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Review article

An integrated and quantitative approach to petrophysical heterogeneity

Peter J.R. Fitch [a,*], Mike A. Lovell [b], Sarah J. Davies [b], Tim Pritchard [c], Peter K. Harvey [b]

[a] Department of Earth Science and Engineering, Imperial College London, London, United Kingdom
[b] Department of Geology, University of Leicester, Leicester, United Kingdom
[c] BG Group, 100 Thames Valley Park, Reading, United Kingdom

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ABSTRACT

Exploration in anything but the simplest of reservoirs is commonly more challenging because of the intrinsic variability in rock properties and geological characteristics that occur at all scales of observation and measurement. This variability, which often leads to a degree of unpredictability, is commonly referred to as "heterogeneity", but rarely is this term defined. Although it is widely stated that heterogeneities are poorly understood, researchers have started to investigate the quantification of various heterogeneities and the concept of heterogeneity as a scale-dependent descriptor in reservoir characterization.

Based on a comprehensive literature review we define "heterogeneity" as the variability of an individual or combination of properties within a specified space and/or time, and at a specified scale. When investigating variability, the type of heterogeneity should be defined in terms of grain – pore components and the presence or absence of any dominant features (including sedimentological characteristics and fractures). Hierarchies of geologic heterogeneity can be used alongside an understanding of measurement principles and volumes of investigation to ensure we understand the variability in a dataset.

Basic statistics can be used to characterise variability in a dataset, in terms of the amplitude and frequency of variations present. A better approach involves heterogeneity measures since these can provide a single value for quantifying the variability, and provide the ability to compare this variability between different datasets, tools/measurements, and reservoirs. We use synthetic and subsurface datasets to investigate the application of the Lorenz Coefficient, Dykstra–Parsons Coefficient and the coefficient of variation to petrophysical data – testing assumptions and refining classifications of heterogeneity based on these measures.

1. Introduction

Petrophysics is the study of the (physical and chemical) rock properties and their interactions with fluids (Tiab and Donaldson, 1996). We can define a number of petrophysical properties, for example porosity, saturation, and permeability, and many of these depend on the distribution of other properties such as mineralogy, pore size, or sedimentary fabric, and on the chemical and physical properties of both the solids and fluids. Consequently petrophysical properties can be fairly constant throughout a homogeneous reservoir or they can vary significantly from one location to another, in an inhomogeneous or heterogeneous reservoir. This variation would be relatively easy to describe if petrophysical analysis was only applied at a single scale and to a constant measurement volume within the reservoir. While many petrophysical measurements are typically made in the laboratory at a core plug scale (cm) or within the borehole at a log scale (m), fluid distribution is controlled at the pore scale (nm to mm) by the interaction of fluids and solids through wettability, surface tension and capillary forces, at the core scale by sedimentary facies, fabrics or texture (mm to m), and at bed-to-seismic scales by the architecture and spatial distribution of geobodies and stratigraphic elements (m to kms). Note we use the words fabric and texture here to indicate generic spatial organisation or patterns. At each scale of measurement various heterogeneities may exist, but it is important to note that a unit which appears homogeneous at one scale may be shown to be

* Corresponding author. Tel.: +44 (0)20 7594 9521.
E-mail address: p.fitch@imperial.ac.uk (P.J.R. Fitch).

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heterogeneous at a finer-scale, and vice versa. Clearly, as more detailed information is obtained, reservoir characterisation and the integration of the various data types can become increasingly complex. It is important to fully understand the variability and spatial distribution of petrophysical properties, so that we can understand whether there is any pattern to the variability, and appreciate the significance of simple averages used in geologic and simulation modelling. This is especially true in the case of complex hydrocarbon reservoirs that have considerable variability. Carbonate reservoirs often fall into this category, and the term heterogeneous is often used to describe a reservoir that is complex and evades our full understanding. Indeed, an early definition states heterogeneous as meaning extraordinary, anomalous, or abnormal (Oxford English Dictionary; Simpson and Weiner, 1989).

Most, if not all, of the literature on reservoir characterisation and petrophysical analysis refers to the heterogeneous nature of the reservoir under investigation. Heterogeneity appears to be a term that is readily used to suggest the complex nature of the reservoir, and authors often assume the reader has a pre-existing knowledge and understanding of such variability. No single definition has been produced and consistently applied. Researchers have started to investigate the quantification of various heterogeneities and the concept of heterogeneity as a scale-dependent descriptor in reservoir characterization (Frykman, 2001; Jennings and Lucia, 2003; Pranter et al., 2005; Westphal et al., 2004).

