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Characterisation of Seasonal Temperature Variation in a Shallow, Urban Aquifer: Implications for the Sustainable Development of Ground Source Heating Systems

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1. Introduction

An initial study mapping groundwater temperatures in Cardiff, U.K., found the shallow, urban aquifer to be thermally enhanced due to a subsurface Urban Heat Island Effect (Farr, *et* al., 2017 [in press]). This resource is now being utilised to heat a building at a test site using a ground source heat pump (GSHP). A monitoring network of 97 temperature sensors installed in 60 boreholes was established to look at the long-term sustainability of operating the system, & the wider patterns of temperature fluctuations across the city. GSHP performance may vary across a city depending on temperature stability. Data from 53 of the sensors in 47 boreholes have been used to characterise seasonal & spatial temperature variation over a one year study period & to relate this to those factors which may influence temperature change. Additionally, 35 boreholes have been profiled at 1m depth intervals in both Spring & Autumn to delineate the base of the Zone of Seasonal Fluctuation (ZSF). Of these, 25 boreholes had Spring & Autumn profiles which converge at depth, defining the zone. The depth to which seasonal effects penetrate was on average 9.35mbgl but this zone ranged from 6.5-14.75mbgl across the sites. The variation in depth to the base of the ZSF is the result of multiple factors as illustrated here. Regulation of heat must consider temperature variation across a small scale & understanding what controls seasonal fluctuation may aid the siting of GSHPs for optimum efficiency.

2. Zone of Seasonal Fluctuation

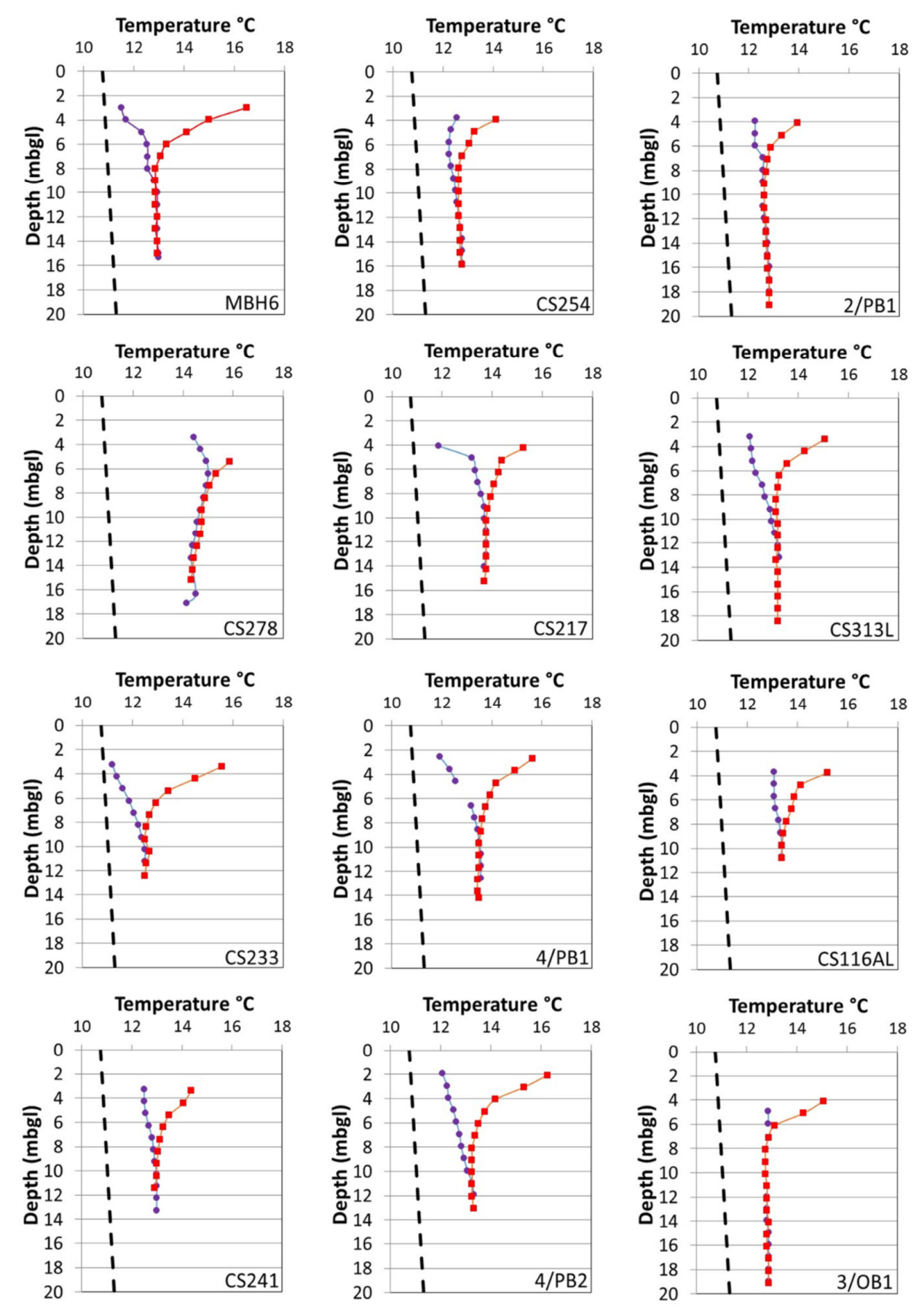


Fig. 1. (From: Farr, *et* al., 2017 [in press]) Spring & Autumn downhole borehole temperature profiles for a subset of measured boreholes. ZSF depth is indicated where profiles converge. Dashed line is the U.K. average geothermal gradient (Busby, *et* al., 2011)

3. Methodology

- Profiled at coolest & warmest times of the year for groundwater
- Variation in ZSF depth compared to site geology, landuse, land cover, degree of shade, & the thickness of alluvium/tidal flat deposits & made ground deposits overlying the aquifer using R code in RStudio
- The amplitude of the difference between Spring & Autumn temperatures varied across the sites & this was also compared to site geology, landuse, land cover, degree of shade, & the thickness of alluvium/tidal flat deposits & made ground deposits overlying the aquifer using R code in RStudio
- Same variables (as well as confined/unconfined nature of boreholes) used in the time series analysis

