Geology and the Emergence of Modern Neighbourhoods and Social Structures

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Abstract
Mixed communities and public policies to enable neighbourhood transformation has a long tradition in the UK. Standard urban economic theory, e.g. monocentric or polycentric city theories, envisages urban structures as endogenously determined by space-access considerations, but the relevance of standard explanations is weakened when households vary along multiple characteristics. Moreover, cities often exhibit considerable stability in socio-spatial structures – even under conditions of significant economic change. On the other hand, amenity based approaches to explaining urban structures have suffered from the hard to observe nature, and quantification, of amenity indicators. This article analyses the impact of geology and topology on social structures and finds that these systematically explain variation in median house prices at MSOA level in England and for individual English GORs. Drawing on a detailed geological study of London in the 19th century the paper argues that geology historically gave rise to systematic variation in amenity value of location and thus the emergence of social structures – separately from access to employment. Nevertheless, while geology is significantly related to modern property prices, the key determinant of median prices remains distance to centres of employment. The implication for policy and theory is, then, that exogenous factors may initiate processes of cumulative causation and persistence, but also that interaction with economic processes may give rise to periods of, seemingly, discrete change.

1 Introduction
UK urban policy has a long tradition for incentivising ‘mixed communities’ and transformation of neighbourhood social characteristics (or structures) (Cheshire 2007; Lupton and Fuller 2009). The Mixed Communities Initiative introduced in 2005, for instance, was aimed at ‘fundamental long term transformation, rather than more modest improvements’ including changes to population mixes (DCLG 2010:20). The introduction of ‘localism’ in 2011 arguably weakens formal structures for delivering mixed communities by strengthening local (communities’ and individuals’) influence over neighbourhood planning and development. However, elements of mixed-communities philosophy are still found in recent estate regeneration initiatives. For instance, densification and private homes development are seen as key to regeneration of a number of post-war public housing estates (Cameron 2016).

From a policy and academic perspective mixed communities are sometimes hypothesized to have a number of positive external effects on behaviour, social cohesion and social capital (Lupton 2003; ODPM 2005; Kearns and Mason 2007). Moreover, mixed communities may be
instrumental in raising the average income level of a community, which in turn maintains the provision of private services (Lupton 2003; Monk et al 2011) – private services that may further contribute to raising the amenity value of neighbourhoods. While conceptually a number of positive effects are associated with mixed communities, the scientific evidence that mixing leads to welfare gains and reduction of social and behavioural issues is often mixed and complex (Kling et al 2005; Cheshire 2007; Galster 2011).

This raises important questions about how social structures arose in the first place? Policies to alter social structures may very well take place against a backdrop where the status quo represents a socio-spatial equilibrium. For instance, the standard monocentric city model would result in high levels of segregation when residents are heterogeneous along a single dimension (e.g. income); distinct clustering also is the likely outcome when residents have weak preferences for neighbourhood characteristics along a single dimension (Shelling 1969).

In the UK, as in many other countries, planning instruments and policy have become vehicles for operationalizing mixed communities, but these are predominantly, and depending on the definition of neighbourhood, affecting social structures at the margin. Communities, and their associated social structures, have typically been in place for very long periods. Evidence from England and London, for instance, suggests that social structures have exhibited considerable stability over at least the last 130 years (Orford et al 2002; Meen et al 2012). Spatial segregation and inequality, thus, may simply be the physical articulation of underlying social and economic drivers interacting with the price mechanisms (Cheshire 2007).

These underlying social and economic drivers may have long historical precedents so that the social structures that we observe today potentially are the cumulative embodiment of centuries of planned and self-organised behavioural patterns (Brueckner et al 1999). On the other hand, although standard predictions in urban economics are common in the empirical literature, levels of mixing (variability around these trends) are nevertheless greater than theory frequently predicts. Indeed, when agents are heterogeneous (vary along multiple dimensions) the relevance of the monocentric city model in explaining residential patterns by income remains questionable (Duranton and Puga 2015). In other words, urban systems are complex, slow to adjust (if at all) to changing economic geography and may be subject to a number of exogenous determinants that public policy only imperfectly may affect.

This paper is concerned with identifying the impact of one of the exogenous determinants, geological conditions, on modern social structures. More specifically, it asks what role geology plays in determining the social structures of cities? In standard urban economic theory, e.g. monocentric or polycentric city models, social structures are endogenously determined by distance to mono, or poly, centres of employment. Unlike most other features of urban systems geology is not the product of human intervention and can thus be considered exogenous.

Geological determinants of residential location have significant implications for public policy, but also for urban economic theory. Geology may be less amenable to public policy, but also modifies standard urban economics theory by weighing land by its geological characteristics. In the latter case income elastic demand for land (housing) does not necessarily translate into
demand for peripheral land if the geological characteristics of peripheral land is inferior to central land.

The key argument of the paper is that the geology exogenously may have given rise to systematic variation in amenity value of location and thus the emergence of social structures – separately from access to employment. Such variation may persist until today due to path dependency and/or their continued relevance for household location decisions. While Brueckner et al (1999) and Evans (1973) theoretically provide a rationale for why topological and geographic conditions might provide amenity value, in limited supply, the ability to empirical test the interplay between amenity and demand has been limited due to the hard to observe nature of the former (Duranton and Puga 2015). This paper therefore introduces an estimation innovation and argument that, in part, explains exogenous determination of social structures.

The paper is divided into 5 sections. Section 2 develops further the theoretical argument for the role of geology on modern social structures. Section 3 provides specific examples of the impact of geology on urban development in the Victorian era. Section 4 shows the result of a reduced form regression of geology and current house prices. Section 5 concludes.