Here we review what heterogeneity means, and how it can be described in terms of geological attributes before discussing how the scale of geological heterogeneity can be related to the measurement volumes and resolution of traditional subsurface data types. We then discuss using a variety of statistical techniques for characterising and quantifying heterogeneity, focussing on petrophysical heterogeneities. We focus here on the principles and controls on the statistics and measures, before applying these to real reservoir data in four case studies. In doing so, we consider approaches used in a range of scientific disciplines (primarily the environmental sciences and ecology) to explore definitions and methods which may be applicable to petrophysical analysis. These statistical techniques are then applied to reservoir sub-units to investigate their effectiveness for quantifying heterogeneity in reservoir datasets.

2. Defining heterogeneity

Heterogeneity refers to the quality or condition of being heterogeneous, and was first defined in 1898 as difference or diversity in kind from other things, or consisting of parts or things that are very different from each other (Oxford English Dictionary; Simpson and Weiner, 1989). A more modern definition is something that is diverse in character or content (Oxford Dictionaries, 2014). This broad definition is quite simple and does not comment on the spatial and temporal components of variation, nor does it include a consideration of directional dependence, often referred to as isotropy and anisotropy. Other words or terms that may be used with, or instead of, heterogeneity include; complexity, deviation from a norm, difference, discontinuity, randomness, and variability.

Nurmi et al. (1990) suggest that the distinction between homogeneous and heterogeneous is often relative, and is based on economic considerations. This highlights how heterogeneity is a somewhat variable concept which can be changed or re-defined to describe situations that arise during production from a reservoir, and is heavily biased by the analyst's experience and expectations. Li and Reynolds (1995) and Zhengquan et al. (1997) state that heterogeneity is defined as the complexity and/or variability of the system property of interest in three-dimensional space, while Frazer et al. (2005) define heterogeneity, within an ecological model, as variability in the density of discrete objects or entities in space. These definitions suggest that heterogeneity does not necessarily refer to the overall system, or individual rock/reservoir unit, but instead may be dealt with separately for individual units, properties, parameters and measurement types.

Frazer et al. (2005) commented that heterogeneity is an inherent, ubiquitous and critical property that is strongly dependent on scales of observation and the methods of measurement used. They studied forest canopy structure and stated that heterogeneity is the degree of departure from complete spatial randomness towards regularity and uniformity. This may seem, at first, counterintuitive because heterogeneity is commonly regarded as being complete spatial randomness. Here, the introduction of regular features, such as bedding in a geological context, adds to the heterogeneous nature of the formation in a structured or anisotropic manner. Nurmi et al. (1990) suggest that heterogeneity, in electrical borehole images, refers to elements that are distributed in a non-uniform manner or composed of dissimilar elements/constituents within a specific volume. Therefore, as well as looking at a specific element or property, it is also suggested that the volume of investigation influences heterogeneity, alluding to the scale-dependence of heterogeneities. Interestingly, Dutilleul (1993) comments that a shift of scale may create homogeneity out of heterogeneity, and vice-versa, and suggests that heterogeneity is the variation in density of measured points compared to the variation expected from randomly spread points. In a discussion of the relationship between scale and heterogeneity in pore size, Dullien (1979) suggests that to be a truly homogeneous system random subsamples of a population should have the same local mean values. Lake and Jensen (1991) provide a flow-based definition in their review of permeability heterogeneity modelling within the oil industry. In this latter case, heterogeneity is defined as the property of the medium that causes the flood front to distort and spread as displacement proceeds; in this context the medium refers to the rock, and fluid front is the boundary between displacing and displaced fluids. Thus many authors provide the foundation in which we begin to see that heterogeneity may be a quantifiable term.

Pure homogeneity, with regard to a reservoir rock, can be visualised in a formation that consists of (1) a single mineralogy with (2) all grains of similar shapes and sizes with (3) no spatial organization or patterns present; in this example, similar grain shapes and sizes, together with lack of spatial patterns would lead to a uniform distribution of porosity and permeability. Therefore, ignoring the scalar component of heterogeneity for a moment, there are two contrasting examples of heterogeneity in a reservoir rock (Fig. 1). The first example is a formation of consistent mineralogy and grain characteristics that has various spatial patterns (for example bedding, foresets, syn-sedimentary faulting, or simply grain packing). The second example has no spatial organisation (it is massive) but has variable mineralogy and grain size and shape, i.e. it is a poorly sorted material. Both are clearly not homogeneous but which has the stronger heterogeneity? Quantifying the degree of heterogeneity would enable these two different systems to be differentiated from each other, and in turn these values may be related to other characteristics such as reservoir quality. In attempting to quantify heterogeneity we can consider several approaches. It is probably best, however, to start by defining the degree of heterogeneity in relation to the nature of the investigation; for example in a study of fluid flow, sedimentological structures may be of more importance than variation in mineralogy. In contrast in an investigation of downhole gamma ray variability the mineralogical variability (or strictly chemical variability of potassium, thorium and uranium) would be more relevant than any spatial variation.