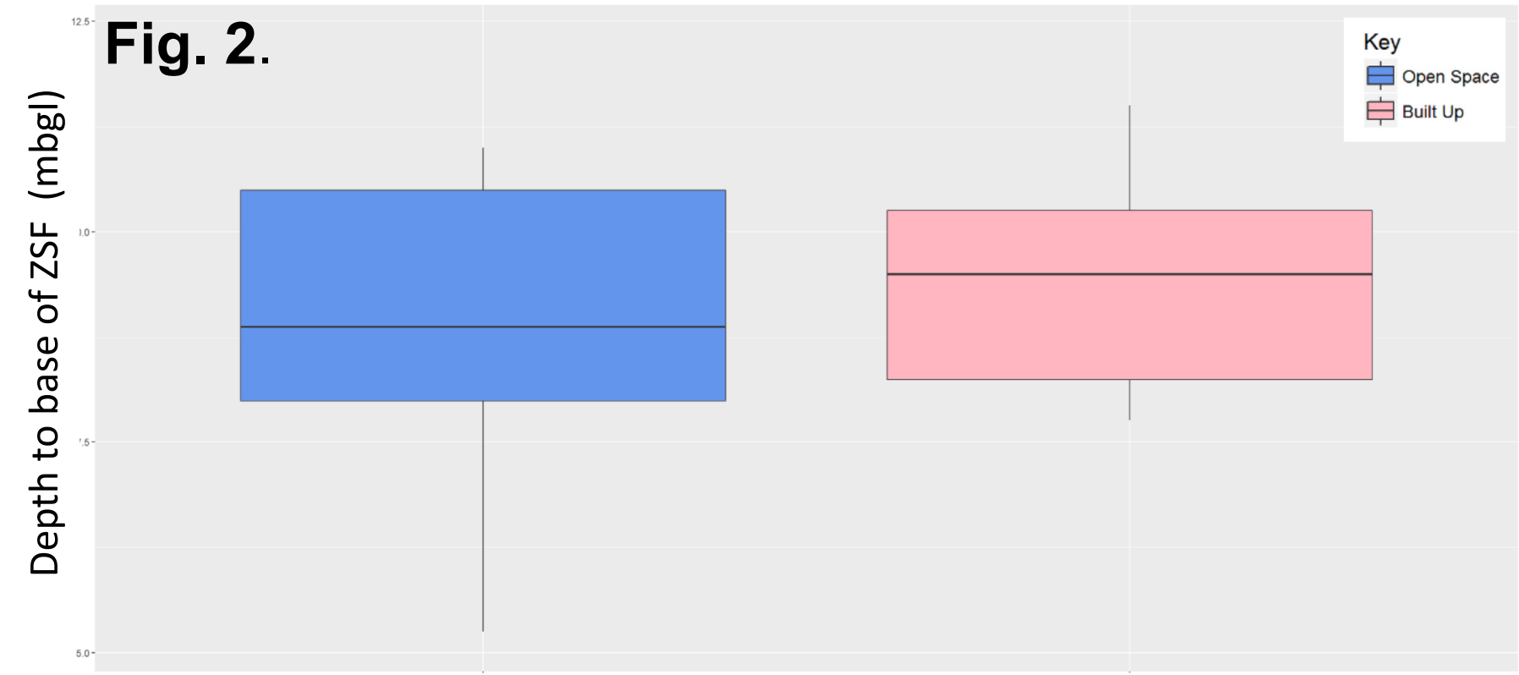


Fig. 2.

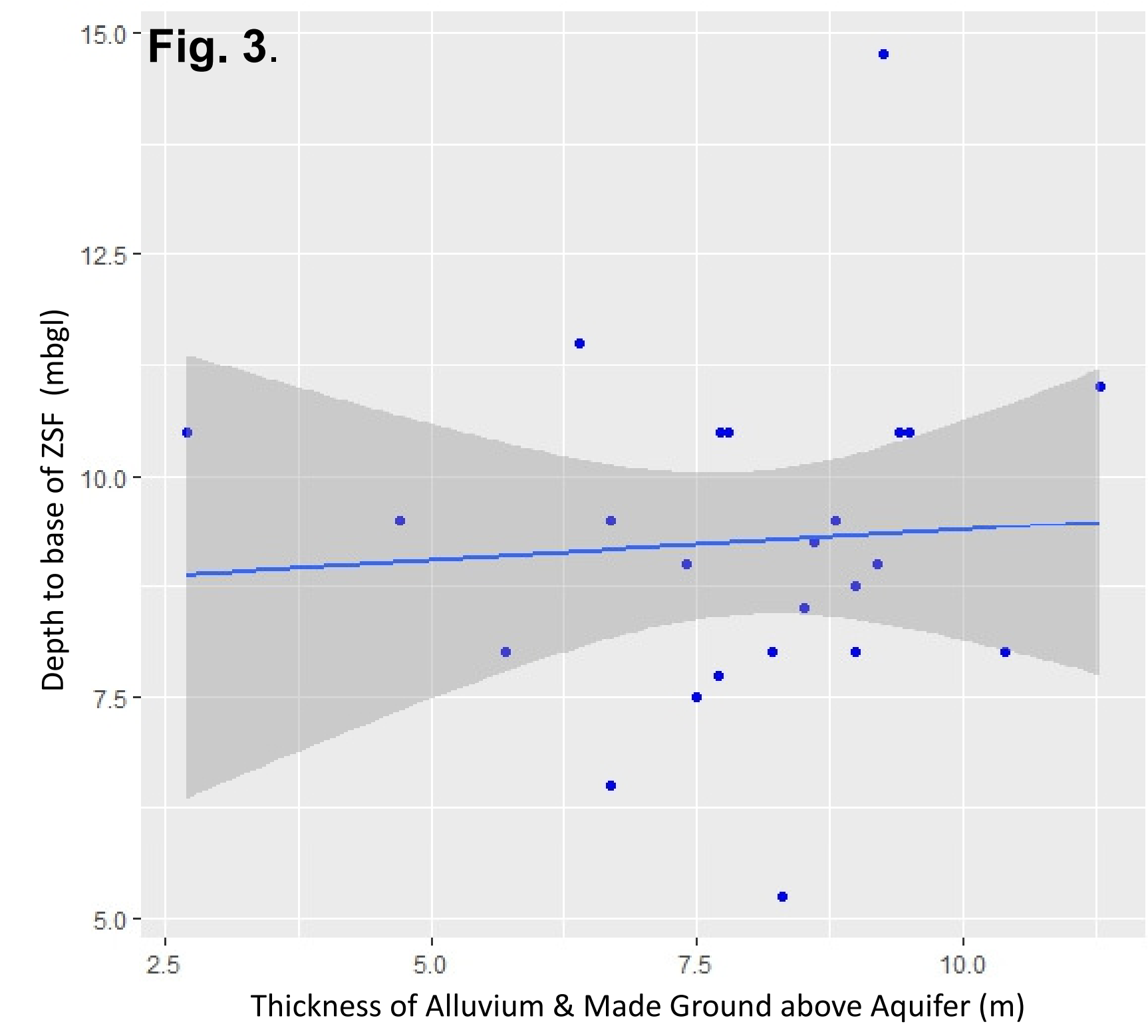


Fig. 3.