2 Segregation, social structures and geology

A key criticism of attempts to plan or engineer mixed communities by Cheshire (2007) is that spatial segregation itself is the articulation of society’s income distribution. Attempts to engineer social mix are thus treating the symptoms of wider economic processes, rather than the cause of these processes. Cheshire’s central argument is that more affluent households, in a market processes, are able to access more desirable housing locations and stock. More desirable stock and locations are more highly priced; and housing-demand is income elastic (Meen 2001). Under conditions of rising income inequality some households will increasingly be able to out-bid other households. To the extent that desirable properties are clustered or share geographical characteristics income inequality will result in spatial segregation.

The Alonso (1964), Mills (1967) and Muth (1969) monocentric city model shows that if commuting costs (opportunity cost of commuting) and housing consumption are both income elastic then patterns of social structures depend on changes in income. If the elasticity of commuting costs, with respect to income, exceeds the elasticity of housing consumption then more affluent households will cluster in inner city locations and visa versa. In terms of social and spatial structures the monocentric city model predicts that land prices, population and employment density declines with distance from the central business district (CBD) as increasing commuting costs need to be offset by lower property prices.

While theoretically elegant and empirically frequently found to conform to observed property values (Ahlfeldt 2011, Duranton and Puga 2015), the model nevertheless requires systematic variation in the commuting-housing consumption trade-off across cities in order to account for some observed variation in social structures (Brueckner et al 1999). To some extent systematic variation in preferences, for otherwise similar social groups, are required to account for differences in the location of affluent households. Moreover, even relaxing assumptions around
homogeneity of agents and monocentricity also results in degrees of spatial sorting that imperfectly reflect observed heterogeneity/social mixing.

The monocentric city model hinges on access to central city amenity, where amenity is defined as access to work. Brueckner et al (1999) develop an alternative theory of urban social structures based on a wider definition of amenity. As in the monocentric city theory income remains the key determinant of access to locations, but amenities now include a set of endogenously (modern) and exogenously (natural/historic) amenities. Endogenous amenities arise when income facilitates the provision of urban amenities and conditions quality of life in a neighbourhood (Brueckner et al 1999). This argument relates to the earlier discussed mixed community policies in that raising the average income of an area may sustain or provide additional private services that improve the attractiveness of a neighbourhood. It also relates to the new economic geography literature and increasing returns from agglomeration (Krugman 1991). Agglomeration, conditioned by income and otherwise ceteris paribus, in principle means that social segregation is expected, but that the precise spatial articulation of this segregation is indeterminate. Cheshire (2007), and the increasing returns literature, argues that neighbourhood specialisation has positive (as well as negative) externalities that are capitalised in local property prices and the spatial articulation of income differentials. Nevertheless, a critique of the amenity approach is that the resulting spatial equilibria, and associated social structures, exclude very little and are rationalised on the basis of hard-to-observe features (Duranton and Puga et al 2015).

In Brueckner et al (1999) exogenous amenities are natural features, such as topographical characteristics and geographic proximity to bodies of water, and historic features, such as past private and public investment in the built environment (historic buildings)/parks or infrastructure. Evans (1973) argues that environmental amenities are likely to be superior goods so that richer households will spend a larger proportion (of a larger income) on securing access. A number of studies show that several of these characteristics are capitalised in modern house prices. For instance, Nygaard and Meen (2013) show that properties located in close proximity to the early (1908) underground network have a price premium. Cheshire and Sheppard (2004) show that, for properties in Reading, river frontage (the Thames) is positively related to property prices. However, it is also clear that the relationship between natural/historic amenities and local social structures are complex. Anderson and West (2006) find a positive relationship between access to open space and property prices, but also show that these relationships are conditioned by a number of other social and economic factors (population density, demographics, distance to CBD). Similarly, Troy and Grove (2008) show that the amenity value of local parks in Baltimore is conditioned by the local incidence of crime. Francis-Brophy and Nygaard (2011) similarly find, in a qualitative study, that many residents perceived a local park in Slough as a liability. A key implication of natural features, including geology, is that the value of land no longer is determined by distance to a CBD alone, but also by its inherent, and often time invariant, characteristics. This latter feature may partially or fully negate the impact of distance to the employment centre on a location’s attractiveness.

Returning to Brueckner et al (1999) the argument is that natural and historic features can be viewed as causal factors in determining location by income, rather than themselves a result of the income distribution. Historic features are largely considered the result of cumulative investment in monuments and public spaces by a central government or city authority. Taking a broader
view of historic features, however, it is also plausible that historic features include the residential housing stock. There is some evidence for this argument. Meen et al (2007) show that there is a price premium for older (pre World War 1) and newer buildings in England and in Melbourne. Lee and Lin (2015) similarly find that pre-1940s homes have a price premium in a sample of US cities. Selective survival, giving rise to historic amenity value rather than age per se, may be the explanation for this price premium.

Social structures and property prices are thus likely to reflect the relative concentration of endogenous amenities and exogenous amenities. Depending on their relative strength, and city specific income structures, the spatial pattern of social structures may vary considerably and exhibit multiple equilibria. Moreover, exogenous determinants of social structures also mean that distinct patterns of advantage and disadvantage may persist in the presence of considerable contextual change. Social interactions, longevity of housing, economies/diseconomies of scale and planning policies may further contribute to exacerbating persistence.

The above studies predominantly consider natural features in terms of access to bodies of water or topological features (e.g. elevation, vistas). For instance, Lee and Lin (2015) show that the persistent natural amenities (oceans, mountains and lakes) anchor US neighbourhood to high incomes over time and that US cities with greater natural heterogeneity also exhibit greater spatial persistence in the spatial distribution of income. Few studies, however, consider the role of geology, although geology has been shown to affect both location and morphology of cities (Leggett 1973). Combes et al (2010) is an exception. They use soil and hydrogeology as instruments for estimating productivity and agglomeration economies in France. In this study geological characteristics are positively relate to market potential.

