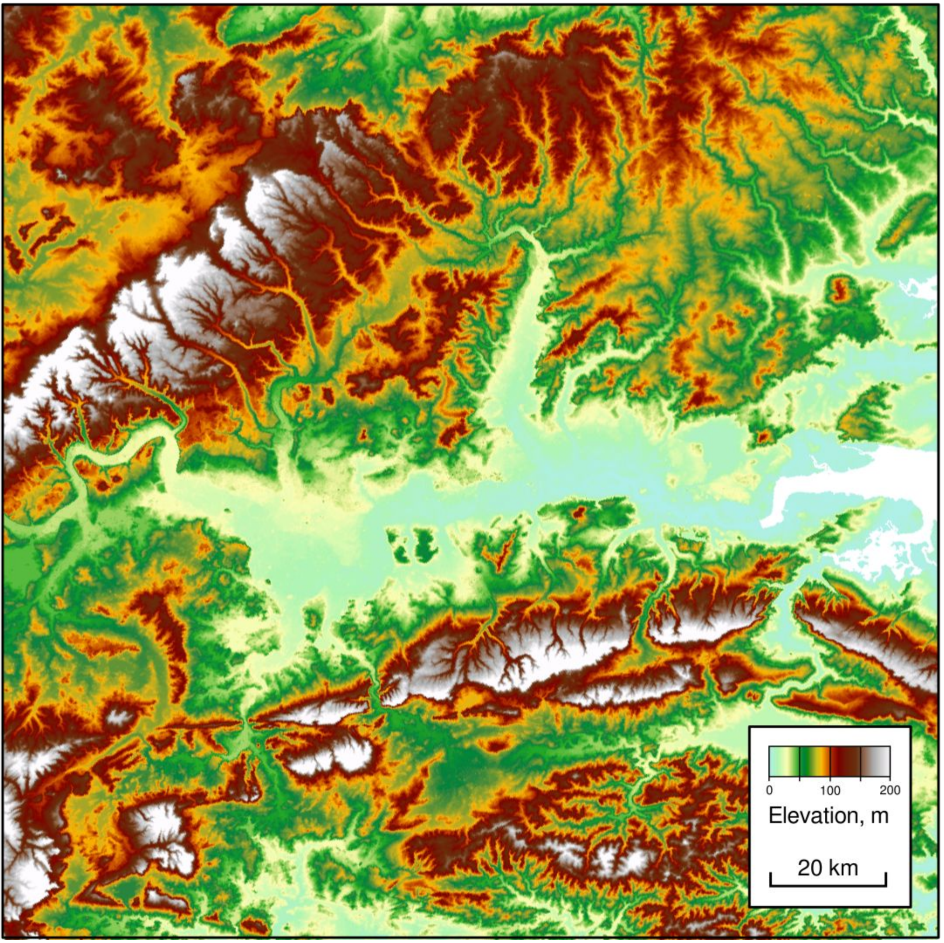
Part 2

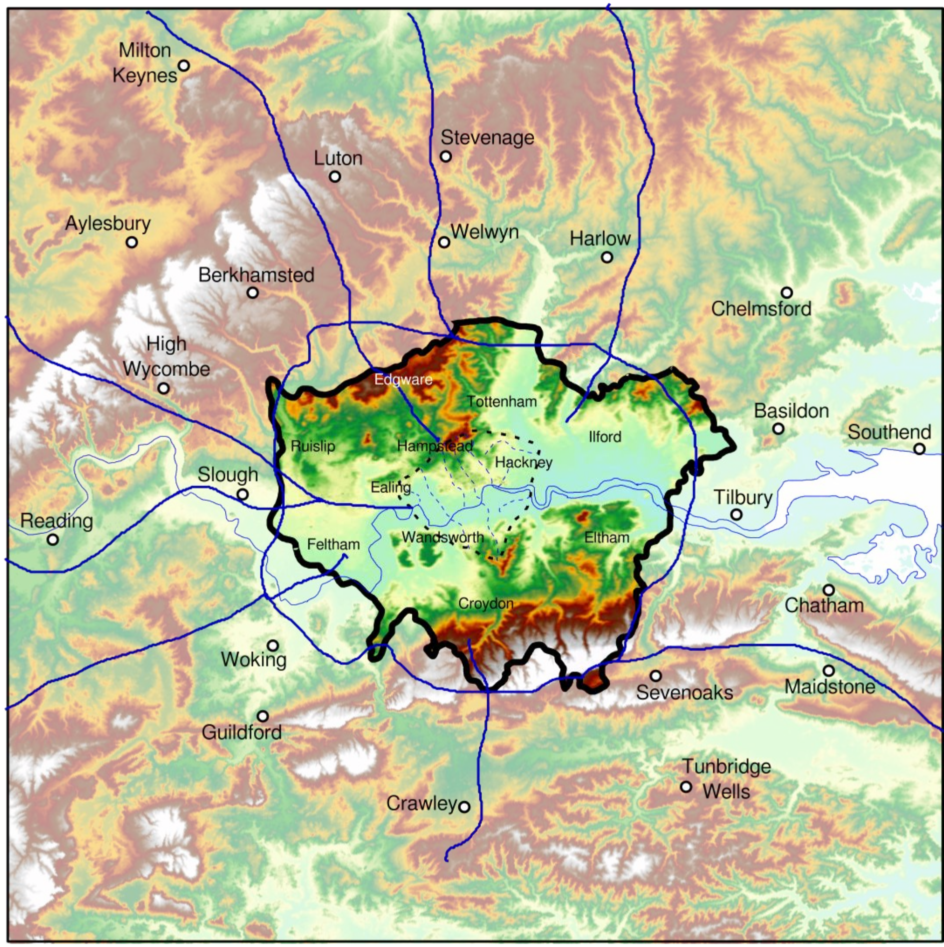
- A history of London’s water resources
- Chalk as a natural filtration system
- Sustainable cooling of London Underground stations

But first: What is London?

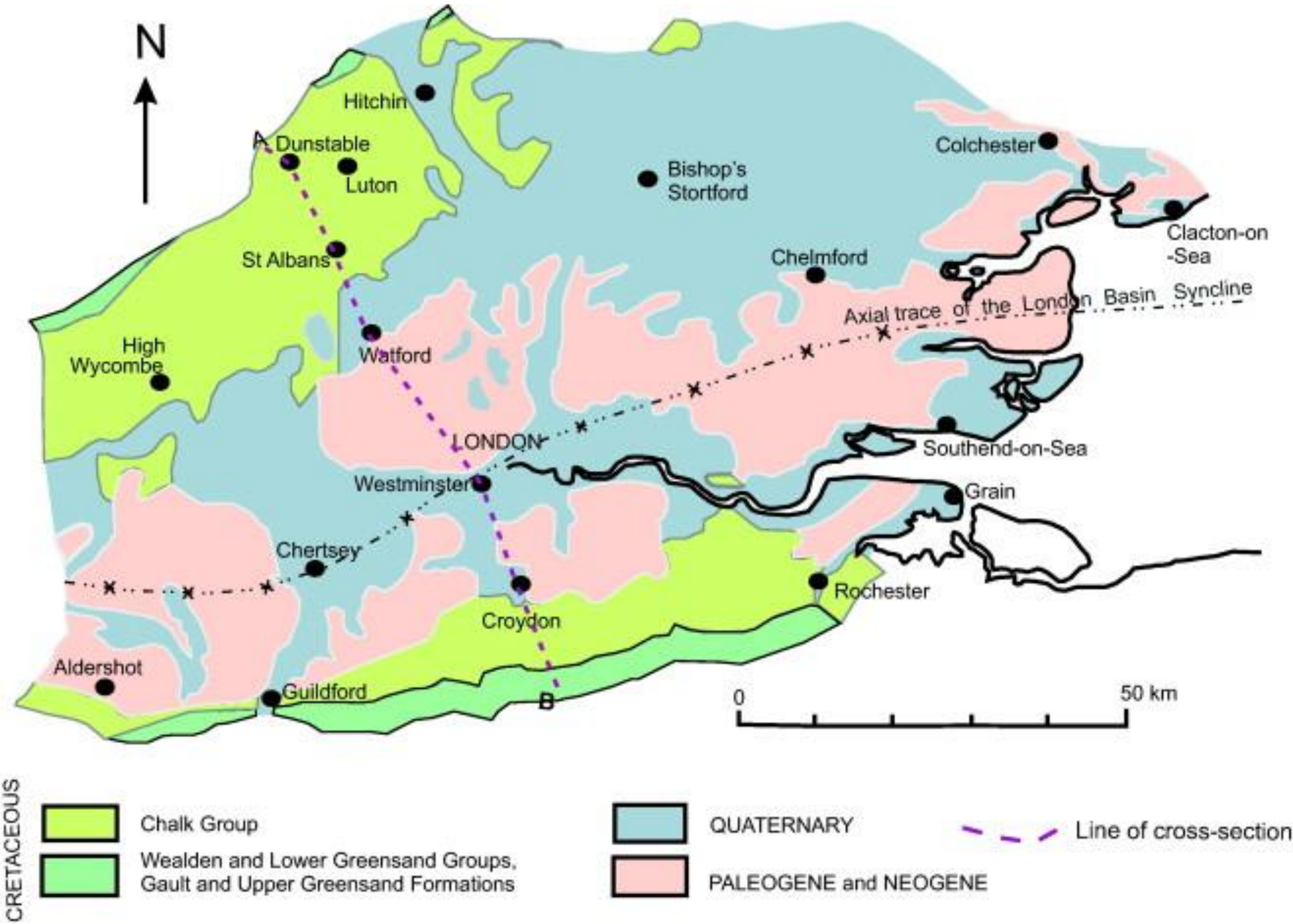


Paul (2017)

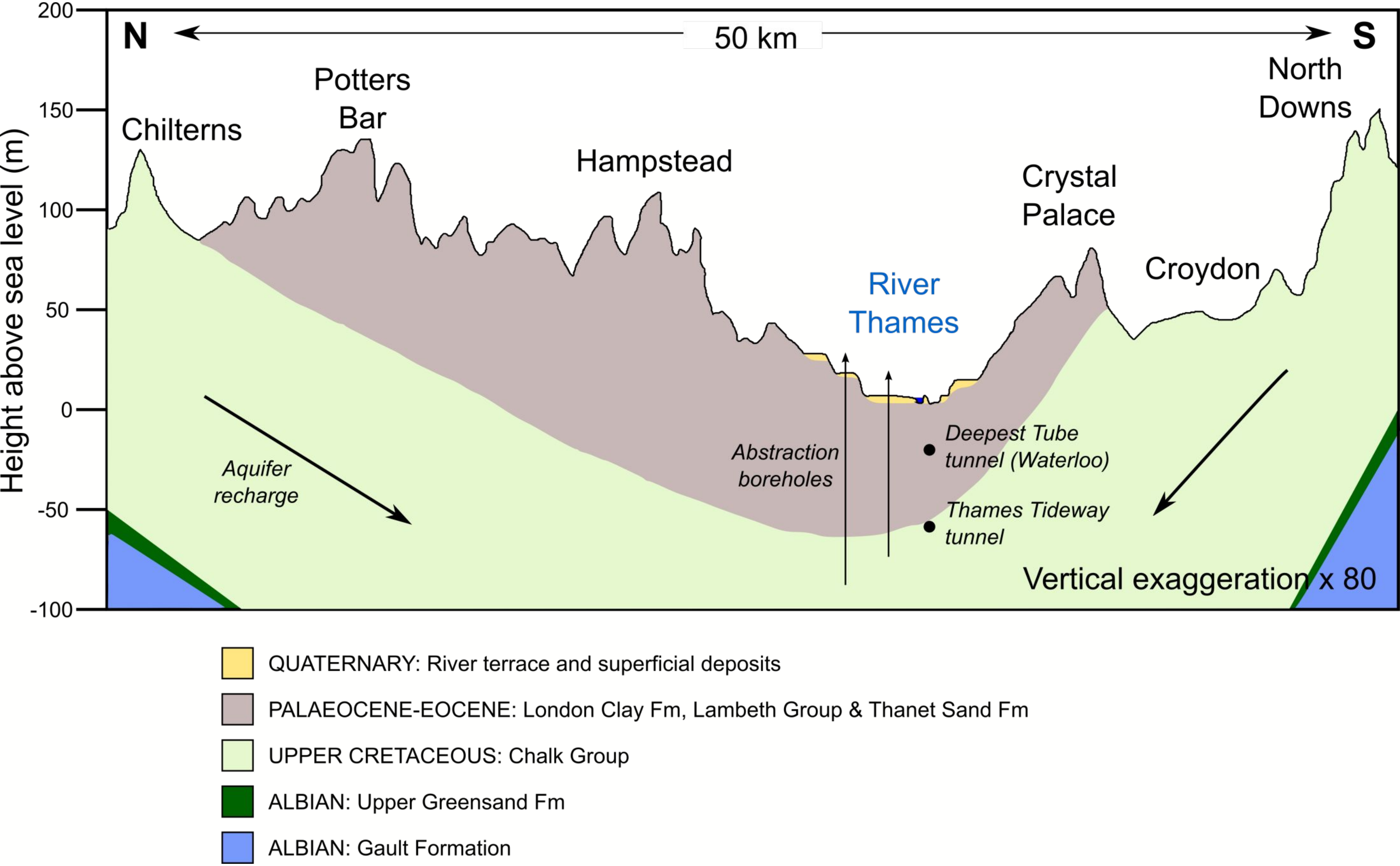

0
100
200
Elevation, m
20 km


Milton Keynes
Stevenage
Luton
Aylesbury
Welwyn
Harlow
Berkhamsted
Chelmsford
High Wycombe
Edgware
Tottenham
Ilford
Basildon
Southend
Ruislip
Hampstead
Hackney
Slough
Ealing
Tilbury
Reading
Feltham
Wandsworth
Eltham
Chatham
Croydon
Woking
Sevenoaks
Maidstone
Guildford
Tunbridge Wells
Crawley