Fig. 2. Plot shows ranges in depth to ZSF base in boreholes in open & built up areas. Plots show range, mean & outliers. **Fig. 3**. Plot shows weak +ve correlation between thickness of deposits overlying the aquifer & the depth to ZSF base. **Fig. 4**. Plots show differences between Spring & Autumn temperature profiles with depth. Sites shown by their **a**. geology, **b**. land cover & **c**. landuse. Grey areas show 95% confidence regions for trend lines.

4. ZSF Results

- ZSF generally penetrates deeper in open (non-built up) sites (Fig.2) & in those covered with tarmac
- Variation in ZSF depth is greater in open sites (Fig.2) & in non-shaded sites (decreasing proportionally with increased shade)
- (Fig.3) Weak +ve correlation with alluvium/tidal flat deposits & made ground thickness, & ZSF depth
- The range between Spring & Autumn profiles is smaller at shallower depths in Mercia Mudstone than Glaciofluvial Sands & Gravels (Fig.4a)
- Seasonal temperature fluctuation is smaller at shallower depths in grass (Fig.4b) , open (Fig.4c) & completely shaded sites

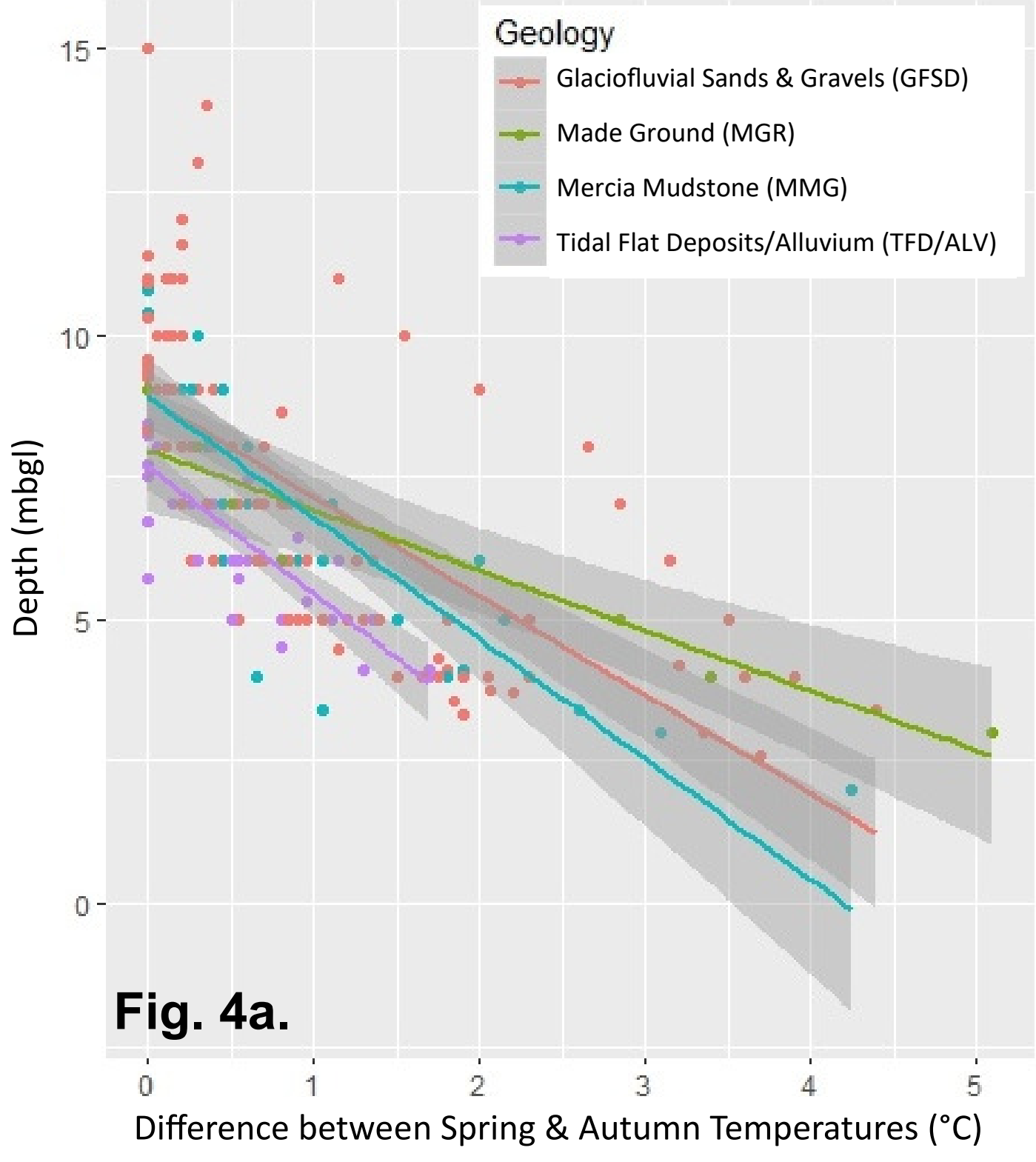


Fig. 4a.

