Multi-Scale Effective Flow Properties of Heterogeneous Mudstones*

Andrew C. Aplin[1], Gary D. Couples[2], Michael Drews[1], Kuncho D. Kurtev[1], and Jingsheng Ma[2]

Search and Discovery Article #120101 (2013)
Posted March 13, 2013

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG Hedberg Conference, Petroleum Systems: Modeling The Past, Planning The Future, 1-5 October 2012, Nice, France, AAPG©2012

[1]School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, UK (andrew.aplin@newcastle.ac.uk)
[2]Institute of Petroleum Engineering, Heriot Watt University, Edinburgh, UK

Abstract

Constraining the flow properties of mud-rich sediments is a multi-scale problem which involves the quantification of properties at a sample (10^{-2} m) scale in the laboratory and their use in the determination of effective properties at the log (10^{0} m) and seismic/basin modelling grid block (10^{2} m) scale. At the sample scale, we generally assume that samples are homogeneous and have compressibilities, permeabilities and threshold capillary pressures which are controlled mainly by lithology, defined, for example, by the proportions of clay, silt and sand. At larger scales, mud-rich sediments cannot be assumed to be homogeneous, so it is necessary to: (1) recognise the geometric arrangements at appropriate length scales; (2) construct models that capture these arrangements; (3) populate them with appropriate small-scale properties; and (4) run flow simulations from which it is possible to determine the effective properties at the target scale. This approach can be repeated at increasing length scales to derive upscaled properties at any scale that is needed in a simulation setting, such as in basin modelling. In the process of determining upscaled properties, knowledge is derived concerning which parts of the sedimentary and mechanical architecture exert critical controls on fluid flow up to and including that length scale.

Modelling of Genetic Units

Here, we consider how to define the flow properties of Genetic Units (GUs), i.e. seismically definable volumes of sediment which represent the results of deposition in a particular setting, and which could readily be represented by cells within a basin model. Our focus has been on those GUs common within continental slope environments such as hemipelagites, mud turbidites and mass transport deposits. We divide the GUs into background and foreground units, in which background units comprise metre-scale, relatively low permeability, mud-rich sedimentary facies, and foreground units that include the higher permeability flow conduits which could be either depositional in nature (e.g. thin sands within a levee) or which could cross-cut the stratigraphy as a result of sand injection or mechanical deformation. The resulting combination of background and foreground elements defines the effective flow properties of any GU of given character; alternatively the approach allows us to define a small set of pre-determined templates which could be used to generate a look-up database from which one could populate a basin model.

In terms of metre- (log-) scale background units, the first step is to constrain the compressibility, permeability and threshold Capillary Entry Pressure (CEP_t) of sample- (cm-) scale sediments as a function of lithology (e.g. sand/silt/clay ratio), often with information from the public domain. A second step involves the definition of a manageable number of heterogeneous mudstone facies (or texture types) for which metre-scale flow properties can be realistically derived and which can be related to the hydrodynamic or immediate post-depositional deformation energy of the depositional environment. Our choice of facies (Figure 1) is based on observations of hundreds of metres of slope sediment core and micro-resistivity logs and aims to capture the critical heterogeneities which control both lateral and vertical fluid flow. Geostatistical methods are used to characterise the spatial arrangements of each of the facies/texture types. Metre-scale stochastic reproductions of the rock based on the geostatistical parameters enable us to distribute lithological types (e.g. grain size proportions), and thus permeability values, at several values of effective stress, across a 2D or 3D grid, creating a range of realisations of each of the fine-grained sediment types. A finite element method is then used to simulate fluid flow through the resulting metre-scale models (here using the 2D realisations), resulting in the computation of both vertical and horizontal effective permeabilities, and their stochastic variations, at effective stresses between 5 and 30 MPa.

CEP_t values were estimated on the same – but in this case, 3D – stochastic 1 m^3 textural models. Each cell is assigned a clay content and we can then determine the connected path of lowest clay content through the model, and thus, given a relationship between clay content and sample CEP_t, the effective CEP_t of the whole volume. Alternatively, each cell can be assigned a capillary entry pressure and the effective capillary pressure of the 1 m^3 volume can be estimated using a percolation model such as MPath.

Results indicate that at a single porosity (e.g. effective stress), the range of potential column heights retained by these facies varies by a factor of two, and the petroleum saturations required to breach the mudstone facies range from < 1% to > 20%. Permeabilities of the facies vary by more than three orders of magnitude and – as expected – laminated and lenticular facies are highly anisotropic.

