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D.C.P. Peacock, M.W. Anderson, A. Rotevatn, D.J. Sanderson, E. Tavarnerelli



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## The interdisciplinary use of “overpressure”

D.C.P. Peacock<sup>1\*</sup>, M.W. Anderson<sup>2</sup>, A. Rotevatn<sup>1</sup>, D.J. Sanderson<sup>3</sup> and E. Tavarnelli<sup>4</sup>

<sup>1</sup> Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway

<sup>2</sup> School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth  
PL4 8AA, UK

<sup>3</sup> Engineering and the Environment, University of Southampton, Highfield, Southampton,  
SO17 1BJ, UK

<sup>4</sup> Dipartimento di Scienze Fisiche della Terra e dell’Ambiente, Università di Siena, I-53100,  
Siena, Italy

\* Corresponding author. E-mail: hermangedge@gmail.com

### Abstract

*Overpressure* is a polysemic word that has a variety of meanings within and across different disciplines. This is likely to be a particular problem in analysis of geothermal resources, where reservoir engineers, volcanologists and structural geologists may each confidently use *overpressure* but mean different things. We suggest that, to avoid confusion, the term should be carefully and accurately defined whenever used. We also suggest that other, less ambiguous terms be used, such as *supra-hydrostatic fluid pressure* when fluid pressure exceeds that expected in a column of water at that depth, and *supra-lithostatic fluid pressure* for the situation in which fluid pressure exceeds the overburden.

**Keywords:** overpressure; polyseme; structural geology; volcanology; geothermal

## Introduction

Fluid pressure and especially *overpressure* are important for a wide variety of reasons, including the following:

- Accurate prediction and measurement of fluid pressures can be critical for the safe and successful drilling of hydrocarbon and other wells (e.g. Taras'ev and Simkin 1969; Gaarenstroom et al., 1993). For example, *overpressure* is related to sediment remobilisation (e.g. Jolly and Lonergan, 2002), seal risk and breaching of hydrocarbon traps (e.g. Ingram and Urai, 1999), fluid-pressure driven deformation (e.g. Cartwright, 1994), and to the danger of blowout during drilling (e.g. Hickman et al., 2012).
- *Overpressure* is important in controlling volcanism (e.g. Fudali and Melson, 1971) and emplacement of igneous intrusions (e.g. Kusumoto et al., 2013a).
- Pore fluid pressure ( $P_F$ . See Table 1 for symbols used) plays a critical role in many structural processes. For example, Hubbert and Rubey (1959) argue that thrust sheets slide on layers of overpressured fluids that reduce friction.
- Overpressured fluids have been cited as contributing to earthquakes (e.g. Blanpied et al., 1992).

In spite of their importance, terms relating to fluid pressure and *overpressure* are commonly used differently within and between disciplines. We argue that *overpressure* is now so polysemic that it must be carefully and accurately defined whenever used to avoid confusion, especially in such interfaces between disciplines as the analysis of geothermal resources. Socrates is quoted as having said that “the beginning of wisdom is the definition of terms” (e.g. Hollingsworth, 2015). The philosophy that the terms used must be carefully defined and precisely used has been a foundation of academic research.

$\sigma_3$	Least compressive stresses
$\sigma_V$	Vertical stress, also called lithostatic stress or overburden
$P_F$	Pore fluid pressure
$P_H$	(Hydrostatic) fluid pressure of an equivalent free column of water
$P_M$	Magma pressure
$P_O$	“Magma overpressure” (Elshaafi and Gudmundsson, 2016)
$P_{\text{FRACT}}$	Fracture pressure, in which $P_F > \sigma_3 + \text{rock strength}$
$\rho_R$	Host rock density
$\rho_M$	Magma density
$g$	Acceleration due to gravity
$h$	Depth
$\sigma_D$	Differential stress at the level of interest
$\sigma'$	Effective stress ( $\sigma - P_F$ ) (e.g. Hubbert and Rubey, 1959)
$\sigma'_3$	Least effective stress

**Table 1.** Symbols used in this paper.

The aims of this paper are to show some of the different uses and definitions used for *overpressure*, to usage, and to suggest more precise terms for certain *overpressure* conditions. The aim is not to give an account of fracture mechanics, including the relationships between fluid pressure and fractures, which is dealt with in various textbooks (e.g. van der Pluijm and Marshak, 2010; Fossen, 2012). The aims of this paper are to discuss and clarify the different uses of *overpressure*.

### **Different uses of *overpressure***

This section illustrates the variety of uses to which the term *overpressure* is applied.

#### *General definitions of overpressure*

*Overpressure*, in this context, is defined by the Oxford English Dictionary (Simpson and Weiner, 1989) as “the difference between the (highest) instantaneous pressure at a point subjected to a shock wave and the ambient atmospheric pressure”, with first usage credited to Goldstine and Von Neumann (1955). Similarly, *overpressure* is defined by the Merriam-Webster Dictionary (<http://www.merriam-webster.com/dictionary/overpressure>) as “pressure significantly above what is usual or normal”. Whilst these appear to be precise and useful definitions, they are vague enough to have been used in different ways by different researchers.