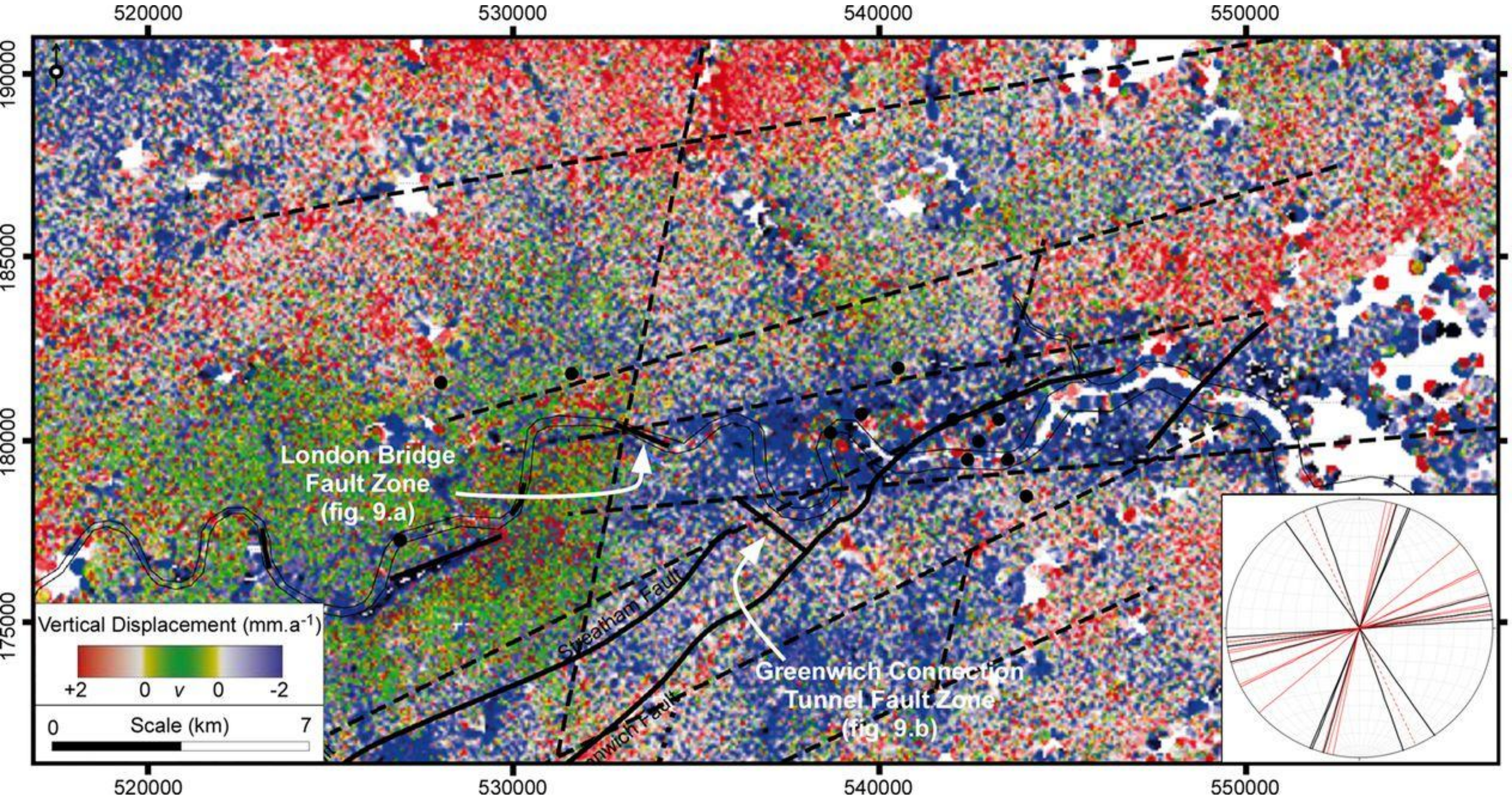
Paul (2017)



Sumbler (1996)

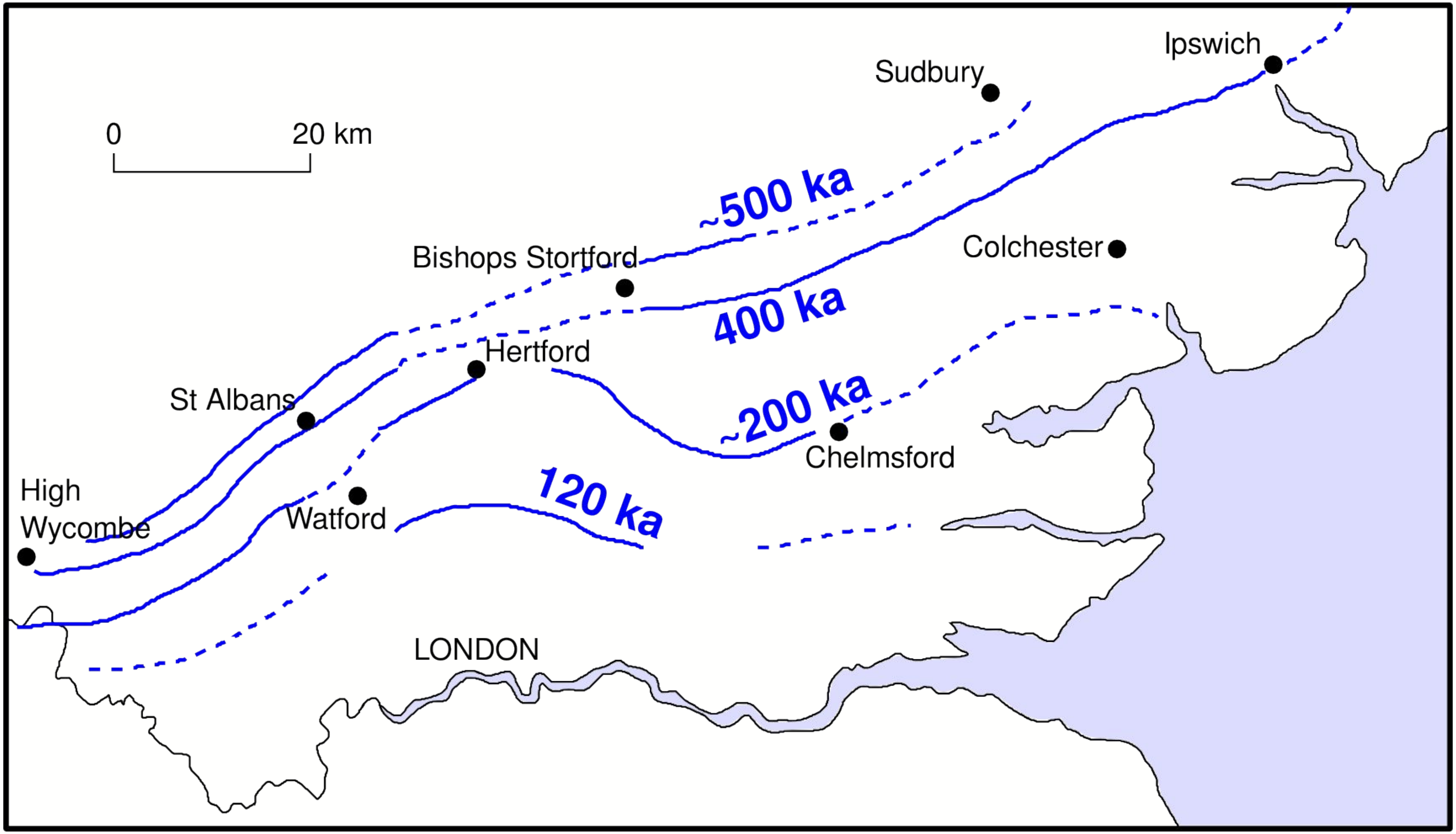


200
150
100
50
0
-50
-100
Height above sea level (m)
N
50 km
S
Potters Bar
Chilterns
Hampstead
Crystal Palace
North Downs
Croydon
River Thames
Aquifer recharge
Abstraction boreholes
Deepest Tube tunnel (Waterloo)
Thames Tideway tunnel
Vertical exaggeration x 80
QUATERNARY: River terrace and superficial deposits
PALAEOCENE-EOCENE: London Clay Fm, Lambeth Group & Thanet Sand Fm
UPPER CRETACEOUS: Chalk Group
ALBIAN: Upper Greensand Fm
ALBIAN: Gault Formation



Morgan et al. (2020)

A brief note about the River Thames



After Green et al.(1982)

Age	Thickness, m		Formation	Description	Unit
	0-15			**Made ground**	
Holocene	0-10			**Thames alluvium**: water-bearing sands and silts	
Pleistocene *160 - 12 ka*				**Gravel Formations**: clean sands and other river terrace deposits	
Eocene *51.5 - 49.5 Ma*		10-25		**BAGSHOT FM**: fine sands with planar cross-bedding	
Thames Group Eocene *58 - 51.5 Ma*	0-70	90-130		*Claygate Member* *Laminated sands/clays* *B* *Silty, laminated clays* *A3ii* *Very stiff clay, frequent sand lenses* *A3i* *Very stiff and heavily fissured clay* *A2* *Hard, very silty clay, strongly bioturbated, bedding planes* **LONDON CLAY FM**: Uniform stiff, bluish, fissured silty clay 4 main slight coarsening-upwards sequences Often heavily bioturbated with pyrite nodules and selenite crystals	**London Clay**
		0-10		**HARWICH FM**: fine, bioturbated sands. Some pebble beds. Very high water pressures	Lower London Tertiaries
Lambeth Group Palaeocene *60 - 58 Ma*	10-25	10-20		*More argillaceous* **READING & WOOLWICH FMS**: Wide variety of red and brown mottled clays and fine sands/silts Some shelly horizons and striped loams Lignite beds contain abundant pyrite nodules *More granular and arenaceous*	
				UPNOR FM: Glauconitic massive, unbedded sands. Basal flint bed; pebble bed at top	
Palaeocene *65.5 - 60 Ma*	0-20	0-30		**THANET SAND FM**: Uniform fine, glauconitic sands, coarsening upwards Bullhead Beds at base: 0.5 m abrasive flints	
Upper Cretaceous	~200	155-265		**CHALK**: Dissolution features (solution pipes) below unconformity Principal aquifer of London Basin Regular flint nodules and horizons	CHALK

London clay

Why did the Tube flourish so early?

London (1863) cf. Berlin (1897) and New York (1904)

Dominant minerals = montmorillonite, smectite (swelling and ground heave!)

Good loadbearing characteristics; relatively impermeable; but vertical/lateral variation

General NW thickening across London:

Maida Vale	*450 ft*
Pall Mall	*120 ft*
Tottenham Ct. Rd.	*63 ft*
W. India Docks	*Absent*

Is this why there are so few Tube lines on the “wrong side of the River” ?

Sometimes absence of the LC forces tunnels up to surface

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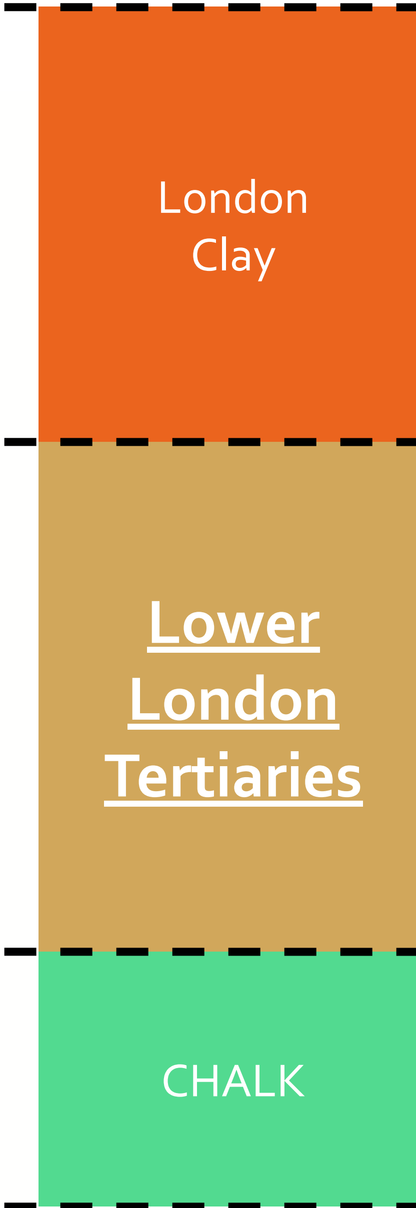

Lambeth Group

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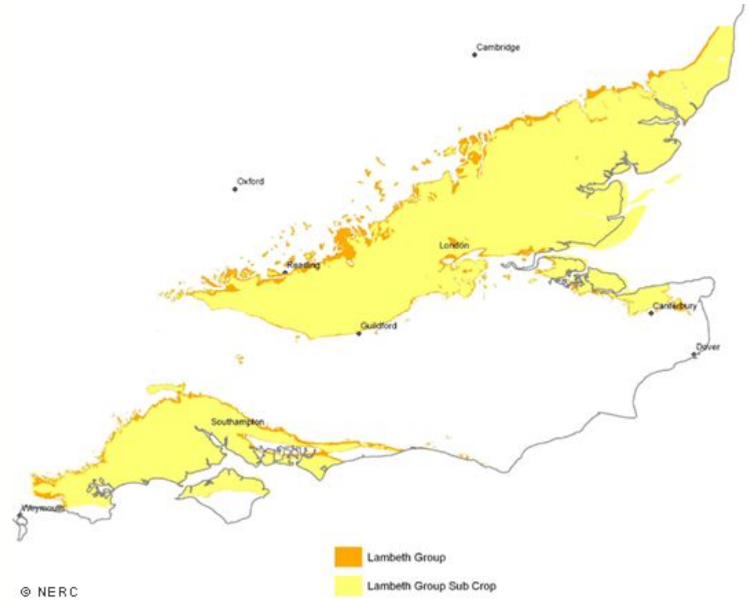
Reading & Woolwich Formations dominate south and east London

Poorly-consolidated shelly clays, striped loams, lignite beds, glauconitic sands

Variable & unpredictable; historically tunnel courses have tried to avoid it

High permeability
Basal beds have a hydraulic connection with the underlying chalk aquifer

Construction calamities, especially with involvement of water



Engineering Geology: problems

Pipes
Natural fissures in highest London clay facies
Connection to solution pipes in chalk

Scour Hollows
Water-bearing superficial drift deposits, up to 475 m in width (melting of pingos)
Delayed construction of Bakerloo line (Northumberland Avenue)
33 m deep – under Battersea Power Station

Subterranean Rivers
Alluvial deposits
Solution: diversions, or dewatering/chemical grouting
Valleys and topography

Engineering Geology: problems

'Aggressive' groundwater

Lambeth Group – high pyrite content in the sand

Oxidised by 'piston' effect of passing trains

Seepage of water from overlying London Clay leads to pH 3 water, 100,000 mg/L SO_4

Necessary to replace corroded tunnel lining

Old Street Tube station, facing S, towards major zone of identified steel & concrete corrosion