Overall, there are at least two reasons for why geological characteristics might determine social structures. Firstly, to the extent that geological characteristics are related to fertility of land it might be hypothesised that, at least historically, more fertile land might have sustained higher populations and potentially higher wages. Moreover, agricultural productivity may have generated surpluses for trade that subsequently provided the basis for the emergence of non-agricultural service functions and trade. For instance, from, at least, the 7th century onwards it is argued that agricultural surpluses enabled the permanent location of non-agricultural activities (Astill 2000) and broadening of the economic base (occupational specialisation and urban services), over the next centuries, of English town and cities (Britnell 2000). This argument then links to the conventional view of industrialisation; that is, that the agricultural revolution (from around the mid 17th century) enabled release of labour, demand for industrial products due to higher wages and savings for industrial investment. A priori though there is little reason why soil fertility should continue to affect social structures. Economic activity in England, and most developed countries, is no longer significantly agricultural. While a large proportion (75 per cent) of land in England is in agricultural use (Khan and Powell 2011), it accounts for a very small proportion of national income or employment – both less than 1 per cent (DEFRA 2012). Since at least the industrial revolution other, geologically determined, factors have arisen that would counter the effect of fertility of soil. A finding that fertility of land has a positive impact on property prices would thus suggest an extreme form of spatial lock-in and path dependence.
It is, however, also feasible that fertility is negatively related to modern property prices. Given the lesser importance of agriculture in economic activity today this, however, would not be evidence of path dependence, but an effect of lower wages associated with agricultural production. Contrary to the conventional view of industrialisation this argument can, a priori at least, also be applied to urban development in England. Until the 17th century there was an urban bias towards the south and south east of England – this bias stretches back as far as Roman times (Palliser 2000). Over the next 200 years, however, the urban hierarchy below London was greatly reversed with industrial cities of the North overtaking, in terms of population, Southern cities (Langton 2000). According to Matsuyama (1991) the comparative advantage of economies with productive agriculture may stymie the emergence of manufacturing and industrialisation while low agricultural productivity, implying cheaper labour, and provides a comparative advantage in manufacturing/industry. According to Glennie and Whyte (2000:176-180) crisis in grain supplies were no longer associated with higher urban mortality after 1590; moreover, by the late 17th century a national market for wheat existed with common price fluctuations. Thus it is feasible that agricultural productivity may be associated with lower, contemporary, property prices if industrial/manufacturing activity emerged in locations with lower agricultural productivity.

Secondly, soil and geological conditions may be directly related to the amenity value of locations. Particular types of soil or rock may have particular properties, or locations, that imbue the thereupon erected structures with particular characteristics in the form of health aspect, housing or structural quality. If this is the case then geological, in addition to topological, factors may have given rise to systematic variation in patterns of land use and neighbourhood characteristics. Variation in the amenity value of soil and rock would have rendered some areas in high demand and other areas in low demand. The 17th - 19th century was an era of urban expansion in London and a number of British towns. Large tracts of London were speculatively developed with developments clearly targeting particular types of consumers. Several large estates in the west end of London were developed for higher income residents (Boulton 2000, Evans 2004). These estates also enabled developers to internalise neighbourhood effects arising from provision of additional amenities (open space) and social clustering. Conversely, large parts of London were developed speculatively for middle and lower income households in more densely constructed rows of terraces.1

Conventional wisdom holds social structures (low income east; higher income west) in part reflect prevailing direction of winds and location of industry during the industrial revolution, but key features of London’s social structure were already in place in the mid-17th century. For instance, lower income residents were more concentrated to the north and east of the city; and along the alluvial parishes either side of the Thames (Boulton 2000). More affluent residents were located within the walls or in the emerging estates of the west end. Social structures in London, then, were already in place prior to the onset of the industrial revolution; and the ‘frequent, soot-laden smog’ that affected mortality rates in Victorian London (Ball and Sunderland 2001:26). What distinguishes areas of the west, east and Thames side is, however, the underlying geological and topological characteristics – and these features were in place before the suburbanisation and expansion of London.
3 Geology and urban development in Victorian England

During the 19th and 20th centuries the urban footprint of London expanded dramatically. London expanded rapidly in all directions. The emergence of mass public transport (suburban trains and underground network) facilitated work and residential areas to be separated. While many lower income households remained dependent on walking for access to places of work, many middle class households took advantage of the greater availability of space at greater distance to the city and suburban building activity. Commuting costs for lower income households began to change towards the end of the 19th century with the introduction of Cheap Trains Act, 1883. Nevertheless, though suburban development sometimes was intended for middle class residents, the speculative nature of development and, sometimes, uncoordinated pace meant that suburbanization also resulted in housing for lower income residents.²

As London expanded its geological foundations became more diverse. Roman London was located on sand and gravel on the north shore of the Thames. The geology to the west of the City is similarly sand and gravel (over a layer of London clay), but as London expanded some previously residentially unsuitable land, such as the Moorfields was drained (17th C) and more marginal/lower demand alluvial land was developed. The south bank of the Thames in large tracts consists of alluvium deposits made of up clay, silt and sand. The same geology is found along the Rivers Lea and Roding to the east of the city, as well as the Isle of Dogs just down from the City itself. The enclosure of previously marginal land was typical of developments of a number of European cities in the 19th and 20th (Legget 1973).

As cities expanded and populations increased the effect of the increasing urban footprint and intensive development of land on the quality of water supplies and health became a matter of public policy concern. The industrial revolution accelerated rural-urban migration and density of population. Improvements in building materials and construction technology, combined with increasing demand for land, intensified land use with taller residential buildings as well subterranean construction. In 1843 a Royal Commission was charged with examining the state of urban centres from a public health point of view. The Commission reported that some 10 and 15 per cent of the population in Manchester and Liverpool, respectively, lived in cellars (Culshaw and Price 2011).

Throughout the 19th century a number of cholera epidemics plagued British cities as a result of poor drainage and problems with clean water supply (Culshaw and Price 2011). The role of geology on public health by now was also a public policy concern in a number of European and colonial cities.