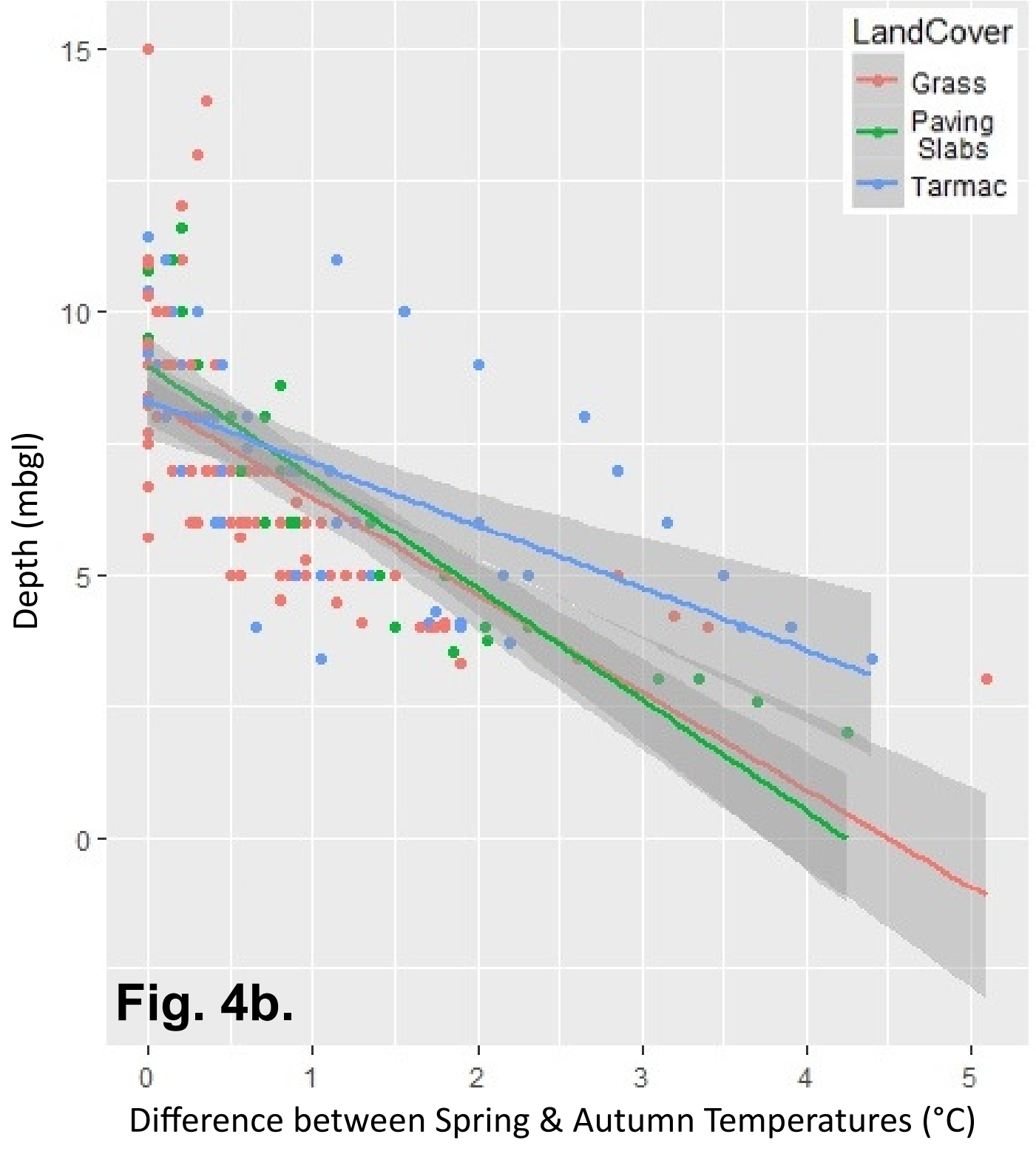


Fig. 4b.