Engineering Geology: solutions

Prototypes of Greathead Shield *specific to* geology

-Hydraulically-operated drum digger: LC: Victoria line

-Bentonite Shield: JLE

-Earth pressure balance: Eurostar tunnels from St Pancras

Increasingly we can tunnel in media previously thought impossible

Engineering Geology: solutions

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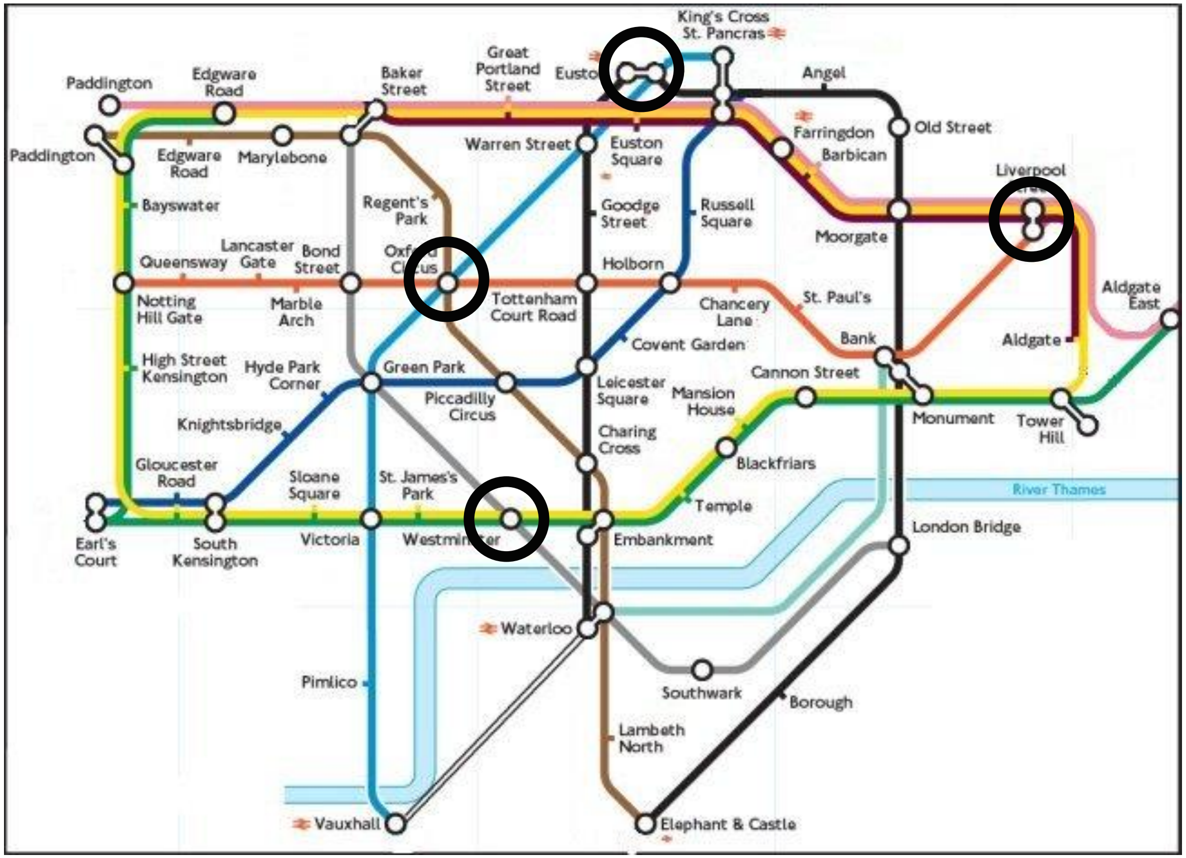
Ad hoc solutions



Ground freezing
Victoria – Oxford Circus

Chemical grouting
Central – Liverpool St & Stratford

Compressed air
Victoria – Euston

De-watering
Jubilee – Westminster

Engineering Geology: solutions

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Also: changes in tunnel lining

(Right) *Baker St. – brick. Currently being reinforced at Farringdon*

(Top-left) *Old Street – "concrete cancer"*

(Bottom-left) *Southwark – Segmented bolted metal sheet ubiquitous to the JLE protects against water-bearing strata*

Lateral changes in tunnel position

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Morden, Northern line

Why the bizarre 90° turn at the southern end of the Northern Line?

Tunnels were bored in a mostly "straight" path over seven miles from London Bridge to Colliers Wood

Answer: highly-permeable lenticular sand unit (really a large sand lens), located near the source of the Wandle River.

The diversion ensured that tunnels were driven through less-permeable strata

Now: GPR and seismic reflection surveys;

Then: trial-and-error

Vertical changes in tunnel position

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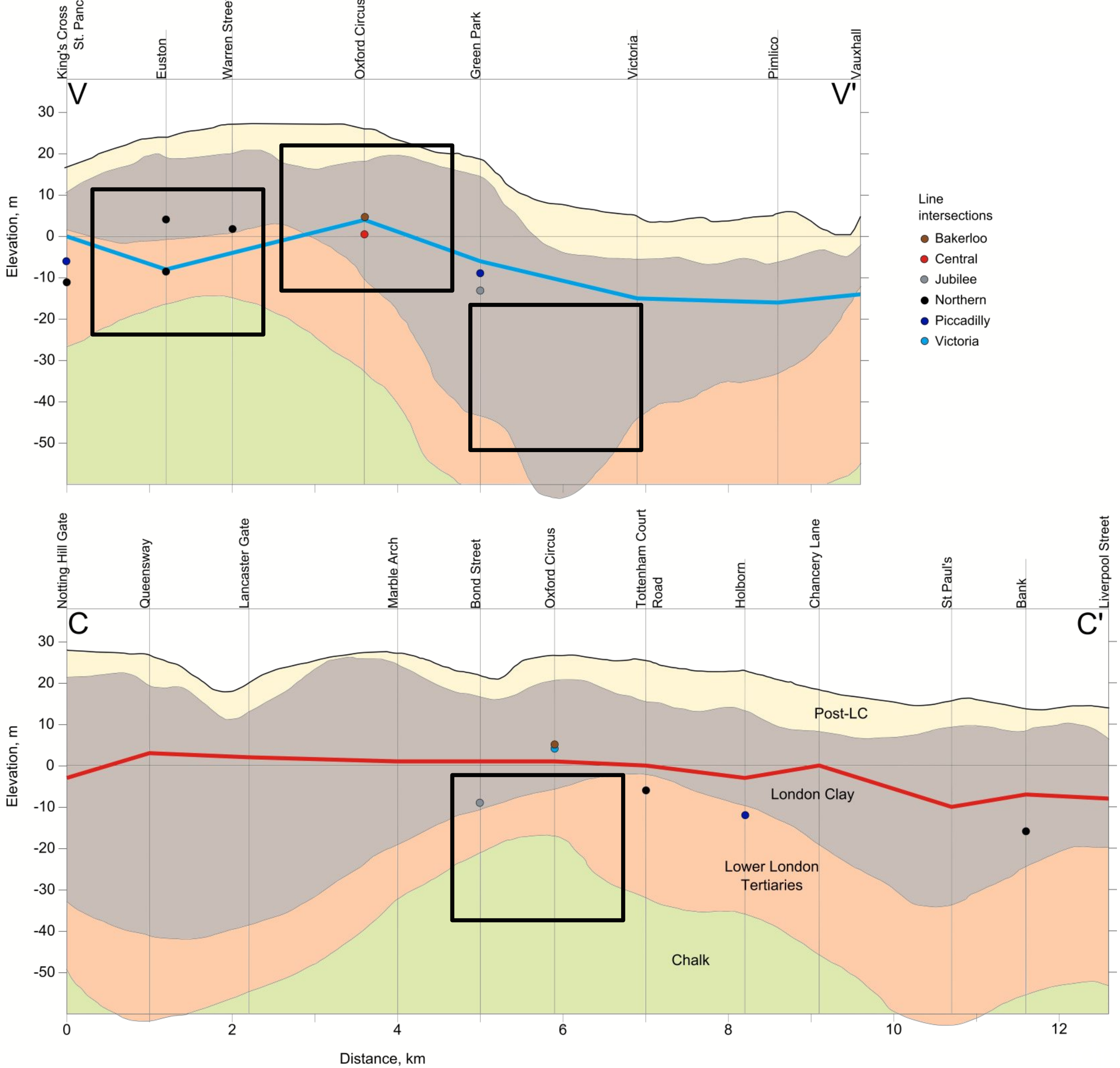
Structure (London clay anticline follows ~Oxford St)

Palaeotopography (Fleet Valley at Kings Cross)

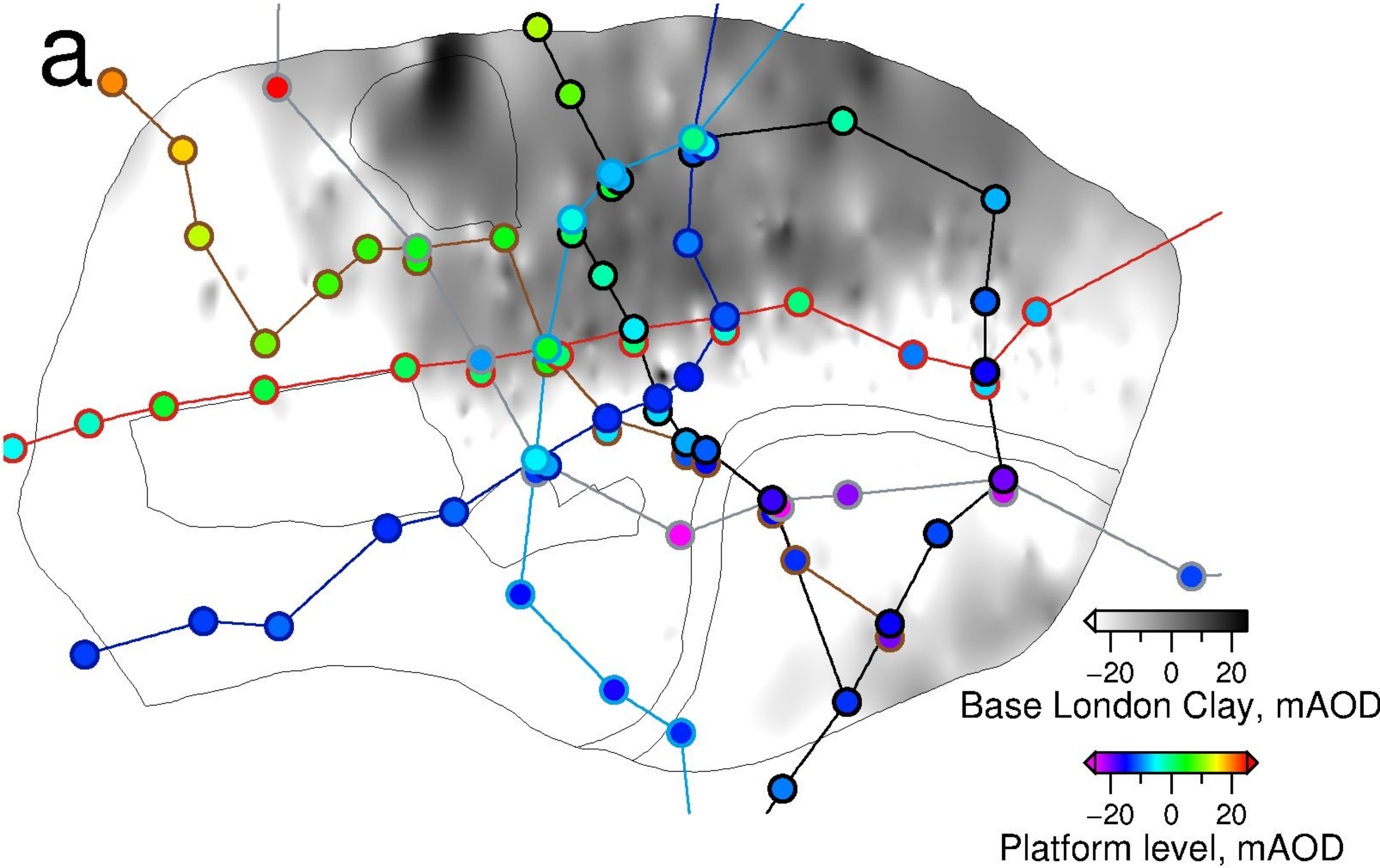
Generally, Underground tunnels will stay within the basal London Clay when it is thin, moving into higher facies where thicker

When London Clay very thin or absent, tunnels driven through Lower London Tertiaries

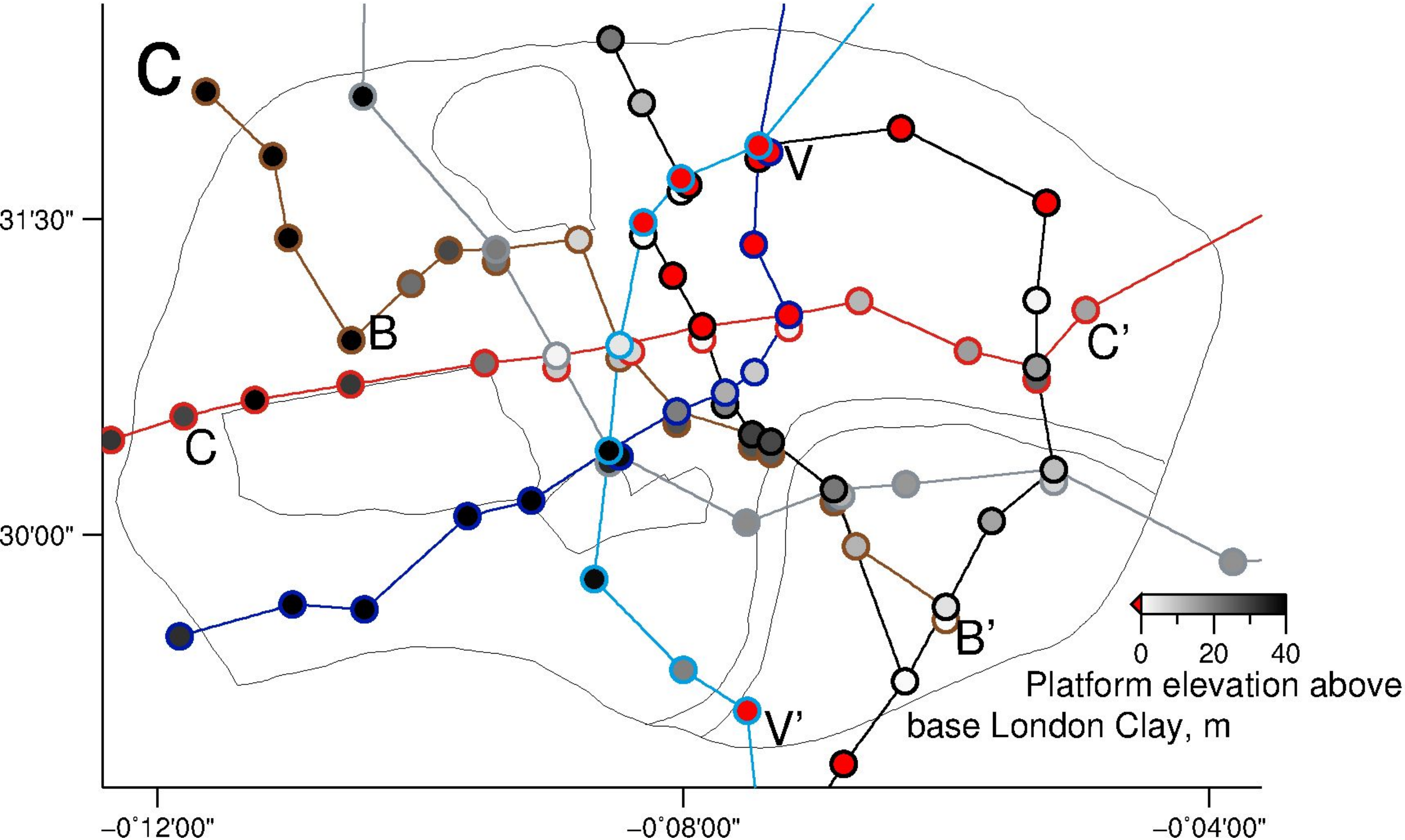


King's Cross St. Pancras
Euston
Warren Street
Oxford Circus
Green Park
Victoria
Pimlico
Vauxhall
V
V'
Elevation, m
Line intersections
Bakerloo
Central
Jubilee
Northern
Piccadilly
Victoria
Notting Hill Gate
Queensway
Lancaster Gate
Marble Arch
Bond Street
Oxford Circus
Tottenham Court Road
Holborn
Chancery Lane
St Paul's
Bank
Liverpool Street
C
C'
Post-LC
London Clay
Lower London Tertiaries
Chalk
Distance, km