In the mid-19th century the geological foundations of buildings and neighbourhoods were linked to damp living conditions, drainage/sewage and water quality. A number of reports and inquiries focused on the sanitary conditions of the working class (Meen et al 2016). Slum clearance programmes in British cities from the mid 19th century onwards were also part of a public health policy aimed at removing unhealthy areas. According to Yelling (1986:10) ‘A defining characteristic of such [slum] clearance is that it stems from the representation of a medical officer of health’. Increasing population densities in, frequently, damp and unhygienic dwellings exacerbated public health concerns. In a report of the Medical Officer of the Privy Council in 1867/68 it was concluded that drainage and a permanent reduction of water, in urban soil, would
result in a reduced death rate from tuberculosis (Woodward 1987/1906). The effect of leakages from sewages or direct disposal of refuse into pits or surrounds on ground water quality is determined by the permeability of soil and rock and the volume of sewage. From the 1890s onwards slum clearance dominated in eastern and southern parts of London (Nygaard and Meen 2013) – frequently in areas from the Victorian era urban expansion on marginal lands.

A specific example of linking health to geological characteristics is found in Woodward’s 1897/1906 ‘Soils and subsoils from a sanitary point of view’. This study, intended to guide homebuyers in response to ‘constant enquiries [] by the public for information regarding sites for houses’ (Woodward 1897/1907: iii), discusses the geology of London and parts of the South East. The study classifies geological formations in accordance with the suitability for residential housing construction and healthy living. Soil is simplified and classified according to its geotechnical and hydrogeological properties rather than its age (Culshaw 2004). As such the study summarises the scientific and public understanding of systematic variation in demand characteristics related to geological foundations, accumulated through the 19th century.

Woodward (1897/1906) divided London’s geology into made ground, natural ground and five types of subsoil. A general description and associated health characteristics (environmental amenity) are provided in Table 1. From Table 1 a number of geological and topological conditions can be derived that were considered conducive to healthy living and linking geology to environmental amenities. Firstly, elevation was important. Elevation ensured quicker draining of the soil. Elevation also ensured absence from underground (and surface) flooding along rivers/bodies of water. Moreover, although John Snow’s work in the 1850s established that cholera was a waterborne disease and not transmitted through miasma, healthy air was nevertheless an additional environmental amenity. Secondly, the geological characteristics of different types of soil and rock also determined the suitability for housing by (co)determining degrees of dampness that could be expected. Alluvial plains, such as those found south of the Thames and to the east of the City of London, were identified as of particularly low amenity value. Sand, gravel and sandstone on the other hand was considered better, particularly in conjunction with elevation. Limestone, except in particular cases, was considered conducive to healthy living. Thirdly, the geological characteristics of soil and rock could affect the stability of the ground itself and thus the structural integrity of housing. Some types of clay for instance, would expand/contract with the seasons/precipitation patterns, resulting in movement of the ground (resulting in cracked walls and foundations). Other types of clay, was considered as giving good foundations.

Linking back to Brueckner et al (1999) and Evans (1973) it is clear that geological conditions were related to the perceived, and actual, amenity value of different locations, at least from the 19th century onwards. While the monocentric city model assumes that the demand characteristics of land are homogenous at different levels from the CBD, location theory based on natural amenity value suggests that demand is, also, conditioned by geological foundations that do not have any a priori specific distribution relative to the urban centre. Geologically conditioned environmental (and natural) amenities in turn may systematically condition modern and historic amenities that generate additional amenity value. In the following section the paper formally test the relationship between geological characteristics and modern property prices/social structures.
### Table 1 Geology and environmental amenity

<table>
<thead>
<tr>
<th>Description</th>
<th>Made soil</th>
<th>Alluvium/marshland</th>
<th>Gravel, sand and sandstone</th>
<th>Mixed soils</th>
<th>Clay (several)</th>
<th>Limestone/chalk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Made soil</td>
<td>Mixture of mould, gravel, and remnants of older buildings and rubbish. In parts of British cities the layer of made soil is quite substantial and can alter the soil mechanics of superficial soil deposits. At the beginning of the 20th century the layer of made soil could vary from 1-25 feet.</td>
<td>Considered as ‘essentially the property of the river’ (Woodward 1987/1906:11) and prone to flooding and rising water in cellars. Within modern London alluvium is particularly found in Enfield, Tottenham, Walthamstow, Hackney and West Ham along the Lea River and lower reaches of the Thames.</td>
<td>Gravel and sand was divided into 'plateau gravel' and 'valley gravel'. A key determinant of the suitability of these types of soil relates to elevation and permeability of the soil. Much of the London area is characterised by valley gravel and sand, but at different levels of elevation and different levels of thickness and thus not uniform in its health characteristics.</td>
<td>A varied range of mixed sandy, loamy and clayey formations are described.</td>
<td>Boulder clay (gritty clay with pebbles of chalk, flint, stones and fossils) to the north of London. Letchworth Garden city was situated on a layer of Boulder clay. London clay, on the other hand, was lower elevation and with greater water content, leaving the ground prone to long spells of dampness and cracking in spells of dry weather.</td>
<td>Described as porous (permeable) and low water supply. Due to the latter residential development had only commenced once public water services were provided to more elevated areas.</td>
</tr>
<tr>
<td>Environmental amenity</td>
<td>Characterised as ‘not always an unsatisfactory foundation for a house’. However, in pockets of London such soil contained decaying organic matter where gravel and sand had been removed and filled in with rubbish. The decaying of organic matter could then result in uneven settlement of the ground and development of methane gas (Leggett 1973).</td>
<td>Woodward remarked that ‘while the necessity of livelihood and calling require residence in [East Ham, Plaistow, Canning Town, Beckton, Silverton and North Woolwich], such areas are in general undesirable’ (1897/1906:13). According to Legget (1973) foundation strength and settlement is often difficult on floodplains, which often consist of low-strength soil with high groundwater levels.</td>
<td>Plateau gravel considered conducive to healthy living, whereas valley gravel might contain much water and caused dampness. Thin layers would be resting on the underlying London Clay strata. Artificial or manmade soil over gravel and sand beds, however, may provide additional elevation and insulation. A belt of hilly ‘Lower Greensand’ stretching through Surry and Kent was characterised ‘admirably adapted for healthy residences.’</td>
<td>Healthy conditions associated with elevation, permeability and the natural drainage capacity of the soil. Several parts of the South East are regarded as dry and healthy</td>
<td>Boulder clay was generally considered as providing a ‘good firm foundation’. London clay on the other hand was considered less favourable. Disadvantage diminished with elevation and drainage. Also artificial soil (on top of the clay) and buildings (paving, roofing) reduced exposure to rainfall and drying out the ground below London.</td>
<td>Except in very low-lying areas limestone/chalk was considered good sites for building and health living.</td>
</tr>
</tbody>
</table>