At a larger length scale (10^2 m+), slope sediments may exhibit well-defined depositional layering, such as occurs in levee and hemipelagite deposits. Here we illustrate the upscaling approach applied to these layered GU types, where higher-permeability layers occur at frequencies determined from the open literature and public databases. Models are constructed by superposing foreground elements onto a chosen background comprising materials whose properties are taken from the metre-scale results described above. To account for depositional scour-fill arrangements (which impact the vertical connectivity), or deformation features (such as sand-filled injectites or fractures), additional foreground elements can be superposed onto any model configuration (Figure 2).

Conclusions

This approach allows us to calculate the effective (upscaled) permeabilities of these layered GUs. If the muddy background elements are of the massive or laminated types, the upscaled properties can be described as a simple relationship governed by the ratio of the foreground to background permeabilities, with little stochastic variance. If the background consists of the more chaotic types, or if there are vertical flow connections, these aspects lead to larger vertical effective permeabilities, but the values are only about two orders larger than in the case with the simple background and no vertical features. Work is underway on upscaling the CEP_t for these GUs.

In order to use these results in basin modelling, the model-builder needs to choose upscaled effective properties from the set of results that fits the geology of that case. A simple flow chart makes this practical, if data exist that permit a robust interpretation (of depositional setting, and the characteristics of the muddy facies). In the situation where data are sparse, the upscaled results provide bounds that can be used to assess the range of basin modelling outcomes that are related to the interpretation uncertainty.

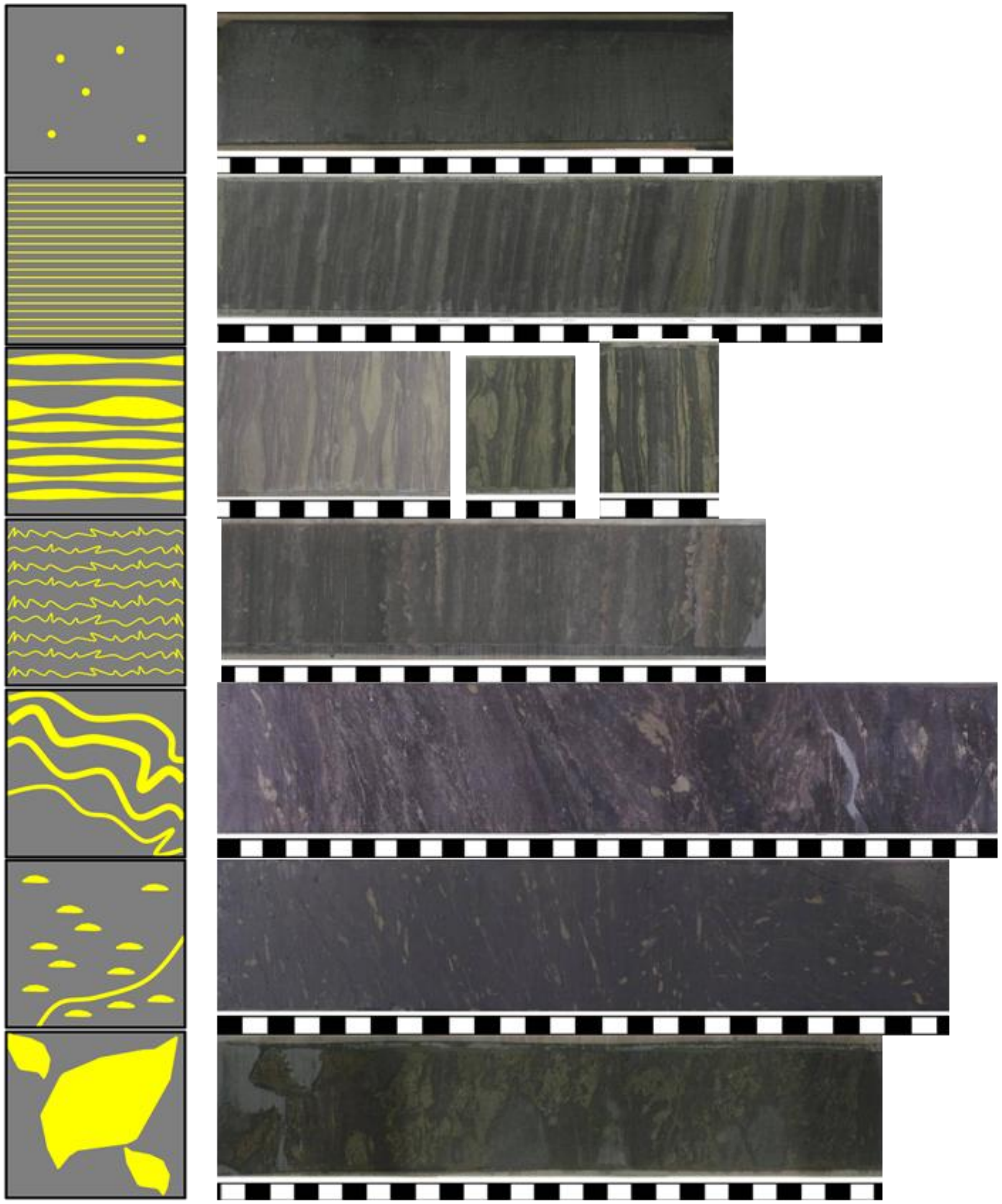

Figure 1. Cartoon mudstone facies and examples from core. In the cartoons, yellow indicates coarser grained areas. From top to bottom: massive, laminated, lenticular/reworked, minor slumped, major slumped, small scale chaotic and large scale chaotic.