Paul (2016)



Paul (2016)


C
B
C
C'
V
V'
B'
31'30"
30'00"
−0˚12'00"
−0˚08'00"
−0˚04'00"
0
20
40
Platform elevation above base London Clay, m

Paul (2016)

Summary Crossrail

In general, stratigraphy and structure affect:

- **How** we tunnel (method & shield chosen varies widely);

- **Where** we tunnel (sometimes lateral alignment, but most often choosing at what depth operations take place);

- **When** we tunnel (and the availability of suitable technology);

- **Problems encountered** (and the provision and derivation of solutions).

What is the most critical aspect of London's geology?

-Stratal continuity under central London	[Ferguson *et al*, 1991]
-Shear strength of the London clay	[Standing & Burland, 2006]
-The "mere presence" of the London clay	[Woods *et al*, 2007]
-Permeability & modelling water flow	(as we shall see in Part Two ...)

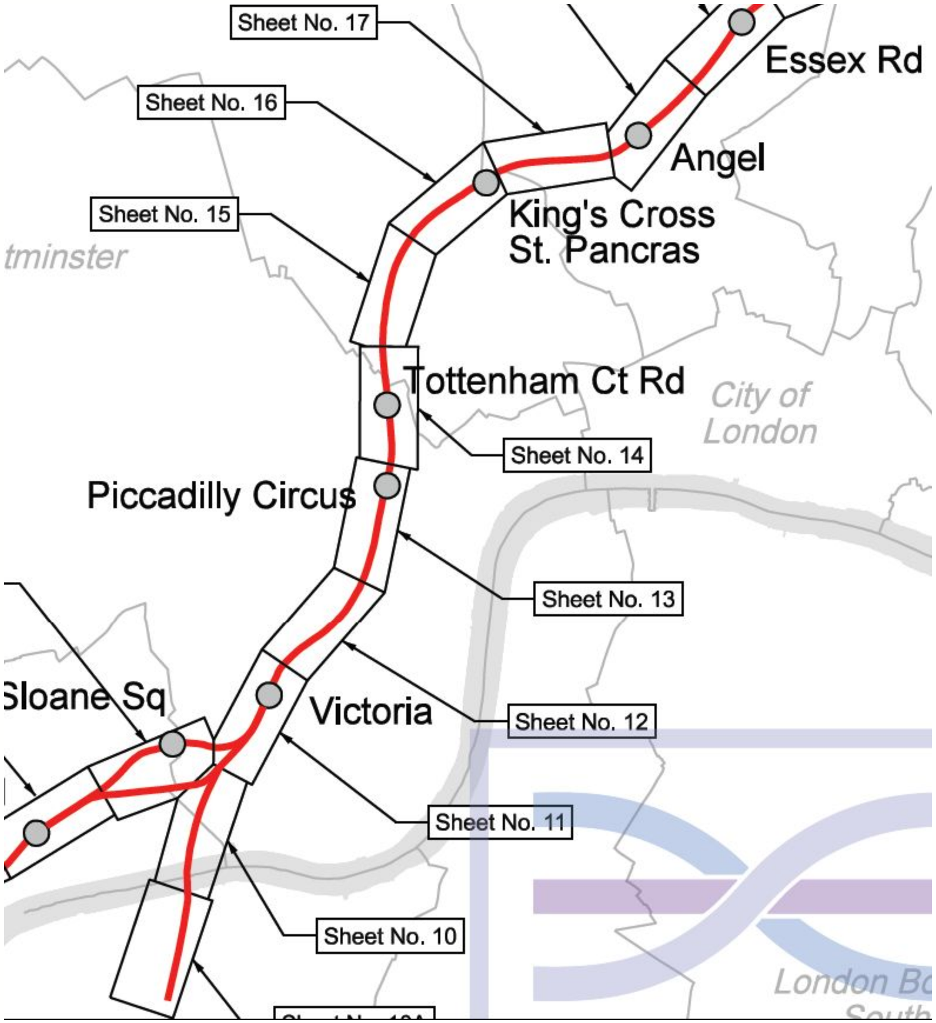
Summary Crossrail (the view from 2009)

This is the current major undertaking beneath London: main-line-bore tunnels. Drilling begun 2008; completed 2019

Future projects:

"Crossrail 2" or "Chelsea-Hackney Line" – slated for possible completion 2022 (right)

Extensions of Bakerloo or Victoria lines SE to serve Peckham or Camberwell – 2021–2024



Summary Crossrail (2022)

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Future projects:

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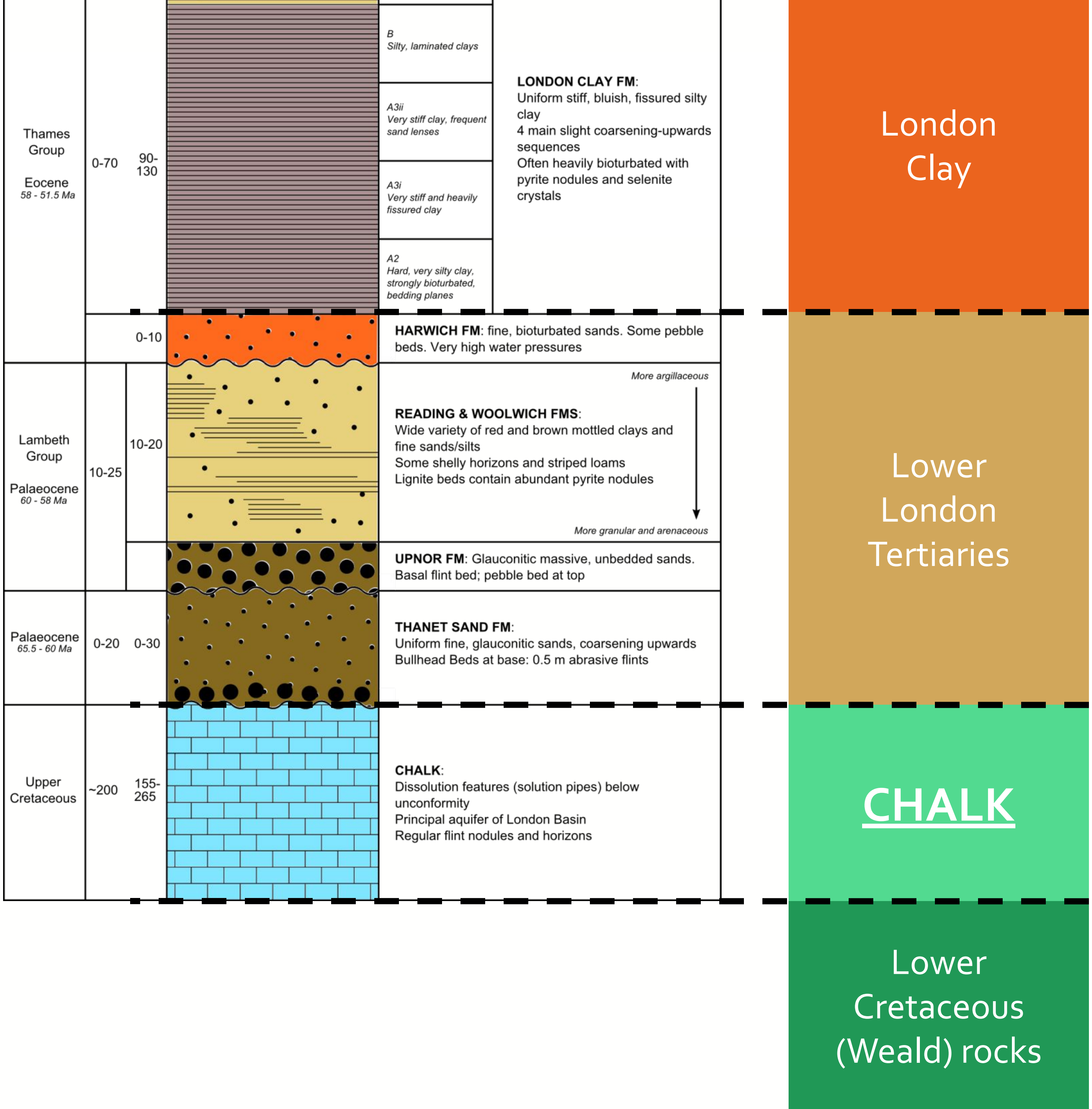
Extensions of Bakerloo or Victoria lines ~~SE to serve Peckham or Camberwell 2021–2024~~ **on ice until at least 2028**

Now: what about the Chalk?

Part 2
London's Water Resources



Thames Group
Eocene
58 - 51.5 Ma
0-70
90-130
B
Silty, laminated clays
A3ii
Very stiff clay, frequent sand lenses
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Very stiff and heavily fissured clay
A2
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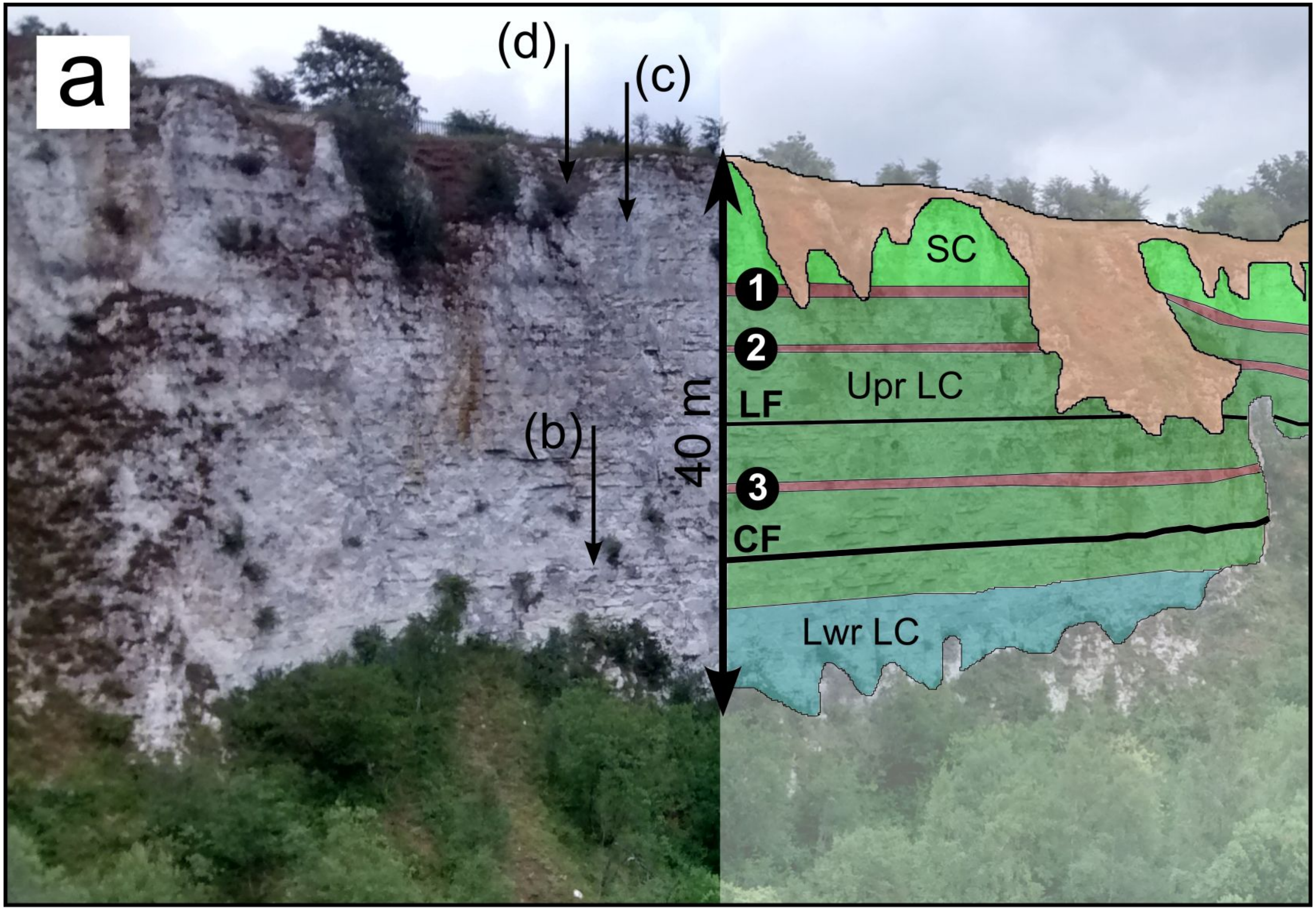
~200
155-265
CHALK:
Dissolution features (solution pipes) below unconformity
Principal aquifer of London Basin
Regular flint nodules and horizons
London Clay
Lower London Tertiaries
CHALK
Lower Cretaceous (Weald) rocks