*Source: Woodward 1897/1906, unless otherwise stated.*
4 Estimating impact of geology on modern house prices and social structures

This section formally tests relevance of geological and topological features on modern property prices. Specifically the paper estimates a reduced from house price regression, where contemporaneous house prices are a function of access to labour markets (distance to CBDs/employment centres) and a range of geological, hydrogeological and topological features (Eq. 1):

\[ h_{pi} = \alpha_i + \beta_1 f_i + \sum_{j=1}^{m} \beta_j d_{ij} + \sum_{x=1}^{2} \beta_x t_{ix} + \sum_{y=1}^{5} \beta_y H_{iy} + \sum_{z=1}^{22} \beta_z G_{iz} + \epsilon_i \]  

(1)

where lower letters denote variables in log, \( i \) is an index of Medium Super Output Areas (MSOAs) in England, \( f \) is a measure of fertility, \( d_{ij} \) is a vector of \( j \) distance to CBD variables, \( t_{ix} \) is a vector of \( x \) typological variables, \( H_{iy} \) is a vector of \( y \) hydrogeological variables and \( G_{iz} \) is a vector of \( z \) geological (lithological) classifications. \( \epsilon_i \) is the error term.

Fertility (\( f \)) is the weighted average of an MSOA’s natural fertility (ranked 1 low to 5 high) sourced from Cranfield University’s Soilscape maps. \( \beta_1 \neq 0 \) would, depending on the direction, provide possible identification of path dependency or Matsuyama’s economic geography argument of industrialization.

The distance vector (\( d \)) is a multi-access measure of the monocentric city theory. Non-linear terms are included for distance to London and distance to one of 75 alternative employment centre – these are based on the 75 largest urban centres outside London (measured by urban footprint) in 2001. The number of distance measure (\( m \)) varies in estimation by functional form and regional estimations. The distance measures are based on author’s calculations using ArcGIS. Following standard urban economic theory/monocentric city model, distances to employment centres are expected to be negatively associated with price levels. The impact of including the exogenous determinants (\( H, G \)) on \( \beta_j \) provides a test of endogenously determined social structures. That is, if \( \beta_j<0 \) after controlling for \( H \) and \( G \) then social structures are a combination of endogenous (mono or polycentric) factors and exogenous factors.

The typology vector (\( t \)) contains distance from the MSOA’s centroid to the coast and elevation. Both variables are measured in meters and sourced from Lindley et al (2011).

The hydrogeology vector (\( H \)) contains measures of ground water in the soil. Data is sourced from British Geological Survey’s 1:625,000 Hydrogeology Map. For hydrogeology the percentage of an MSOA falling into one of four classifications is estimated using ArcGIS.

The geology vector (\( G \)) consists of 22 lithological main classes. These classes are combinations of a much larger set of lithological classes available from the British Geological Survey’s
The 1:625,000 DigMapGB-625 map. The geology map consists of bedrock and superficial formations related to their geological age. As the objective of the paper is not to access the impact of geological age, but rather the potential impact of geotechnical qualities on amenity value the two maps are combined to produce a single surface map of England. Lithological classes are further combined to assist identification. In combining the classes the paper loosely follows Woodward’s (1897/1906) approach and bases each of the classes around the first type of rock or soil listed in the lithological explanation of DigMapGB-625. The percentage of an MSOA falling into one of the 22 different classes was estimated using ArcGIS. For the purpose of this paper $\beta_z \neq 0$ tests whether the geology is systematically related to contemporaneous property prices.

A finding that $\beta_z \neq 0$ provides support for the key hypothesis of the paper – that geological determinants historically gave rise to systematic variation in land use. Such systematic variation in turn gave rise to particular spatially distributed social structures that may, due to longevity of housing stock and/or social interacts persist until the present day. In terms of mixed communities it further suggests that cities are not featureless plains – income inequality in a market based housing system thus enables some households to access more desirable housing. The aggregation of this process in turn generates spatial segregation. Rising income inequality intensifies this spatial sorting.

The approach used here differs from the conventional two main strands of the empirical literature on house price formation. The first of these, the macroeconomic perspective, attempts to explain aggregate movements in prices over time. The second of these models the prices of individual dwellings through hedonic analysis, where the prices of properties are related to their structural characteristics and those of the local neighbourhood. Hedonic models can thus be used to derive the implied willingness to pay for neighbourhood amenities as well.

The approach employed in this paper draws on the hedonic approach, but differs in important respects. Firstly, the prices are based on MSOA aggregates rather than individual properties. Secondly, characteristics of properties and neighbourhoods are deliberately excluded. The reason for this is that these characteristics are considered endogenous. That is, if evidence is found for the hypothesis then property and neighbourhood characteristics themselves are also conditioned by geology factors. Path dependency is tested by the inclusion of the fertility variable, however, as argued earlier this is not expected to be significant.