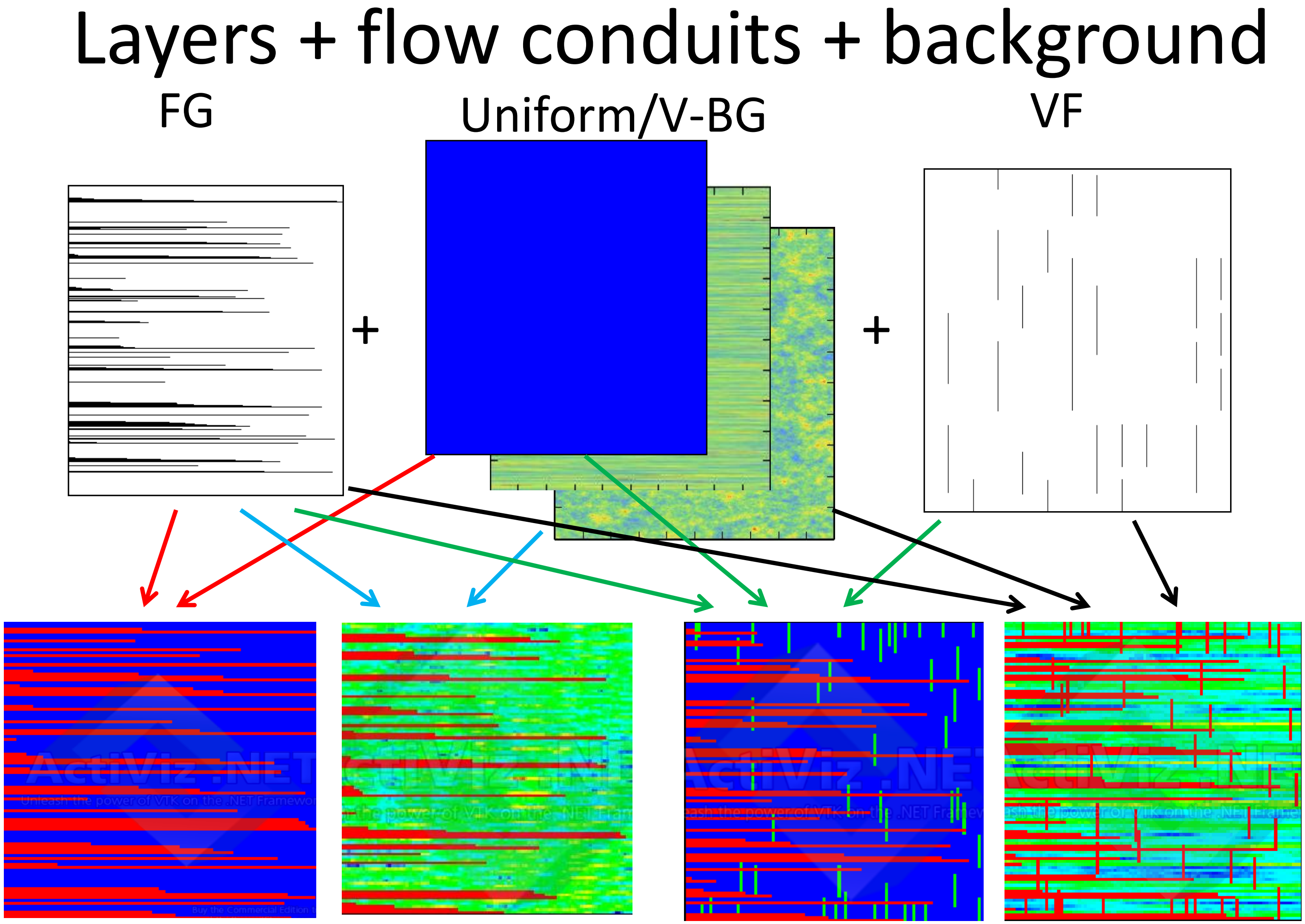

Figure 2. Illustration of the model-building possibilities using a foreground (FG) distribution (left), a background (BG) type (middle), and vertical features (VF, right).