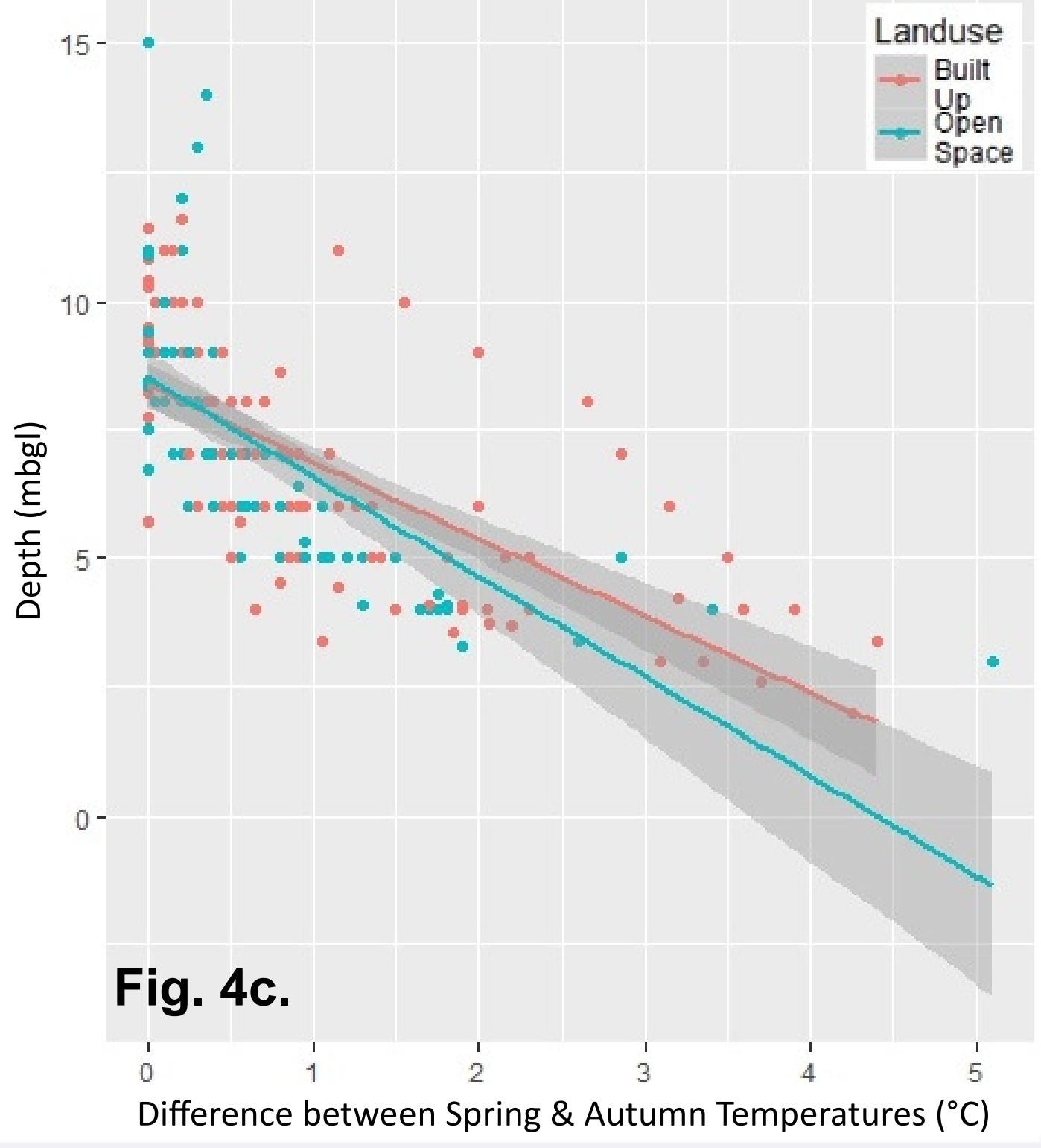


Fig. 4c.

5. Time Series Data (July 2015-June 2016)

Fig. 5. Borehole locations. **Fig. 6**. Plot shows weak +ve correlation between temperature sensor depth & average temperature. **Fig. 7**. Plot shows -ve correlation between temperature sensor depth & high seasonal temperature variation. **Fig. 8**. Plots show the annual range in temperatures at each borehole sensor, presented by **a**. geology, **b**. confined/unconfined nature of the site, **c**. landuse & **d**. land cover. Plots show range, mean & outliers. **Fig. 9**. Plot shows the annual temperature range at each site by thickness of deposits over the aquifer. Insert highlights the -ve correlation.

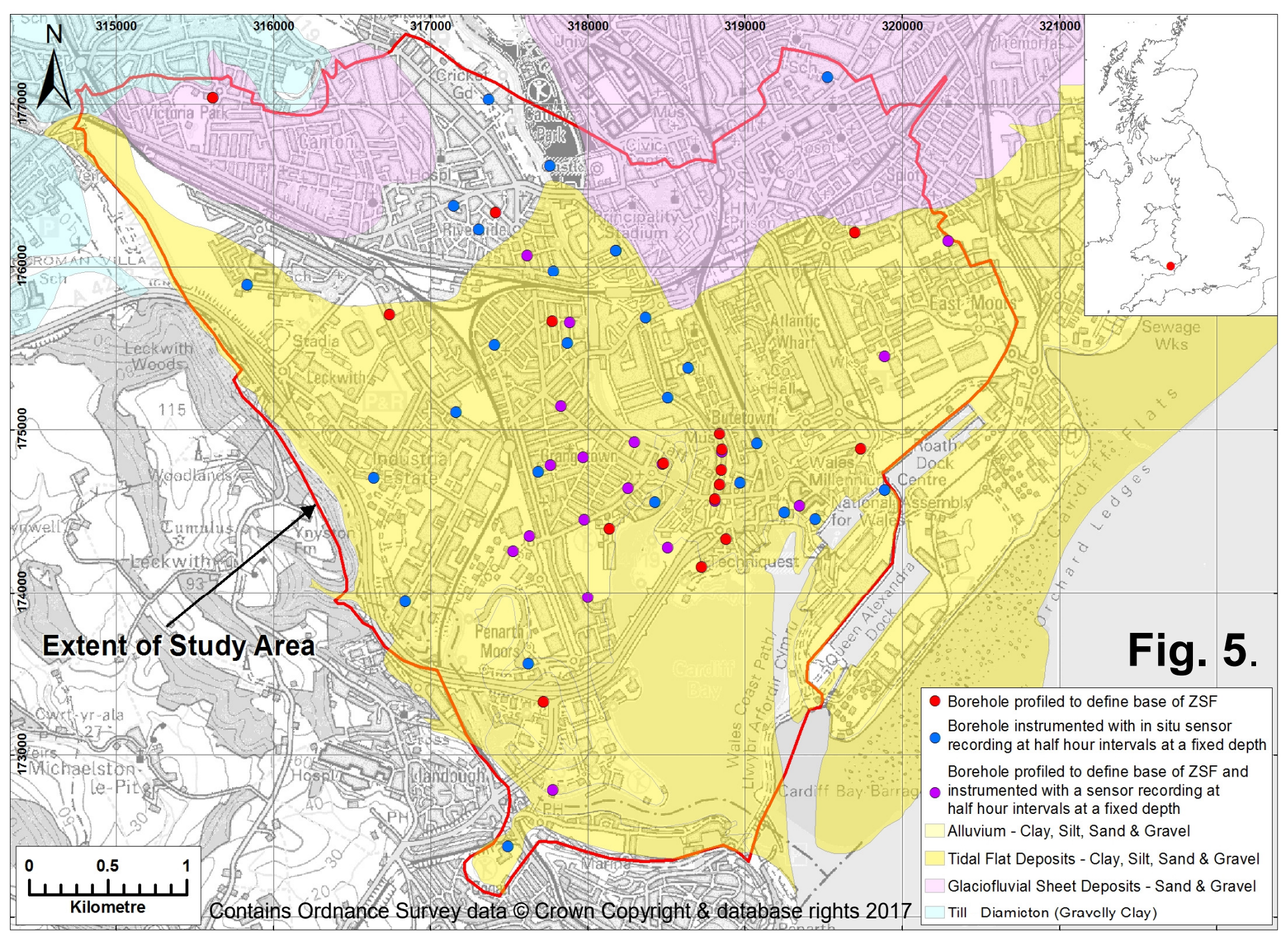


Fig. 5.