Table 2 summarises key results for England and for the north and south of England. The division of North and South is intended to capture the urban bias towards the south that existed in England in Roman and medieval times. This urban bias was conditioned by the greater availability of agriculturally fertile land in the south in a period where urban centres predominantly were centres of consumption, rather than production. The concentration of these functions evolved from Roman times onwards and experienced a significant shift during the industrialization of England.
### Table 2 Geology and HP for England, southern and northern regions combined

<table>
<thead>
<tr>
<th>Variable</th>
<th>England</th>
<th>England</th>
<th>South (robust se)</th>
<th>North (robust se)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ln London</td>
<td>-2.7046***</td>
<td>-3.3663***</td>
<td>-2.5597***</td>
<td>-4.4747***</td>
</tr>
<tr>
<td>Ln London^2</td>
<td>0.2489***</td>
<td>0.3015***</td>
<td>0.1908*</td>
<td>0.1863***</td>
</tr>
<tr>
<td>Ln London^3</td>
<td>-0.0082***</td>
<td>-0.0095***</td>
<td>-0.0048*</td>
<td></td>
</tr>
<tr>
<td>Ln second urban</td>
<td>0.0046</td>
<td>-0.8408**</td>
<td>-0.7798**</td>
<td>-2.4190***</td>
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**Note:** Ln (natural log), London is distance to London (meters), second urban is distance to second closest urban centre (meters), coast is distance to coast (meters), elevation is height above sea level (meters) PROD (aquifer productivity), fertility is a measure of natural fertility (min 1, max 5), CSS (clay, silt, sand, gravel) SUPER (superficial deposit), ALLUV (alluvial deposit), BR (bedrock). Remaining variables are lithographic classes of soil/rock. Omitted categories: NO GROUND WATER and SANDSTONE BR. Lower letters are measured in logs, coefficient are elasticities. Capital letters are measured in per cent, coefficients are semi-elasticities. Dependent variable is the log value of the average of median house prices 2005-2011 for MSOAs. */**/*** p=0.1/0.05/0.001. **Source:** See text for data sources.

In Eq (1) the monocentric city model is captured in the distance to urban centres measures. Column 2 in Table 2 shows the result of the monocentric city measures of Eq (1) only. The distance to London is highly significant, but the distance to secondary urban centres is not. For England as a whole distance to London explains some 46 per cent of the variation in median property values at MSOA level.

In its basic form the monocentric city model/declining price-distance gradients reflect locational attributes, declining land rents with distance from city centres and increasing per capita housing
consumption (Alonso 1964, Muth 1969). It also implies that the demand characteristic of land is entirely determined by distance, e.g. that all land at a given distance is equally attractive/unattractive. The amenity approach in Brueckner et al (1999) suggests that land at any given distance may not have homogenous demand characteristics, but that these are conditioned by modern as well as historic and natural amenities. Clearly for England, as a whole, additional factors are relevant.

As pointed out above, a criticism of the amenity approach is that social structures can be rationalised on the basis of hard to observe features (Duranton and Puga et al 2015). Here we argue that geology provides an observable determinant of these features and demand characteristics of different locations. Woodward’s analysis of geology and housing demand characteristics show that geology did constitute a relevant factor in the choice of location of building for different socio-economic groups, at least during the period of rapid urban growth of industrial Britain. In column 3 geology and topology are added as exogenous determinants of house prices and thus social structures.

Compared to the results in Column 2 the price-distance gradient to London becomes steeper and local price-distance gradients become significant. This has a number of implications. Firstly, if property prices reflected income and accessibility only then geological determinants should turn out to be insignificant, provided the latter is not systematically related to CBDs as well. In Column 3 this is not the case. Their inclusion increase the explanatory fit of the model. Secondly, the steepening of the price-distance gradient implies that accessibility remains central, indeed in the case of second employment centre it only now becomes central, but that the proximity is positively and negatively offset by factors unrelated to distance to CBDs. Waddell et al (1993) argue that such offsets may reflect lower quality of developments and neighbourhood characteristics. The argument in this paper is that geology, in part, conditioned the emergence of development quality and neighbourhood characteristics and so contributed to the creation micro-geographies of advantage and disadvantage. Although not tested in the Eq (1) persistence of such micro-geographies might be related to the longevity of housing stock, economies/diseconomies of scale (social interactions) and planning policies, each of which may be geologically and topologically conditioned, but also the enduring demand characteristics of geology and topology. The resulting social structures following the former represent examples of cumulative causation in the development of neighbourhoods and social structures. The latter, on the other hand and to the extent that they are not negated by technology, are factors that may remain attractive to modern homebuyers too. The associated social structures, then, are a result of income differences, rather than cumulative causation.

Geologically/topologically conditioned property and neighbourhood characteristics and enduring geological/topological demand characteristics imply that urban areas do not necessarily adjust to economic or institutional change in an easily predictable manner. The interaction of these with economic determinants (space-access) may result in longer periods of spatial stability and persistence in social structures, but also, seemingly discreet, periods of change.

In aggregate geology and typology improve the estimation of current property prices. Individually the variables in column 3 test the relationship between types of geological characteristics and property prices. Following from Woodward’s (1897/1906) analysis key
variables of interest are elevation and specific types of soil. Elevation is found to be positive and significant. Elevation increases the probability of attractive vistas and, for several types of soil, implied better drainage. The latter implied improved health value of location. Although incorrect, worries about miasma were also a health concern, at least until the mid 19th century. On a more prosaic level elevation provided some relief from other smells/stenches of concentrated populations. Sewage and rubbish removal became widely spread public services only towards the end of the 19th century and the organisation of local authorities. A 10 per cent increase in elevation is still associated with a 4 per cent increase in median property values. Although the smell/miasma concern may no longer be relevant, vistas and fresher air may still be attractive environmental amenities. Elevation is found to be significant for England as a whole and for the southern parts of England, but negative for northern parts of England. Compared to the southern part of England the northern part is substantially more mountainous and the variation in elevation is substantially higher. Northern cities are predominantly located in the lower lying areas. Elevation may here therefore capture more rural effects.