Southern England in Upper Cretaceous times (65–100 Ma)

Riddlesdown Quarry, Croydon



Riddlesdown Quarry, Croydon

SC	Seaford Chalk Fm ("Upper Chalk")
LC	Lewes Nodular Chalk Fm (lower-most "Upper Chalk")
LF	Lewes Tubular Flints
CF	Criel Flints

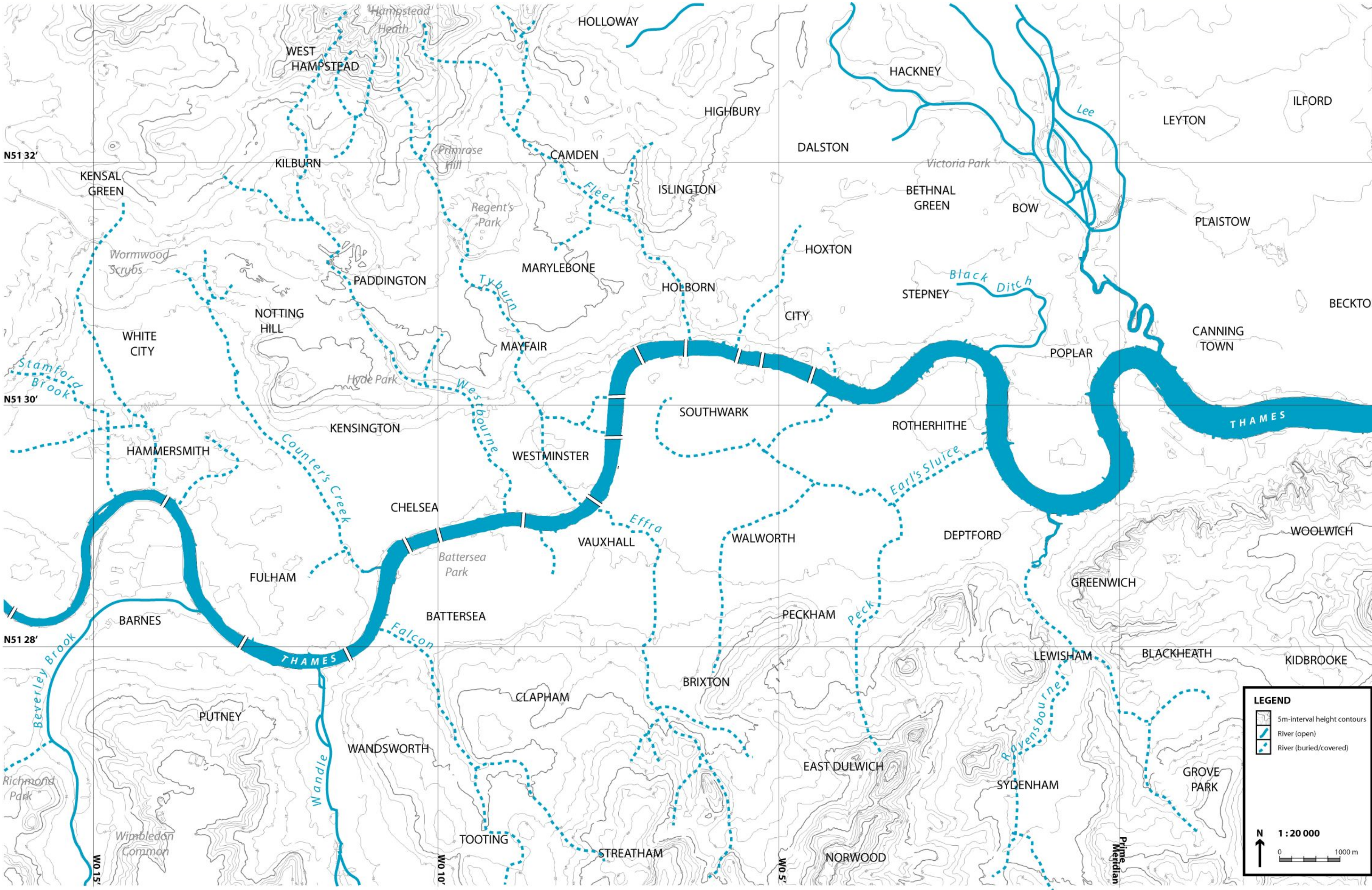
Paul (2016)

The Criel Flint marker horizon

Entrance to the Fleet River, Samuel Scott, c. 1750

Today's view west along Fleet St

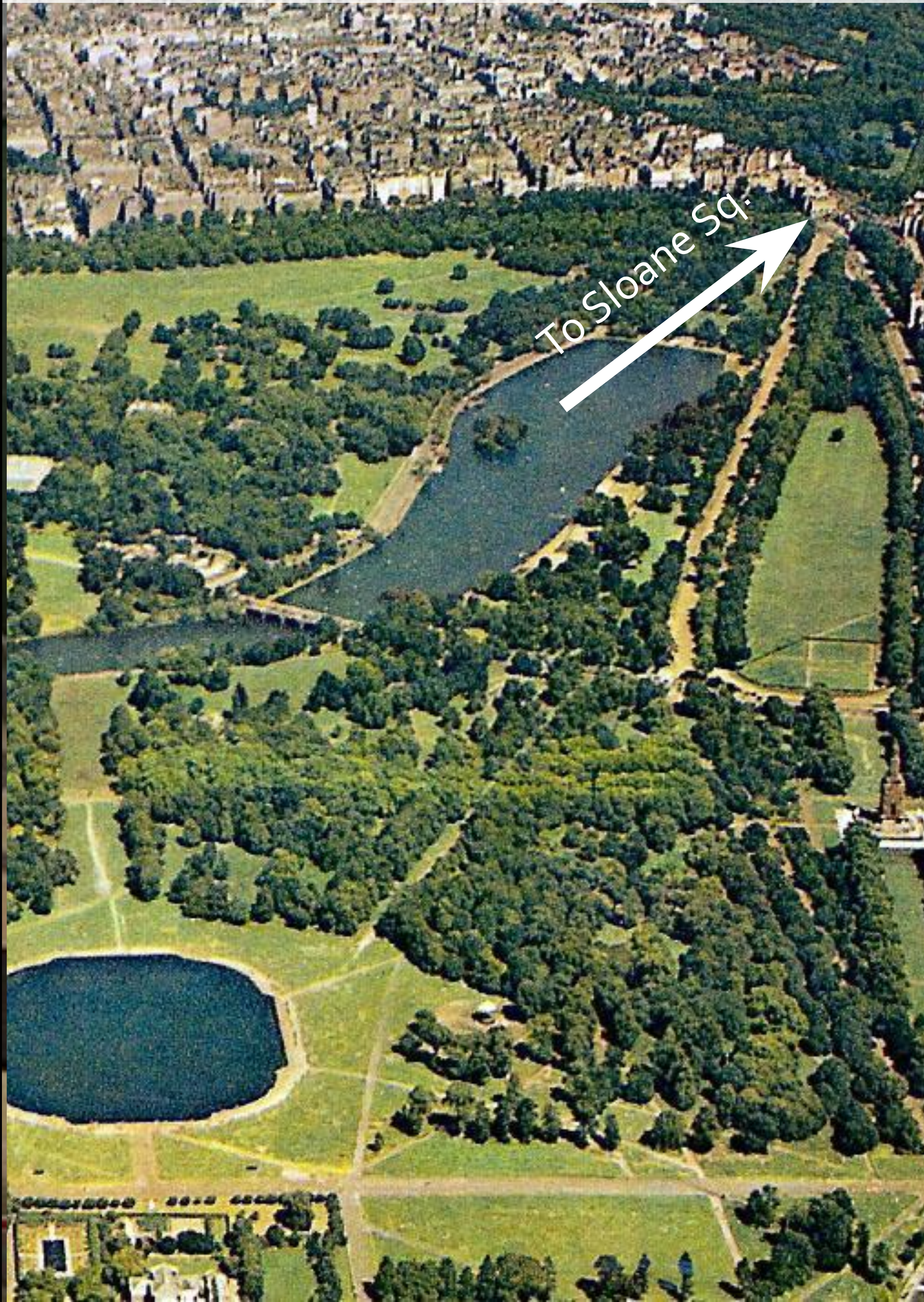

Today's view west along Fleet St
Flow of R. Fleet
Kempton Park
Gravel Fm. (~60 ka)
Bus stop
Bus stop
EAT.
ARCHWAY
Metroline



Paul & Blunt (2012)

River Tyburn, Gray's Antiques, Mayfair

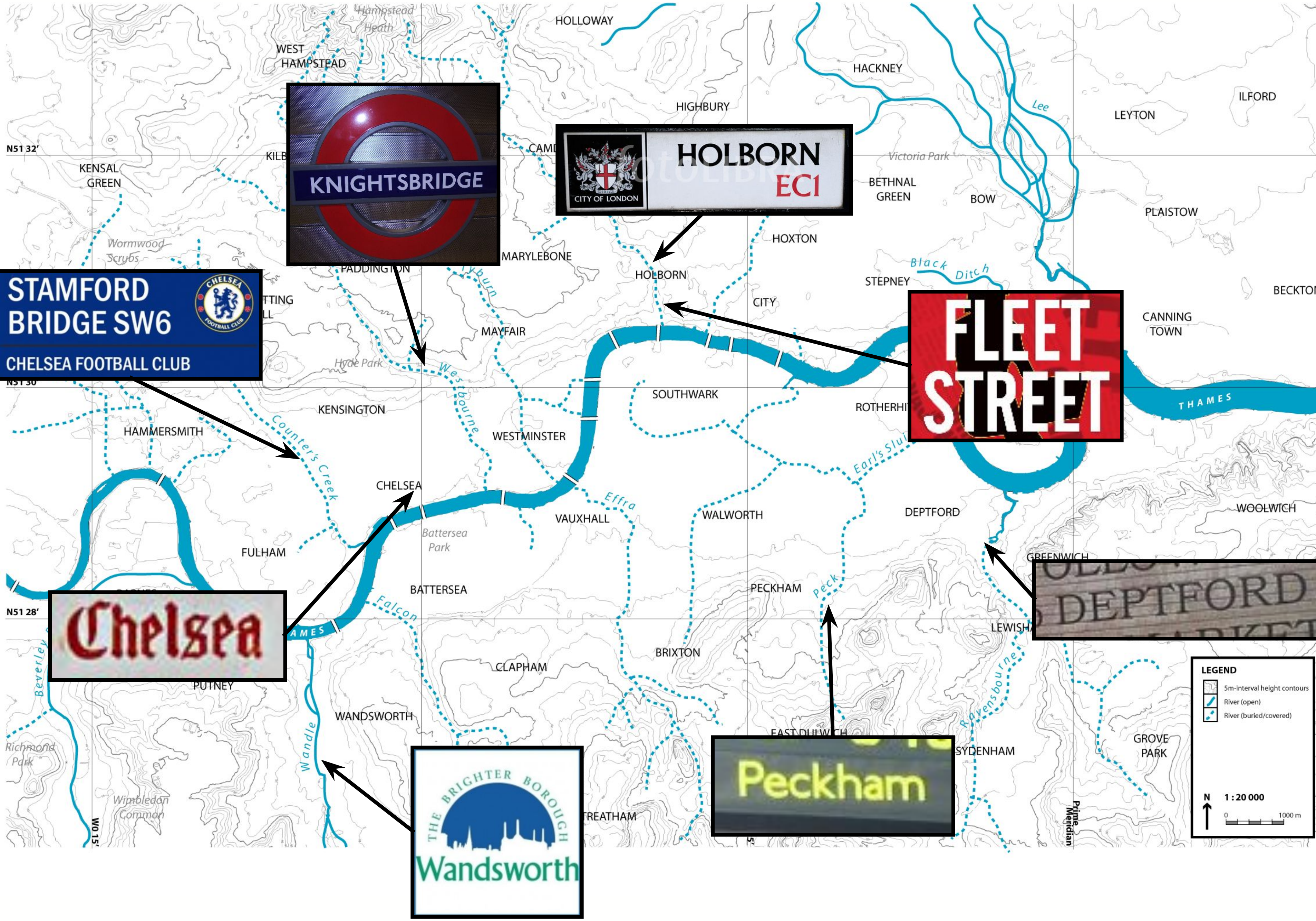
River Westbourne, Serpentine, Hyde Park



River Westbourne at Sloane Square tube station


(a) Farringdon
(b) Marylebone
Park
Pine St
The Bowler
Pub & Kitchen
Sans Walk
Sekforde St
St. James's
Church Garden
Aylesbury St
Brewhouse Yard
Dallington
Baker's Row
Ray St
A201
Farringdon Ln
Herbal Hill
The Zetter
A5201
Clerkenwell Rd
Clerkenwell Rd
Clerkenwell Rd
Britton St
St John's
Gate
Briset St
Albion Pl
St. John's Ln
St. John St
Hatton Wall
Saffron Hill
Hatton Pl
Turnmill St
Access
Accommodation
Holborn London
St. Cross St
St. John's
Gardens
Farringdon
Farringdon
Kirby St
Leather Ln
Peter's Ln
Atelier EC1 by
BridgeStreet
Farringdon Rd
fabric
St Etheldreda's
RC Church
Hatton Garden
Charterhouse St
E Poultry Ave
Long Ln
Brooke St
Ely Pl
Shoe Ln
A40
A40
W Smithfield
Hosier Ln
W Smithfield
The
Marylebone
Thayer St
Marylebone Ln
Queen Anne St
Marylebone
Harley St
Chandos St
A4201
Mortimer St
Bentinck St
Welbeck Way
Cavendish Pl
B524
A5204
Wigmore St
A5204
Cavendish
Square
A5204
Margaret St
Ivanhoe
Suite
Marylebone Ln
Welbeck St
Henrietta Pl
Holles St
Topshop
Picton Pl
Oxford
Circus
James St
Stratford Pl
Vere St
Oxford St
Duke St
Bird St
Oxford St
Dering St
Princes St
Oxford St
Bond Street
Tenterden St
Hanover
Square
Ukrainian Catholic
Cathedral of the
Holy Family in Exile
New Bond St
Hanover St
Balderton St
Lumley St
S Molton St
S Molton Ln
Binney St
Brook St
London
Marriott Hotel
Brook St
Claridge's
St Georges
Hanover Square
Avery Row
Mill St
Grosvenor Square
Grosvenor St
Grosvenor Hill
Davies St
Grosvenor
The
Westbury


(a) Farringdon
Course of R. Fleet
Clerkenwell Rd
Farringdon Rd
Farringdon
(b) Marylebone
Course of R. Tyburn
Oxford St
Wigmore St
Bond Street
Oxford Circus
Brook St
Grosvenor Square



STAMFORD BRIDGE SW6
CHELSEA FOOTBALL CLUB
KNIGHTSBRIDGE
HOLBORN EC1
CITY OF LONDON
FLEET STREET
Chelsea
Wandsworth
THE BRIGHTER BOROUGH
Peckham
DEPTFORD
HOLLOWAY
WEST HAMPSTEAD
Hampstead Heath
HIGHBURY
HACKNEY
ILFORD
LEYTON
KENSAL GREEN
BETHNAL GREEN
BOW
PLAISTOW
HOXTON
MARYLEBONE
PADDINGTON
HOLBORN
STEPNEY
CITY
BECKTON
CANNING TOWN
MAYFAIR
Hyde Park
SOUTHWARK
ROTHERHITHE
KENSINGTON
HAMMERSMITH
WESTMINSTER
CHELSEA
VAUXHALL
WALWORTH
DEPTFORD
WOOLWICH
FULHAM
Battersea Park
BATTERSEA
PECKHAM
GREENWICH
LEWISHAM
BRIXTON
CLAPHAM
PUTNEY
WANDSWORTH
EAST DULWICH
SYDENHAM
GROVE PARK
STREATHAM
Richmond Park
Wimbledon Common
Wormwood Scrubs
Victoria Park
THAMES
Lee
Black Ditch
Counter's Creek
Westbourne
Tyburn
Effra
Falcon
Earl's Sluice
Peck
Ravensbourne
Wandle
Beverley
N51 32′
N51 30′
N51 28′
Prime Meridian
LEGEND
5m-interval height contours
River (open)
River (buried/covered)
N
1 : 20 000
0
1000 m

Punch cartoon published during the height of the "Great Stink" – July 3rd 1858

FATHER THAMES INTRODUCING HIS OFFSPRING TO THE FAIR CITY OF LONDON.