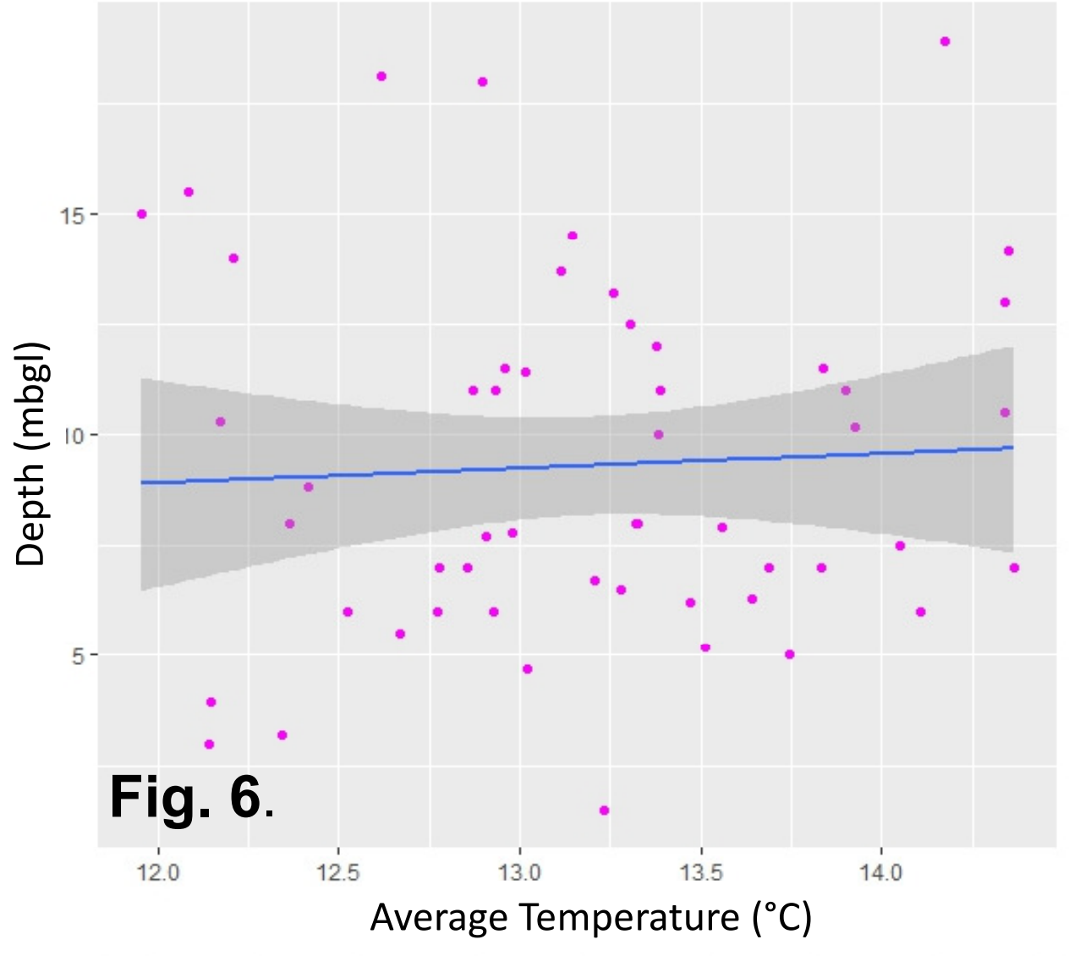


Fig. 6.

