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Testing the application and limitation of stochastic simulations to predict the lithology of glacial and fluvial deposits in Central Glasgow, UK

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ABSTRACT

Glacigenic and fluvial deposits of variable lithological composition underlie many major cities in Europe and North America. Traditional geological mapping and 3D modelling techniques rarely capture this complexity as they use lithostratigraphic designations which are commonly based on genesis and age rather than lithological compositions.

In urban areas, thousands of boreholes have been, and continue to be, drilled to facilitate the planning, design and construction of buildings and infrastructure. While these data may provide the basis for geological maps and 3D models based on lithological interpretation, they are too numerous for manual correlation to be undertaken efficiently. In this paper we explore the application of largely automated stochastic modelling techniques to develop predictive lithology models for glacial and fluvial deposits in the city of Glasgow, UK. These techniques are commonly used to assess facies variation in oilfield models and are applied here in an urban setting using over 4000 borehole records.

Predictions derived from these methods have been evaluated by removing control data and re-running the simulations. We demonstrate a moderate improvement in the prediction of lithology when using a lithologically-derived stochastic model compared with a conventionally interpolated lithostratigraphic model. It is possible to report uncertainty within the resulting models, either with probability maps or through a suite of plausible simulations of the lithologies across the study region.

1. Introduction

The growth and decay of high- and mid-latitude Pleistocene ice sheets have left 8% of the Earth's land surface, including one third of Europe and a quarter of North America, covered by glacigenic and fluvial deposits (Ehlers and Gibbard, 2004a, 2004b). These deposits underlie many major cities and much of their associated infrastructure networks, and exert a significant influence on the groundwater system. Increasing urban development, and its demands (e.g. suitable foundation conditions, the need for waste storage, contaminant migration, drainage re-routing) requires that information about subsurface glacial deposits, which are often highly lithologically variable across short distances, is available for those involved in planning and construction (Campbell et al., 2010). A key challenge for the three-dimensional (3D) geological modelling community is therefore to represent these subsurface deposits in appropriate ways across large, city-wide areas (Culshaw, 2005; MacCormack et al., 2005; Kessler et al., 2009).

In Glasgow, west central Scotland (Fig. 1), the British Geological Survey (BGS), in partnership with Glasgow City Council and other local authorities, have used extensive borehole datasets to develop and successfully apply a suite of 3D Quaternary lithostratigraphic models (Merritt et al., 2007; Campbell et al., 2010) (Fig. 2). A key strength of lithostratigraphic modelling is that it brings together the expertise of geologists and known geological relationships, enabling a geologically realistic representation, even where subsurface data are lacking (Kessler et al., 2009). However, owing to the complex and heterogeneous nature of glacial deposits (Hambrey, 1994; Meriano and Eyles, 2009; Benn and Evans, 2010), lithostratigraphic modelling may not always represent the full subsurface variability that is of direct relevance to end-users, such as ground engineers or groundwater modellers. Furthermore, this approach is time-consuming. For example, extending the same detailed lithostratigraphic modelling methodology that was used for Glasgow, to all UK cities would be highly protracted engaging considerable resources over a number of decades — too long to be of use to many current and planned urban redevelopment schemes. In this paper we explore a largely-automated facies-based stochastic modelling approach to investigate lithological variations within glacial and postglacial fluvial and marine deposits. Stochastic models can be used

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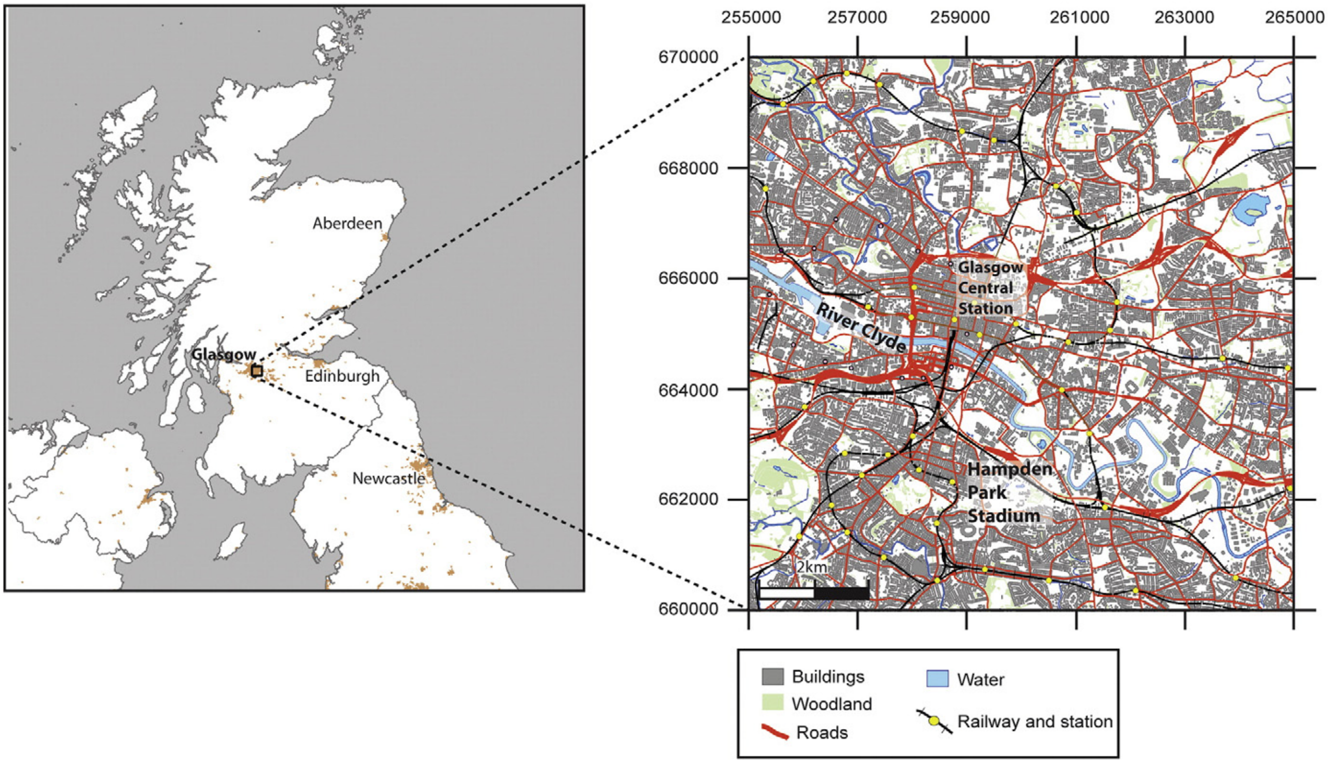