(A Design for a Fresco in the New Houses of Parliament.)

From *Burke's Peerage* (1879)

METROPOLITAN

Drinking Fountain & Cattle Trough

ASSOCIATION.

Supported entirely by Voluntary Contributions.

Offices: VICTORIA HOUSE, 111, VICTORIA ST., WESTMINSTER, S.W.

President—His Grace the DUKE OF WESTMINSTER, K.G., &c., &c.
Chairman of Committee and Treasurer—JOSEPH FRY, Esq.
Secretary—M. W. MILTON.

This is the ONLY AGENCY for providing
FREE SUPPLIES OF WATER FOR MAN AND BEAST
in the STREETS of LONDON,
and the relief it affords, both to human beings and dumb animals, is incalculable.

The total number of Troughs and Fountains now erected, and at work in the Metropolis, is as follows:—**597 Troughs** for Animals, and **575 Fountains** for Human Beings, at which multitudes of Men, Women, and Children, Horses, Oxen, Sheep, and Dogs quench their thirst daily, amounting in the aggregate to probably not less than the enormous total of **250,000,000** drinkers in a year.

All the Fountains and Troughs require constant care and supervision, and are regularly inspected, cleaned, kept in repair, and well supplied with water by the agents of the Society. Half-an-hour spent at one of them during the heat of the summer would do more to secure sympathy and support for the Association than any words which the Committee can use.

Contributions are earnestly solicited to enable the Committee to sustain and extend this simple scheme for the amelioration of animal suffering and the promotion of habits of temperance amongst our itinerant and working population. Contributions may be paid to the Bankers, Messrs. RANSOM, BOUVERIE & Co., Messrs. BARCLAY, BEVAN & Co., or at the Office, to M. W. MILTON, *Secretary.*

FORM OF BEQUEST.

"I give and bequeath the sum of   to be paid (free of Legacy Duty), out of such parts of my personal estate as can be lawfully applied for that purpose, unto the Treasurer for the time being of a Society called or known by the name of THE METROPOLITAN DRINKING FOUNTAIN AND CATTLE TROUGH ASSOCIATION, to be at the disposal of the Committee for the time being of the said Society."

Drinking fountain, Holborn, 1859

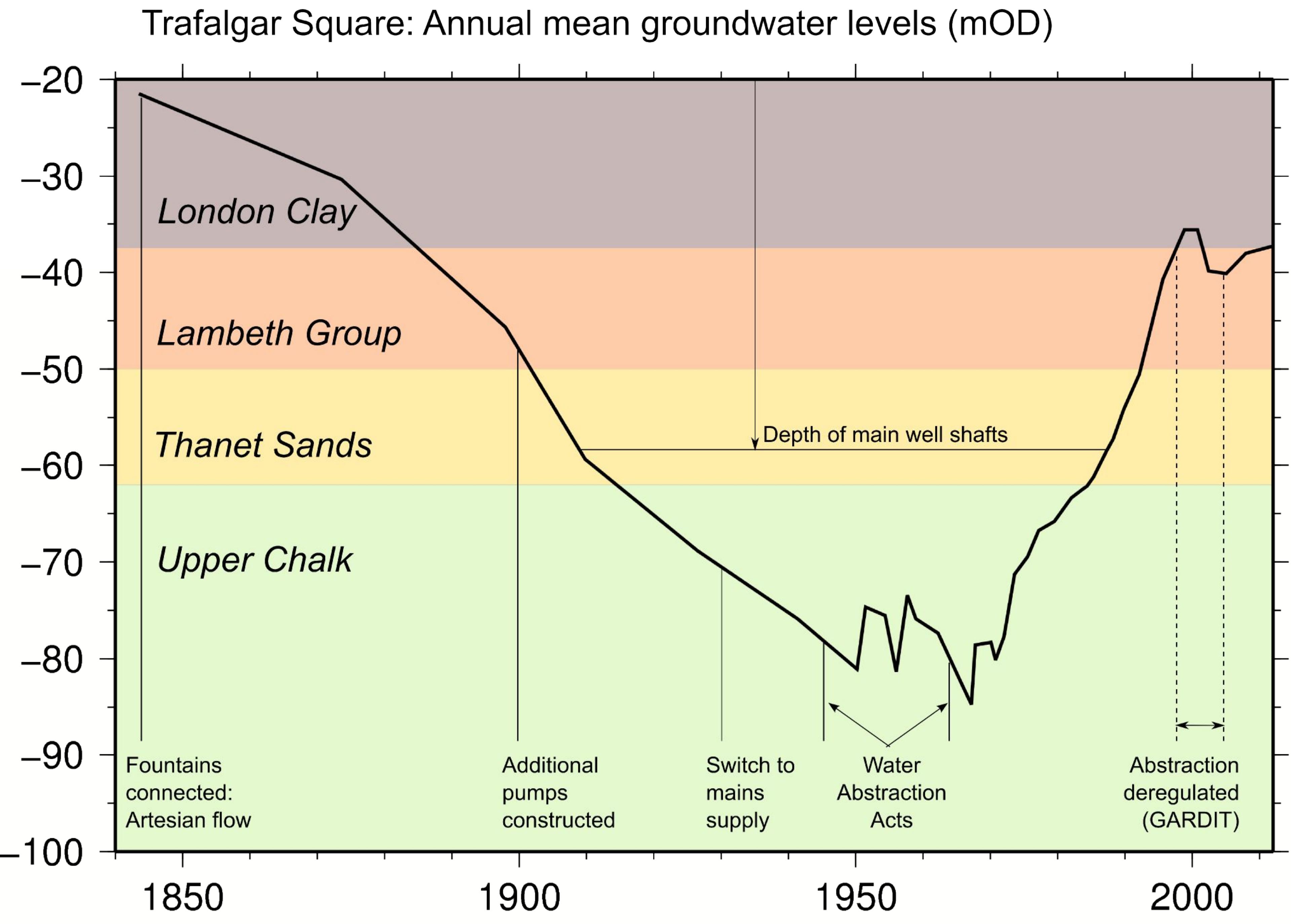
Crossness pumping station, Thamesmead, SE London – opened 1865

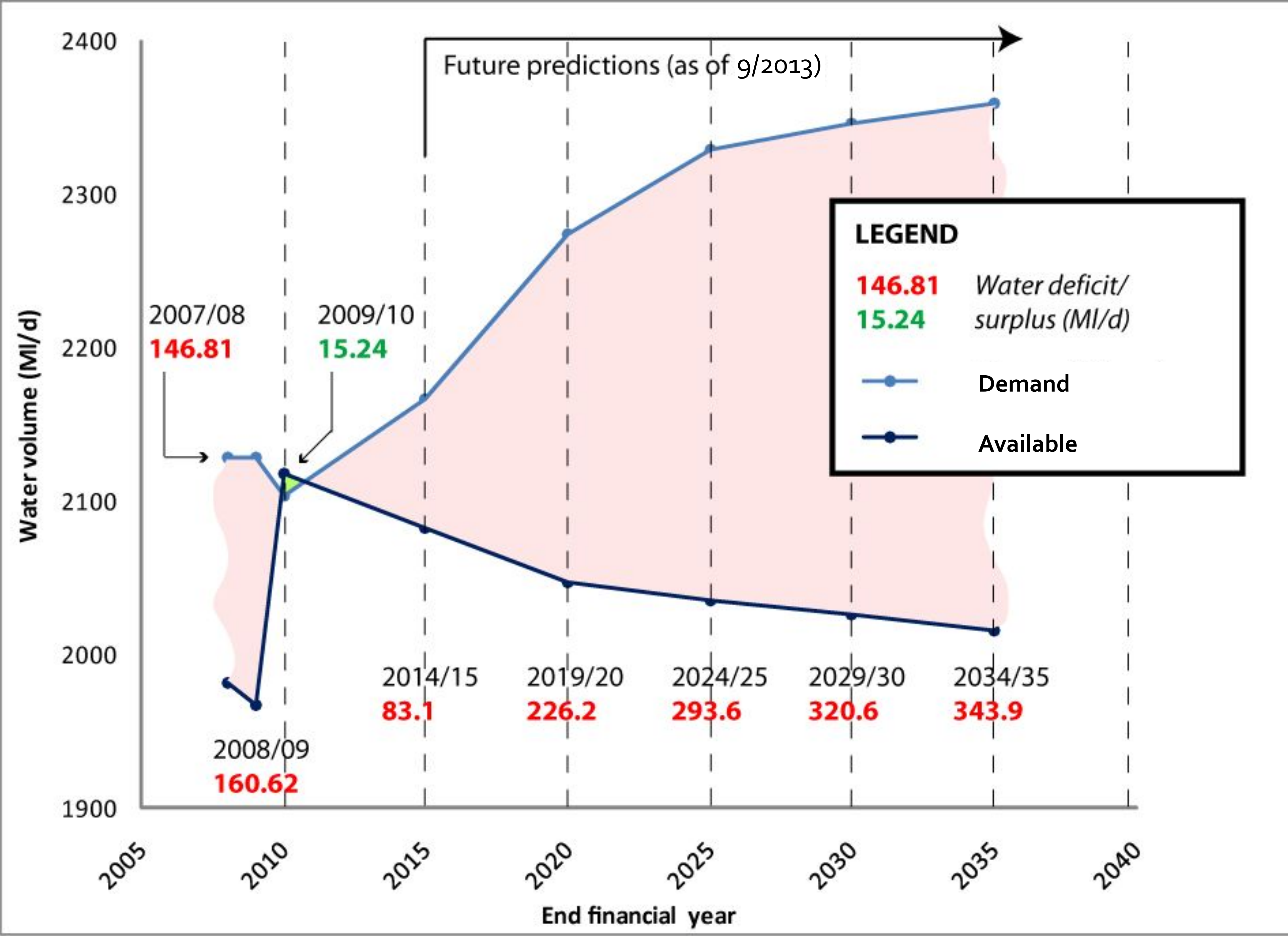
Interior of a typical Bazalgette sewer. River Westbourne, Pimlico

Replacement of old, cast iron water pipes with plastic piping in London clay, Southwark

Water leak causing disruption at Notting Hill Gate (January 2012)

Flooding at Old St tube station (June 2011): "Aggressive groundwater" in Lambeth Gp.


Trafalgar Square: Annual mean groundwater levels (mOD)
−20
−30
−40
−50
−60
−70
−80
−90
−100
1850
1900
1950
2000
London Clay
Lambeth Group
Thanet Sands
Upper Chalk
Depth of main well shafts
Fountains connected: Artesian flow
Additional pumps constructed
Switch to mains supply
Water Abstraction Acts
Abstraction deregulated (GARDIT)



Future predictions (as of 9/2013)
Water volume (Ml/d)
2400
2300
2200
2100
2000
1900
2007/08
146.81
2009/10
15.24
2008/09
160.62
2014/15
83.1
2019/20
226.2
2024/25
293.6
2029/30
320.6
2034/35
343.9
LEGEND
146.81
15.24
Water deficit/
surplus (Ml/d)
Demand
Available
2005
2010
2015
2020
2025
2030
2035
2040
End financial year

Thames Water desalination plant, Barking (commenced operation June 2010)