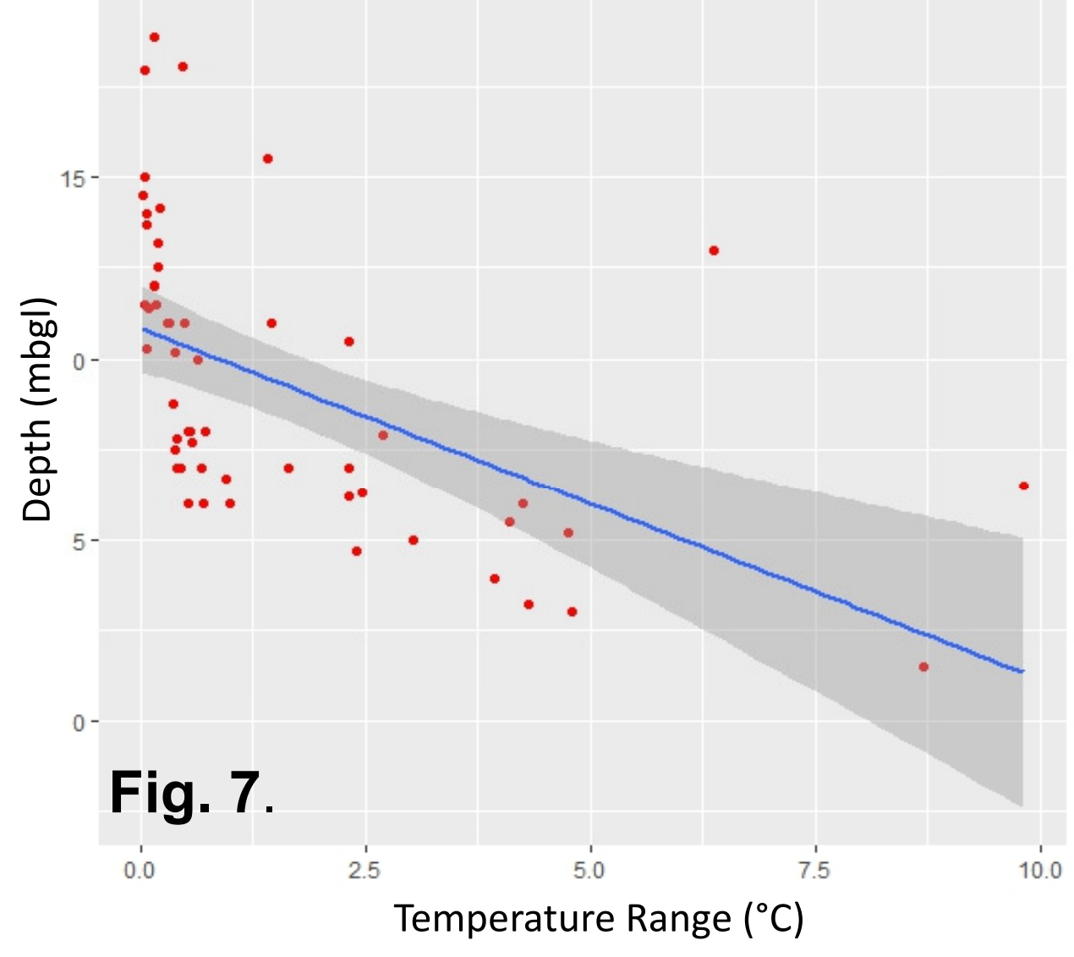
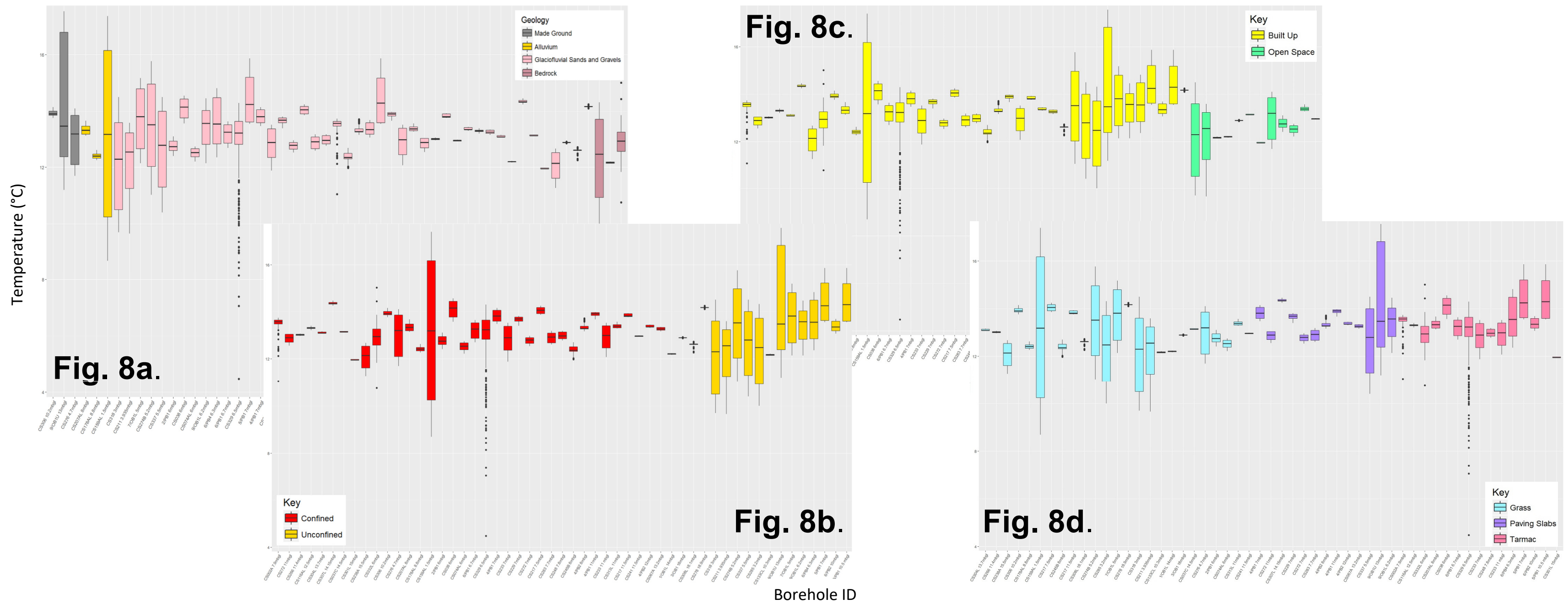