Woodward’s analysis of soil singled out the negative demand characteristics of alluvial deposits. In column 3 a number of clay deposits are included. The British Geological Survey contains a number of clay, silt and sand (CSS) based deposits. In order to identify the alluvial effect separately (as identified by Woodward) the different clay measures are kept separate (this differs from the other types of soil which are grouped according to their lead soil/rock type). For England as a whole there is a negative and significant effect of clay, silt and sand deposits. Some of the CSS measures are omitted due to collinearity northern region regression, but the alluvial CSS measure is negative and significant across each of the specifications. The coefficient implies that the median property value for an MSOA entirely located on alluvial clay is some 20-25 per cent less than the median property value of the reference category (sandstone bedrock). Alluvial CSS is consistently negative and significant across each of the specifications of Eq (1). This is also the case for Diamicton and gravel/sand deposits, also with negative effects, and felsic bedrock with a positive effect. Diamicton is a mixture of poorly-sorted sediments of undefined composition. The effect for Diamicton is somewhat smaller than that of alluvial CSS. Felsic bedrock is a volcanic rock (igneous rock). The effect for MSOAs entirely on felsic bedrock is large (20-60 per cent) compared to MSOAs entirely on sandstone bedrock.

The regression diagnostics in column 3 show that while there is no evidence of heteroscedasticity in the England regression, it fails the Ramsey reset test. The splitting of the sample into a southern and northern part thus also provides an additional specification robustness test. The diagnostics for the northern and southern regions, on the other hand, does suggest some heteroscedasticity. Robust standard errors are reported in column 4 and 5, but results should be interpreted with some caution. Distance to London remains relevant for the southern region, but is not found significant for the northern region and therefore dropped. Distance to second urban centre remains significant across both the southern and northern regions. The gradient, however, is steeper for the northern region, potentially signalling that locational advantages (in terms of the monocentric city theory) are more strongly offset by local housing market characteristics here than in the southern region.

There is some evidence that, while controlling for elevation, aquifer productivity/ground water is associated with lower property prices. This is especially the case for the areas with moderate
aquifer productivity, which has a consistent negative and significant effect. The overall effect aquifer productivity/ground water is, however, diluted by the opposing directions of the highly productive aquifer variable. This latter is positive for southern regions, but negative for northern regions.

For England as a whole and for the southern region clay, silt, sand and gravel based deposits are also associated with a negative effect on median property prices. Similarly, superficial clay deposits have a negative and significant effect in the southern region. There is no significant effect in the northern region where the CSS variable is omitted due to collinearity with the sandstone bedrock category and superficial clay has no significant effect. According to Woodward’s analysis of the health amenity of CSS and superficial clay a negative effect is expected when controlling for elevation.

Similarly, Woodward highlighted the positive health effects associated with (elevated) sand deposits and limestone formations. Both of these are significant for England as a whole – MSOAs entirely on these deposits have a median price some 10-30 per cent above the reference bedrock – but there is some variation between the southern and northern regions. The positive effect for limestone bedrock is particularly pronounced for the northern region, with no significant effect established for the southern region. Conversely, sand bedrock is significant for the southern region, but omitted due to collinearity from the northern region. Made soil was not found significant in the national level regression and subsequently dropped from estimation.

While geological and topological determinants may have amenity value that remains relevant in contemporaneous property markets – either directly through absence from flooding or geotechnical properties or indirectly through geologically conditioned systematic variation in land use that gave rise to historic and modern amenity value – fertility of land is not, a priori, expected to have a particular impact on current housing markets. A positive effect of fertility would indicate an extreme form of path dependence/hysteresis in property markets. A negative effect, on the other hand, would conform to the fundamentals of price determination, but might, as discussed earlier, also signal historical variation patterns of industrialisation due to land productivity differentials and increasing returns in manufacturing/industry development. For England as a whole there is a positive, but not significant effect of natural fertility. There is thus no evidence of fertility induced path dependency. When splitting the sample fertility remains positive, but not significant, for the northern region, but is negative and significant in the southern region. The south is, as discussed earlier, the location of greater concentrations of fertile land and it is feasible that higher agricultural productivity in the southern region inhibited industrialisation. Two effects need to be kept in mind here. The south generally has higher property prices than the north – this is an effect of closer proximity to London (the fertility effect is measured holding distance constant). Agricultural fertility may relate to later industrialisation within the region, rather than between the regions. To explore regional variation in greater detail Table 3 summarises the results for Eq (1) for each of the government office regions (GOR) for England.

Overall the general conclusions from Table 2 are confirmed by Table 3. Given that the geological variation declines as areas get smaller there is a larger number of omitted variables or collinear variables. The base soil in each of the regressions is sandstone bedrock. As before the
access to urban centre/monocentric city model remains highly relevant. At the GOR level, however, distance to London, is not always relevant or negative. Outside the South East and East of England distance to London varies in direction and strength of the relationship. Elevation is generally positive and significant. The exception here is the West Midlands where elevation is negative and significant. Outside London distance to coast tends to be positive. This suggests that it is the strong effect for distance to coast for London that determines the England level outcome in Table 2. Alluvial CSS is predominantly negative and significant, but no longer exclusively so. Clays and other CSS tend to confirm the southern-northern difference.

At the GOR level fertility also varies in direction and strength. The fertility effect is particularly strong for the South East GOR (and for London when controlling for x and y coordinates). In the remaining GORs it is either not significant or has a smaller positive or negative effect. Clearly, the impact of fertility requires further research, but it is feasible that, particularly in the South East, agricultural fertility (and the dominance of London) may have resulted in slower industrialisation in areas benefitting from high agricultural productivity. An inspection of the urban centres of a number of towns/cities shows that many historical places – Colchester (in the East of England GOR), Abingdon, Wallingford and Windsor – were located on highly productive land, whereas places like Reading, Newbury and Maidenhead were located on less fertile land.