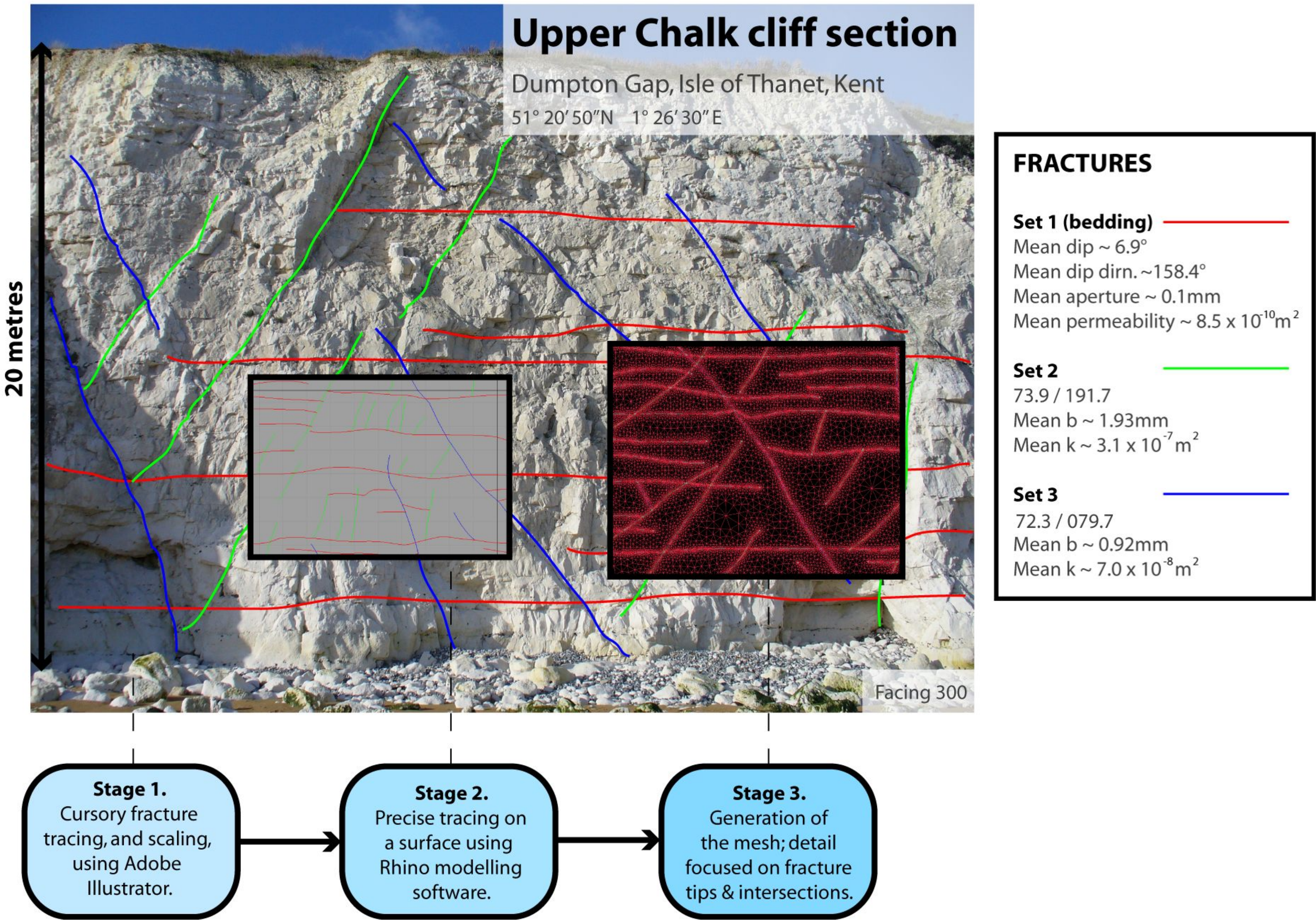
"... such a natural [chalk] reservoir does exist, deep under the London clay, capacious enough to hold many times our necessary annual supply, and provided with a natural system of filter beds which arrest or destroy impurities and transform the dirty water into a soft water suitable for man and beast."

London Evening Standard, February 1924

"... communities in all parts of the world have begun to build and plan plants to turn salty groundwater and grey water into clean water for factories, farms and homes ... the [related] rise in fresh water production is the biggest ever recorded."

Juliette Jowit writing in *The Guardian*, 31st March 2010

Upper Chalk outcrop, Dumpton Gap, Ramsgate, Kent



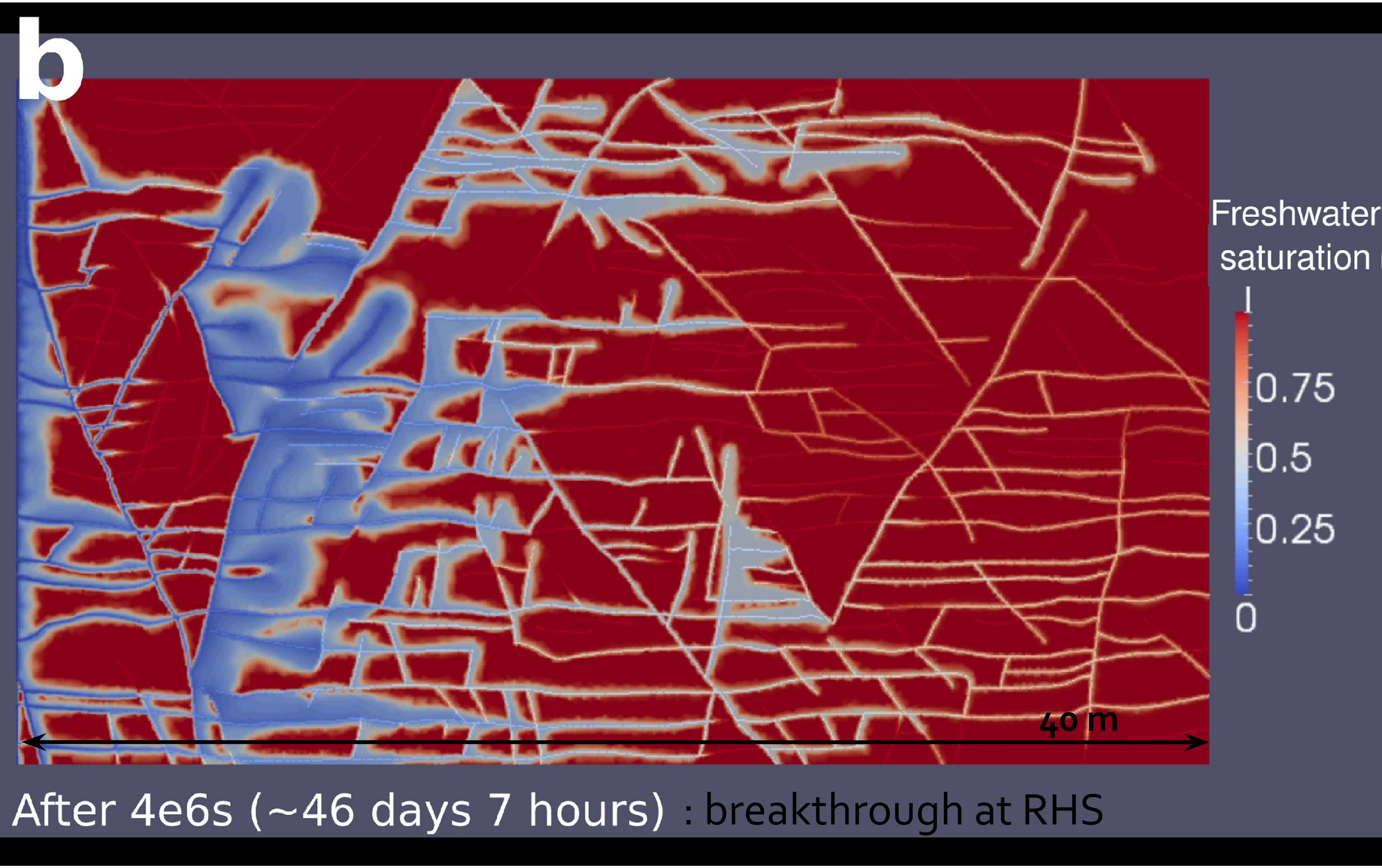
Upper Chalk cliff section
Dumpton Gap, Isle of Thanet, Kent
51° 20′ 50″N 1° 26′ 30″ E
20 metres
Facing 300
FRACTURES
Set 1 (bedding)
Mean dip ~ 6.9°
Mean dip dirn. ~158.4°
Mean aperture ~ 0.1mm
Mean permeability ~ 8.5 x 10^{-10} m^2
Set 2
73.9 / 191.7
Mean b ~ 1.93mm
Mean k ~ 3.1 x 10^{-7} m^2
Set 3
72.3 / 079.7
Mean b ~ 0.92mm
Mean k ~ 7.0 x 10^{-8} m^2
Stage 1. Cursory fracture tracing, and scaling, using Adobe Illustrator.
Stage 2. Precise tracing on a surface using Rhino modelling software.
Stage 3. Generation of the mesh; detail focused on fracture tips & intersections.

Simulated wastewater flood (from LHS)

$\Delta p = 4 \times 10^5$ Pa

Paul & Blunt (2012)

Simulated wastewater flood (from LHS) $\Delta p = 4 \times 10^5$ Pa



Paul & Blunt (2012)

Laboratory work procedure

"Brine" prep

De-ionised water + excess ground chalk

Mix overnight

Separate with centrifuge (15min, 1500rpm), then double filtration

Saturate core with remaining liquid in vacuum chamber for ~1 hour (150psi)

Core saturation & measurements

Average length
L = 75.93mm

Average diameter
d = 38.00mm

Bulk volume
Vb = 86.117cm^3

Weight (dry)
w(d) = 131.20g

Weight (saturated)
w(s) = 168.21g

Pore volume
Vp = 37.057cm^3

"Effluent" prep

1L "effluent" solution + excess ground chalk

Mix overnight

Separate with centrifuge (2 x 15min, 1000rpm)

No filtration used: risk of heavy metal ions adsorbing onto paper

Calculations

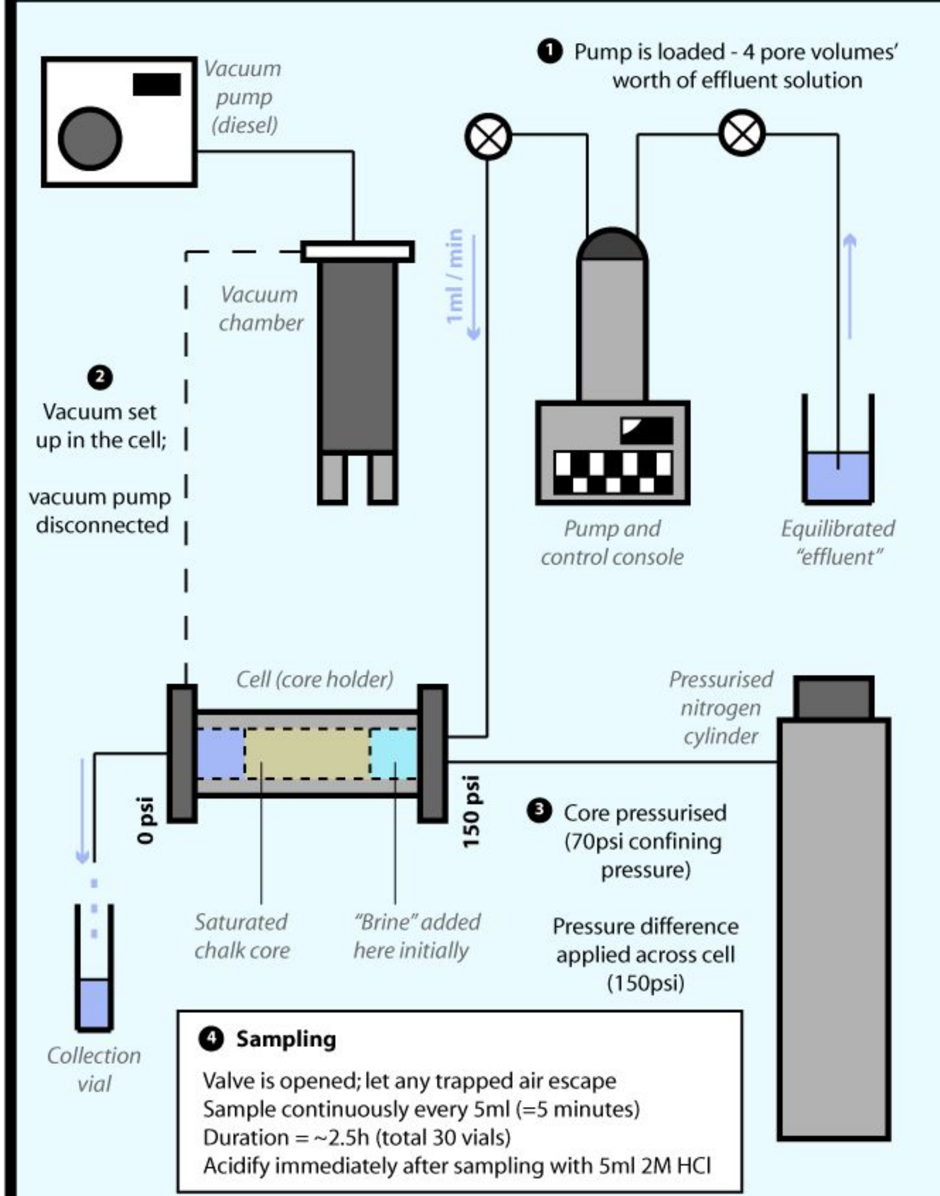
Porosity
$\boldsymbol{\phi} = \mathbf{Vp/Vb} = 0.430$

Permeability from Darcy's Law, viz.,

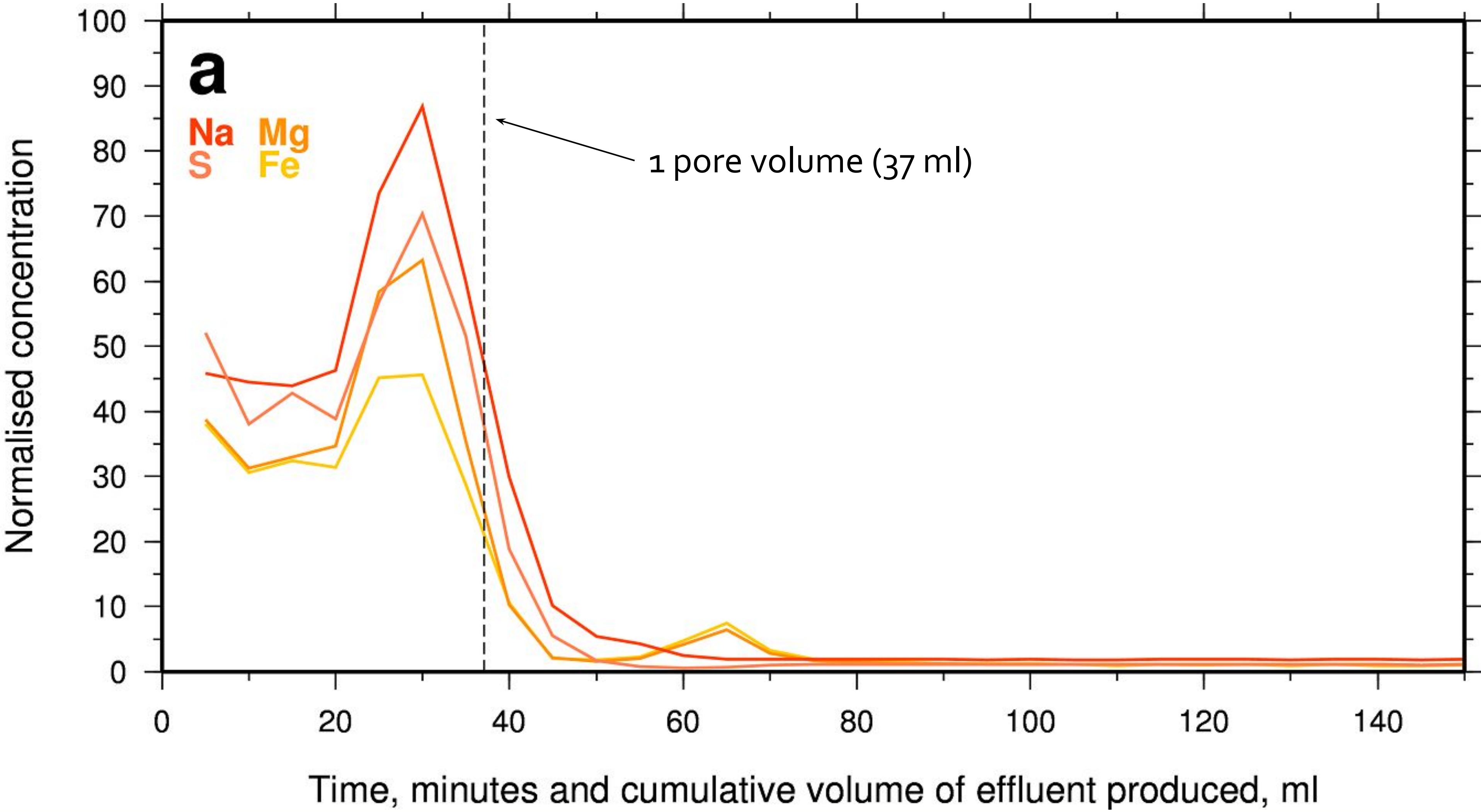
$$\mathbf{Q} = \mathbf{Ak}\,.(\mathbf{\Delta p} / \mathbf{L})$$