Fig. 7.



6. Time Series Results

- Built up sites = higher temperatures & variations (Fig.8c)
- Tarmac sites are similar but grass is not consistent in its seasonal variation. Tarmac sites are warmer (Fig.8d)
- Greater variation in unconfined (Fig.8b) & unshaded sites
- Thicker deposits over the aquifer result in less seasonal variation but also lower temperatures (Fig.9)
- Pearson's correlation coefficient coded in R found no correlation between groundwater & air temperature in real time, nor with rainfall, pressure or solar radiation
- 22 week delay between peak air & groundwater temperature for most sites
- 69% sites have a +ve correlation with air temperature offset by 22 weeks (41% Pearson's r>0.4) (Fig.10)
- 2 other peaks correlated with 10 & 36 week offsets

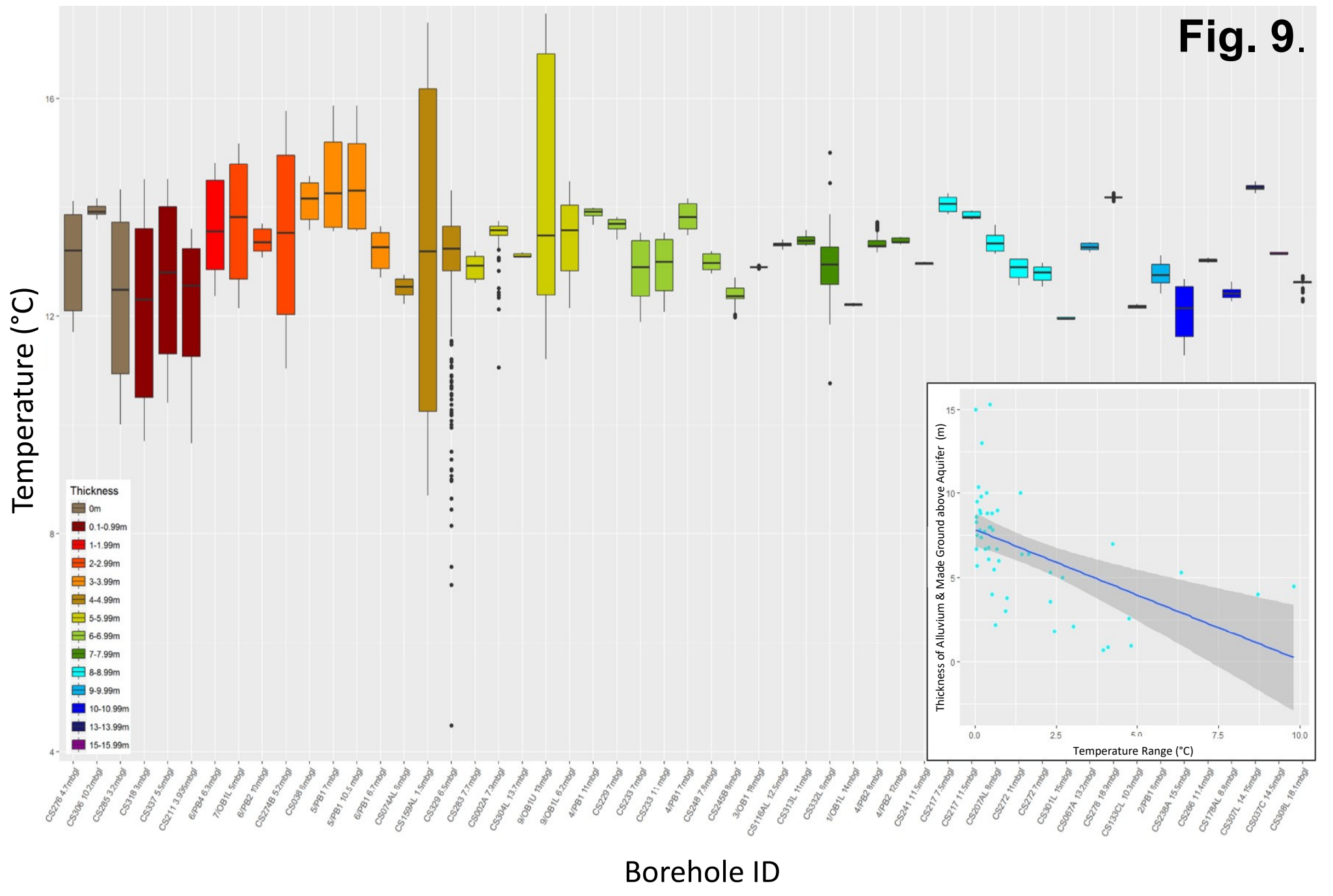


Fig. 9.

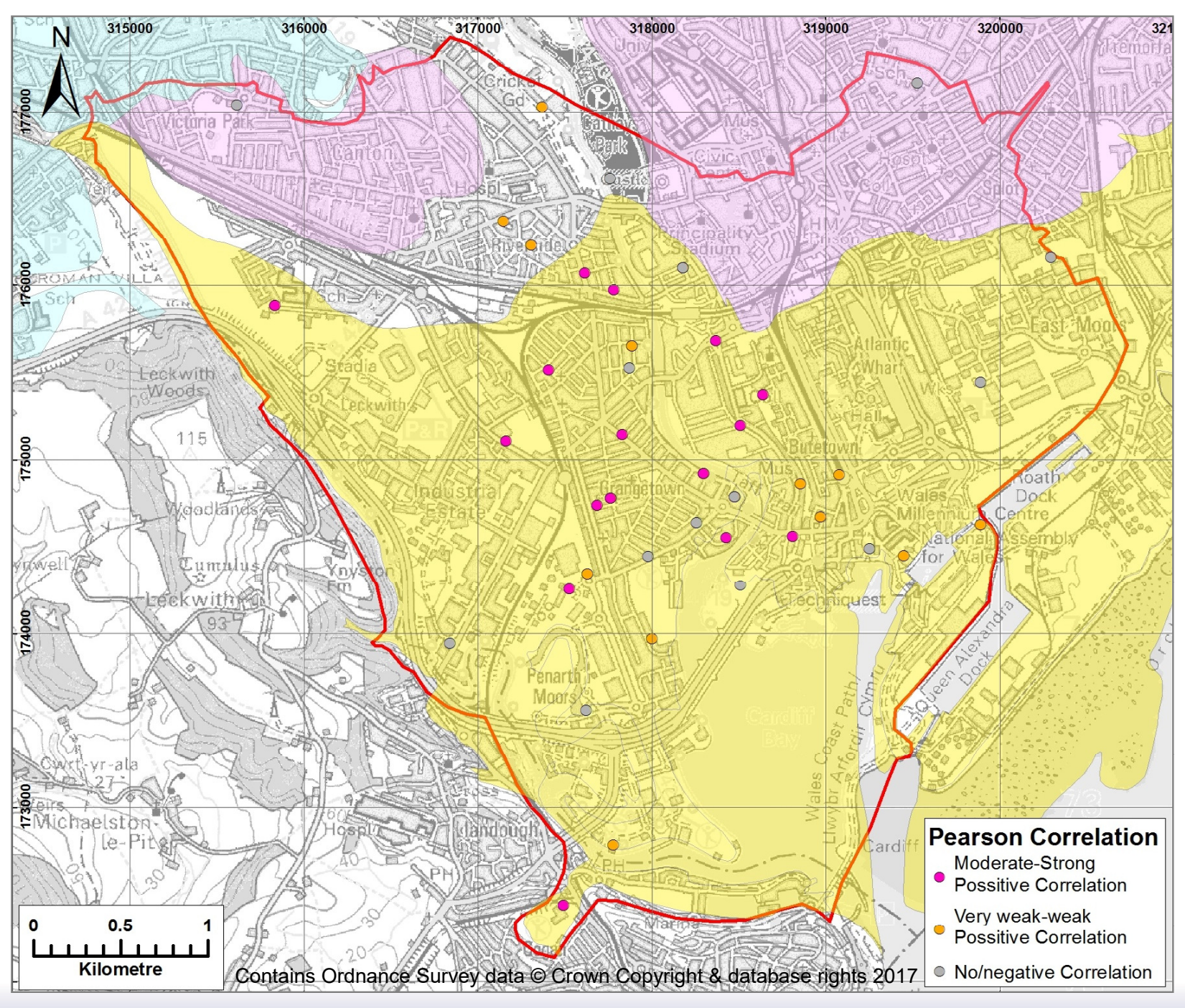


Fig. 10. (Left) Map shows boreholes which had a moderate-strong (r>0.4) +ve correlation with air temperature offset by 22 weeks

7. Next Steps

- Influences on those sites that do not follow the trends
- Coupled interactions involving multiple factors influencing groundwater temperature together
- The effects of anthropogenic features such as buildings & sewage systems
- Thermal conductivity
- Factors resulting in time lags between maximum air temperature & maximum groundwater temperature
- Lessons on ground conditions, depth of saturated layer, heat pathways & thermal rejuvenation response time

References: Busby, J., Kingdom, A. & Williams, J. 2011. The Measured Shallow Temperature Field in Britain. Q. J. Eng. Geol. Hydrogeol., 44, 373-387. Farr, G.J., Patton, A.M., Boon, D.P., James, D.R., Williams, B. & Schofield D.I. 2017. Mapping Shallow Urban Groundwater Temperatures, a Case Study from Cardiff, UK. Q. J. Eng. Geol. Hydrogeol [In press] | **Acknowledgements:** Mark Cave (BGS), Benjamin Marchant (BGS), David Schofield (BGS), Bernard Williams (Cardiff Harbour Authority) & Heather Patton

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