Fig. 1. Map of central Glasgow with area of this study. Grid show in British National grid (m) contains Ordnance Survey data © Crown copyright and database right 2014.

to produce multiple realisations of the lithological variation across the model domain. Rather than producing a single solution, this allows a wide-range of realisations. These multiple solutions can be used to generate lithology probability maps, which capture the lithological variation. In this way, stochastic simulation, as opposed to interpolation techniques, captures not only the most likely lithology at a given location, but also uncertainty within the simulations. This may be particularly beneficial if the lithological simulation is to be subsequently used to model the distribution of hydraulic or geotechnical parameters, as it allows for different scenarios to be modelled. From a ground engineering perspective, it is also useful because it can highlight areas in the model that are data poor and require further ground investigation.

Stochastic geological modelling owes its origins to the hydrocarbons industry, where it is widely used to characterise and simulate reservoir heterogeneity (Wach et al., 2004; Yarus and Chambers, 2006; Falivene et al., 2007). Rather than producing sharp boundaries between units, it allows lithologies to grade into each other which better captures the inter-fingered nature of heterolithic deposits. Central Glasgow is well suited for this type of approach, as more than 4000 geotechnical and lithological borehole logs are available to condition the simulation.

Our motivation is to test whether a lithology-based stochastic modelling approach can produce a geologically valid representation of subsurface lithological variation in a complex depositional environment affected by glaciation — typical of the Quaternary geology under many cities in North America and Northern Europe.

2. Research aims

Few studies have attempted to apply stochastic modelling to the lithology of terrestrial Quaternary deposits (c.f. Comunian et al., 2011). However, the technique has been demonstrated to be a valid and potentially successful approach in fluvio-deltaic sediments of the Netherlands (Stafleu et al., 2011). To our knowledge, the technique remains untested in a complex formerly glaciated environment affected by a combination of ice sheet oscillations, relative sea level changes and postglacial fluvial processes, such as occurred in Glasgow (Browne and McMillan, 1989; Finlayson et al., 2010). In this paper, and for the first time in the UK, we developed and tested a stochastic approach to modelling the distribution of complex Quaternary deposits at a city-wide scale. Our principal research goals are listed below.

1. Apply facies-based stochastic modelling methodologies to simulate the distribution of Quaternary deposits in central Glasgow.
2. Describe the basic characteristics of the model, and highlight the assumptions and the limitations of using a stochastic modelling approach.
3. Compare two different stochastic models with each other and the lithostratigraphic model by: i) removing a portion of the input boreholes and re-running the simulation to look at internal variance in the model (Haas and Formery, 2002; Scheidt and Caers, 2010); ii) evaluation of the model was also done by testing it against boreholes that were not used in the stochastic modelling (Browne and McMillan, 1989; Hall et al., 1998).
4. Offer recommendations as to the future applicability of the technique to other cities built in formerly glaciated environments.

3. Geological setting

The Glasgow conurbation, Scotland's most densely populated area, is located alongside the River Clyde in west central Scotland (Fig. 1). In the 19th and early 20th centuries, much activity in Glasgow (and surrounding areas) was based around mining and heavy industry (Browne et al., 1986). Subsequent industrial decline has left significant areas of dereliction, which have been the targets of a major 25-year regeneration plan (Campbell et al., 2010). It is recognised that future sustainable development in Glasgow requires an understanding of the nature and distribution of subsurface Quaternary deposits (Glasgow City Council, 2011). The present study focuses on a 100 km^2 area in central Glasgow (55.813°N–55.903°N; 4.157°W–4.319°W) (Fig. 1).