Taking $\mathbf{Q} = 1\text{cm}^3/\text{min}$,
$\mathbf{A} = 11.34\text{cm}^2$, and
$\mathbf{\Delta p} = 150\text{psi}$, then
$\mathbf{k} = 1.079 \times 10^{-12}\ \text{m}^2$
(~1D)

Experimental set-up

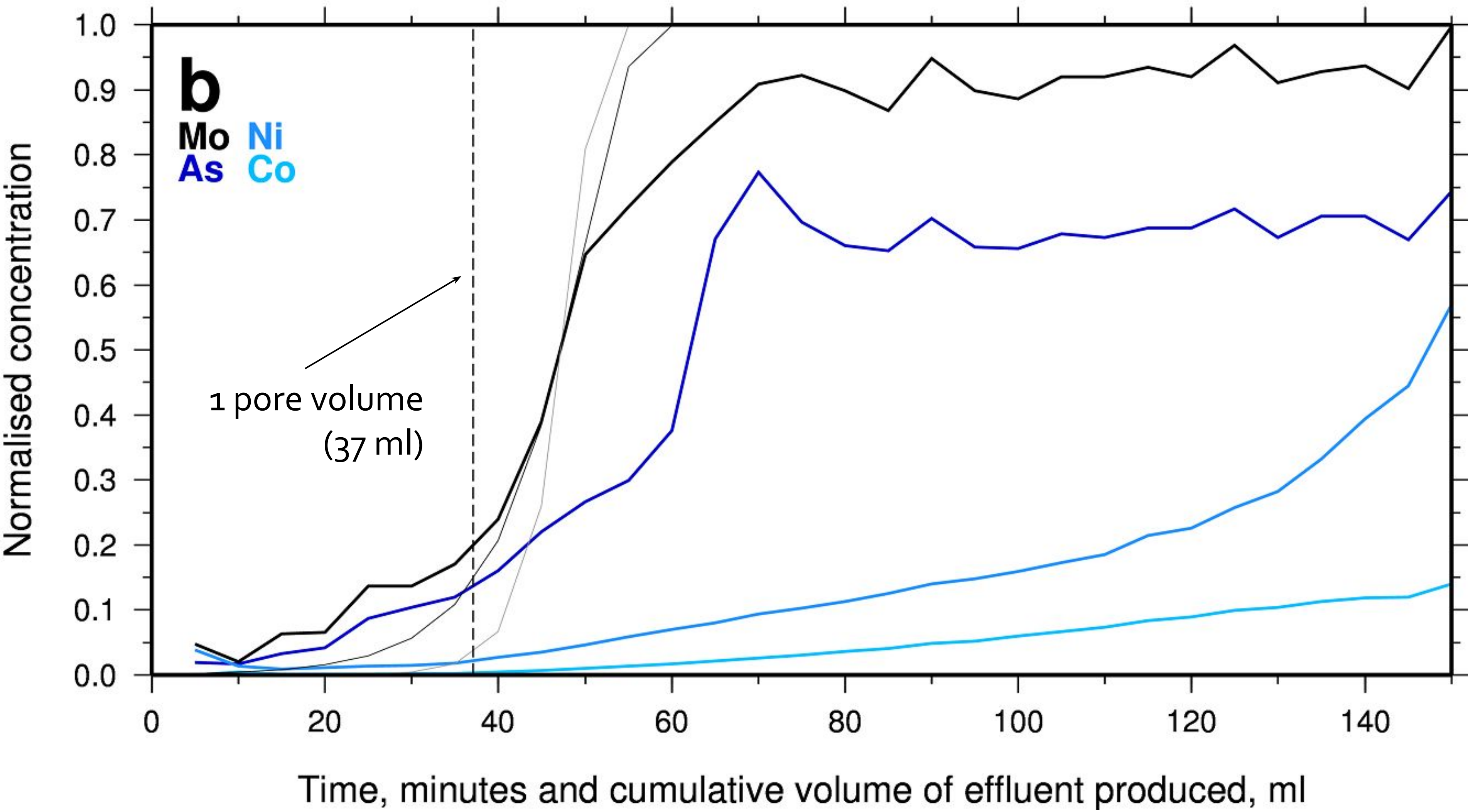


Waterflood: innate “seawater” elements



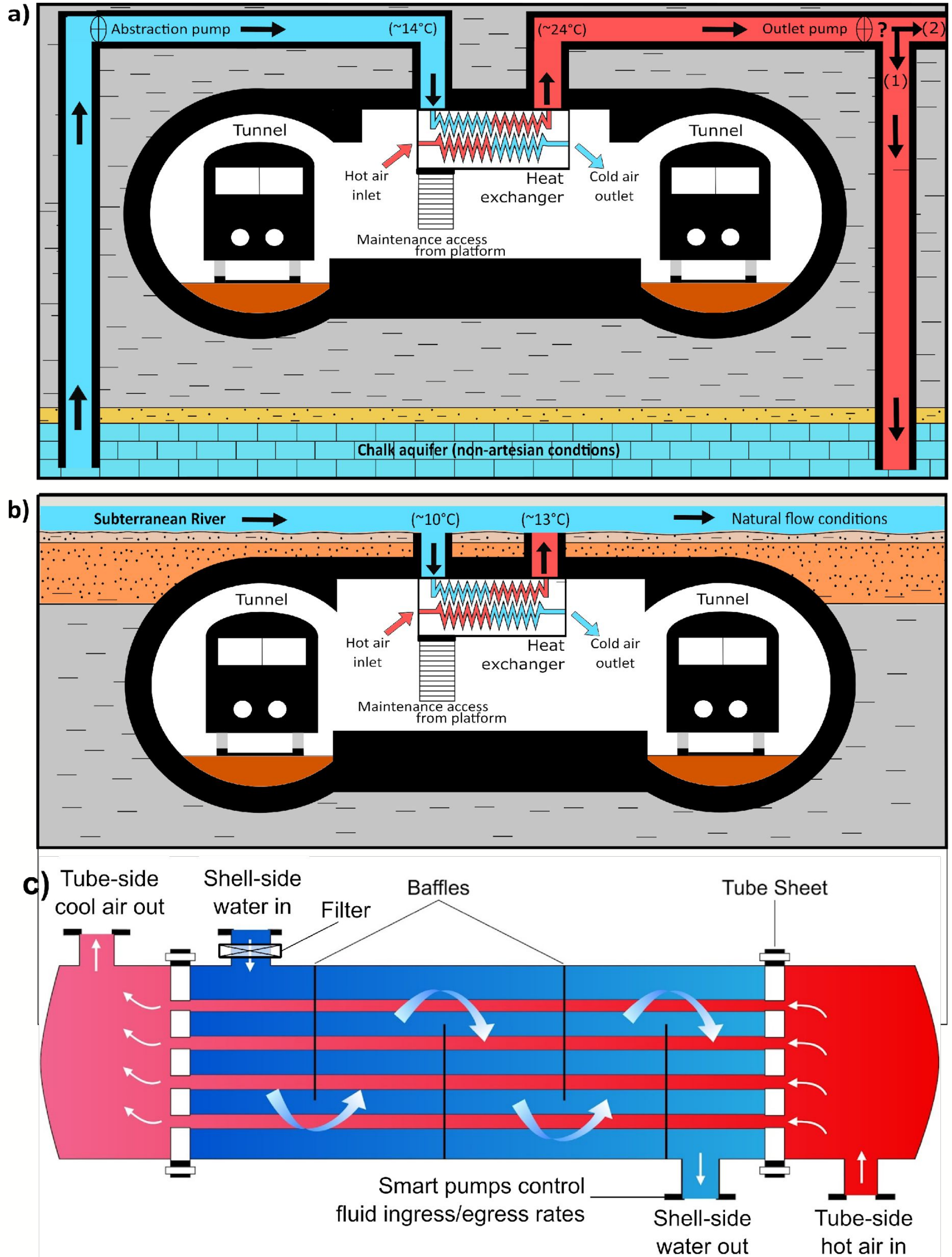
Paul & Blunt (2012)

Waterflood: heavy metals



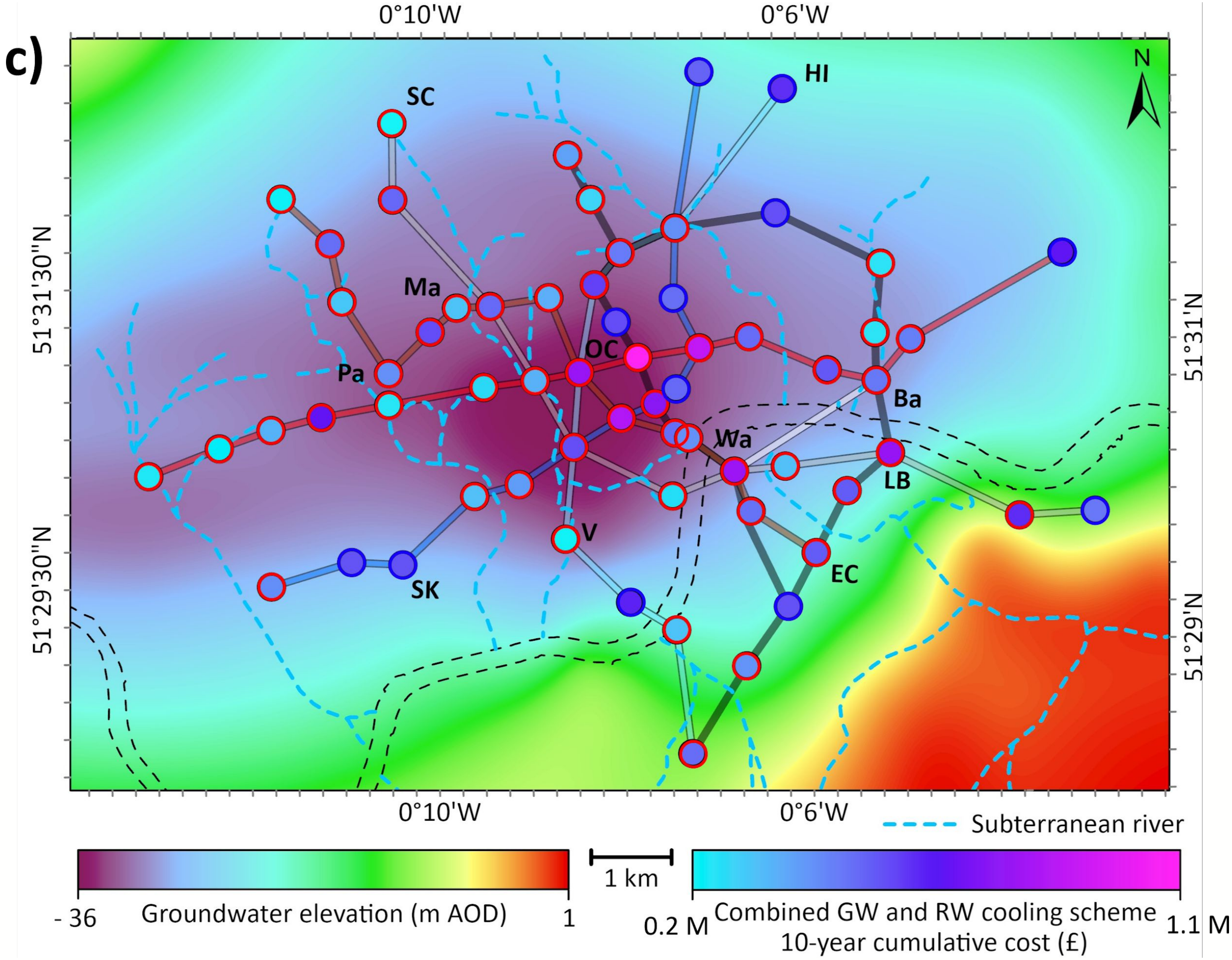
Paul & Blunt (2012)

Sustainable cooling of Tube stations



Rowe & Paul (2022)

Sustainable cooling of Tube stations



Rowe & Paul (2022)

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Tube cooling: Rowe J.M. and Paul J.D., 2022. Cooling the London Underground: Evaluating the use of groundwater and subterranean river water. *Sustain Cities & Society* **76:** 103531

London boundaries: Paul J.D., 2017. The limits of London. *Int J Urban Sci* **21(1):** 41–57

Borehole strat maps: Paul J.D., 2016. High-resolution geological maps of central London, UK: Comparisons with the London Underground. *Geosci Frontiers* **7(2):** 273–286

Croydon chalk: Paul J.D., 2016. Managing London's finest Chalk exposure: Riddlesdown Quarry. *Earth Heritage* **45:** 10–11

Chalk as a natural filter: Paul J.D. and Blunt M.J., 2012. Wastewater filtration and re-use: An alternative water source for London. *STOTEN* **437:** 173–184

More Tube: Paul J.D., 2009. Geology and the London Underground. *Geol Today* **25(1):** 12–17