Finally, the estimation at GOR level enables testing of the predominant wind hypothesis. This holds that areas that where the recipients of industrial smoke/smog were less attractive to higher income households (reduced amenity effect). If prevailing winds gave rise to systematic variation in land use or demand characteristics then property prices in London’s east and north east should have price discount. In London the dominant wind direction is south south-westerly. Column 3 in Table 3 includes x and y coordinates for London (the hypothesis can only be tested for London as other regions contain multiple urban centres). A negative effect on the x coordinate would imply lower prices in the east. A negative effect on the y coordinate would imply lower prices in the north. The estimations suggest that adding x and y coordinate significantly increase the explanatory power of the model – the r\(^2\) increases from 0.33 to 0.41. However, only the x coordinate has the expected negative sign. The y coordinate is positive (and significant, rather than negative. Property prices in the north of the city are thus higher than in the south of the city. Importantly the inclusion of x and y coordinates do not substantially affect the geology and topology variables. The negative price effect for alluvial CSS remains high (approximately 30 per cent), where as the elevation elasticity is marginally reduced. We cannot exclude thus reject the prevailing winds theory, but neither does the prevailing winds control affect the implied amenity value of geology and topology.

The estimates in Table 2 and Table 3 aggregate the average effects of geology across all of England or GORs. The London GOR, however, enables testing of geology in a single city. For England overall the inclusion of geological determinants raises the r\(^2\) by some 5 percentage points. However, the increase in r\(^2\) for London is nearly double at 9 percentage points (not shown). The impact of geology in Table 2 and 3 may thus be downward biased. The interactive effects of geological and economic determinants may also, then, be more significant in cities with greater geological variation.
Table 3 Geology and HP for government office regions (GOR)

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</tbody>
</table>

*Note and source: see Table 2. BP is Breusch-Pagan test.
The estimations in Table 2 and Table 3 suggest that geology plays a significant role in the emergence and persistence of social structures, but that the effects are complex and show little evidence of geological determinism. The economic dynamics of cities, as captured by distance to CBDs, dominate the results. In some cases expected gradients first emerge with the inclusion of geology though. This suggests that geological conditioned social structures continue to play a role in positively/negatively compensating for locational advantages/disadvantages. Persistence of such structures, especially where technology in practice renders the geological amenity less relevant, may reflect the role of social interactions, housing longevity and planning system in weakening the scope for spatial readjustment.

5 Concluding remarks

British urban policy has for some time encouraged the emergence of mixed communities. In policy terms mixed communities are considered beneficial for social cohesion/inclusion and vehicle for community and neighbourhood regeneration that, jointly or separately, may improve aggregate welfare. This paper asks whether geology affect the social structures of our cities? The discussion of historic geological studies suggests that geological characteristics historically affected demand characteristics of land. The analysis in this paper shows that, firstly, the distribution of property prices and the associated social and economic structures are dominated by standard access/centrality determinants. Nevertheless, and secondly, the estimation innovation, geology, is found to have a significant impact – although the ability to identify impact is constrained by the degree of geological and topological variation within urban areas. This implies, thirdly, that urban areas do not necessarily display or converge towards spatial equilibria in terms of more conventional neoclassical utility theory in a smooth or easily predictable process. Moreover, income elastic demand for geologically conditioned amenity means that the income distribution and inequality affects spatial mobility and location of labour in a manner not necessarily consistent with conventional notions of spatial efficiency.

Two models/theories of urban spatial structures formed the basis for the empirical testing of geology and topology on contemporaneous property prices. Both models – the monocentric city model and an amenity based residential location model – will, in the light of income differences and growing income inequality, result in spatial sorting. At the national level distance, geology and topology measures account for roughly half of the variation in median MSOA prices. The reduced form estimation only contains these measures as other variables, such as income, property and neighbourhood characteristics, are considered determined by the underlying geology. At regional and government office region level the explanatory power of the model falls to some 14-40 per cent.

The analysis shows a clear price discount for median property price of MSOAs on alluvial clay. This finding conforms to Woodward’s (1897/1906) analysis of the health amenities (demand characteristics) associated with different types of soil. Clays more generally, especially in the southern region, is associated with lower MSOA median property prices. Elevation is generally found to have a positive effect on median MSOA prices and again conforming to Woodward’s analysis.
Although not examined in this analysis the implication of geologically conditioned neighbourhood characteristics also means that neighbourhoods might be subject to cumulative causation – acting through a variety of channels (e.g. low demolition rates, planning, social interactions, increasing returns, external economies and diseconomies).

Cumulative causation is likely to lead to longer periods of stability, even under conditions of contextual economic change, in urban social structures and the micro geographies of advantage and disadvantage. Nevertheless, the interaction of geology/topology with economic processes will nevertheless subject social structures to periods of, seemingly, discrete change. Change may, for instance, occur in response to significant local disequilibria, where locational advantage/disadvantage is negated by the combined immediate and expected realisation of longer-term returns or where technology, such as building materials and technique, negate geologically conditioned amenity.

What is captured in geology and topology, then, are time-invariant demand characteristics as well as the origins of social structures and neighbourhood characteristics through cumulative causation that, in conjunction with wider urban economic processes, gave rise to present historic and modern amenities.
REFERENCES


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1 Evans (2004) also argues that property rights and ownership structures played an important part in the nature of residential construction.

2 For instance, many parts of the Holloway area in Islington towards Highgate Hill to the north of the City was initially developed for middle class residents by a number of Freehold Land Societies, but social decline set in in several streets due to uncoordinated development and lack of local amenities (Baggs et al 1985). In this case developments commenced in the 1850s and 1860s sometimes remained incomplete throughout the 1870s and 1880s. As a result resulted local amenities (e.g. street lighting) was not installed and streets remained unpaved (ibid). The incomplete nature of many estates rendered them in low demand and several were subsequently subdivided and rented out to lower income/working class families. In other streets detached housing was removed and replaced with terraced housing. The concentration of the latter subsequently resulted in social decline (ibid). Several streets with high concentration of poverty and vice in the 1930s had gone through similar stages of development (ibid).