#### *Use of overpressure outside of geosciences*

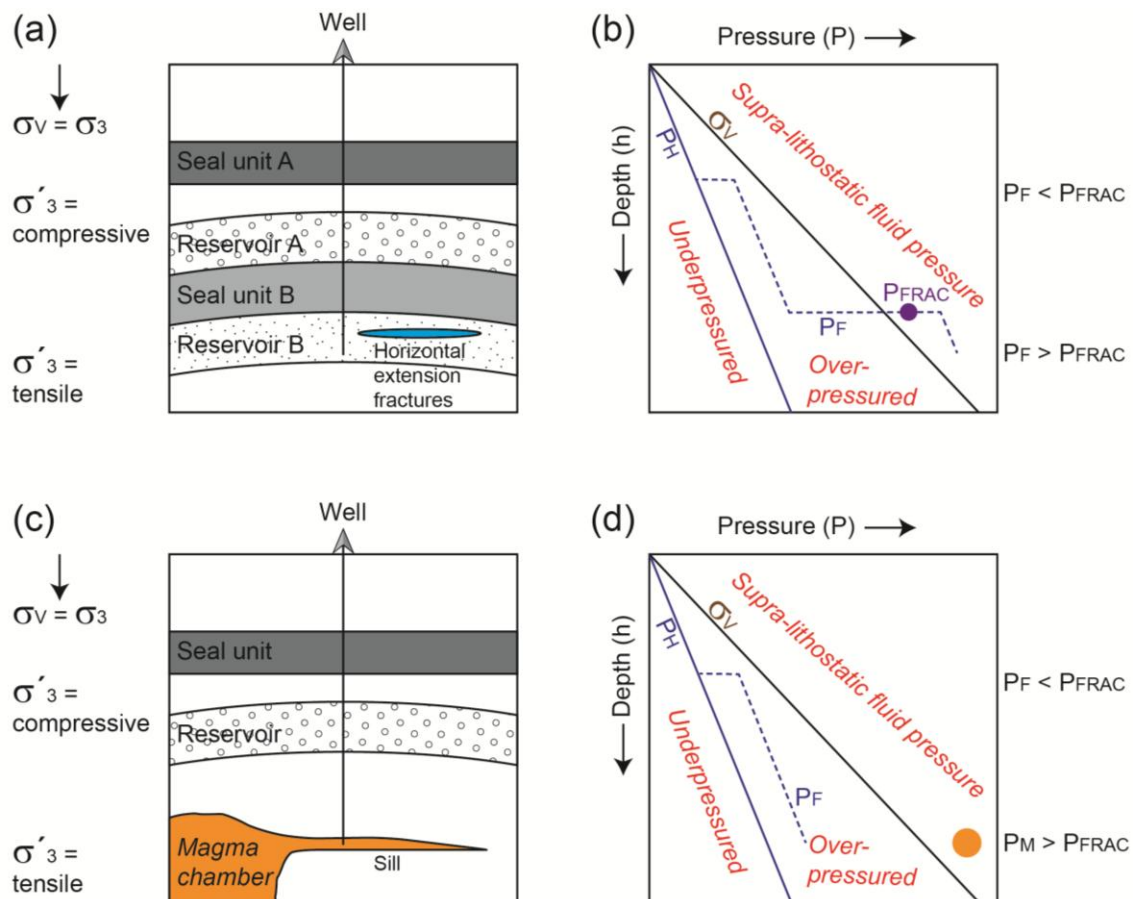
The word *overpressure* is used in a wide range of disciplines, including acoustics (e.g. Sapozhnikov et al., 2002), aerospace science (e.g. Hammitt, 1961), astronomy (e.g. Jog and Das, 1992), biology (e.g. de Rycke, 1966), education (e.g. Robertson, 1972), engineering (e.g. Selig et al., 1960), medical sciences (e.g. Harpöth and Gad, 1938; Mayorga, 1997), physics

and chemistry (e.g. Potts and Pearson, 1966) and psychology (e.g. Bateman, 1896-7; Rubin et al., 2014). We do not give definitions of *overpressure* as used in each of these subject areas, but present these examples simply to illustrate the variety of situations in which the word is used.

#### *Overpressure in the hydrocarbon industry*

The importance of *overpressure* is reflected in its consistent usage in the hydrocarbon industry, where *overpressure* is defined as the condition in which  $P_F$  exceeds the value that would be expected for that depth in a water column, i.e. above hydrostatic pressure ( $P_H$ , e.g. Fertl and Chilingarian, 1989; Caillet et al., 1997; Swarbrick and Schneider, 1999; Yardley and Swarbrick, 2000; Bowers, 2002; Bjørlykke et al., 2010) (Figure 1a). The situation in which  $P_F$  is sufficient to cause fracturing is commonly termed *fracture pressure* ( $P_{FRAC}$ ) (e.g. Morgenstern, 1962; Swarbrick and Lahann, 2016). This is commonly inferred to be the situation in which  $P_F$  exceeds the least compressive stress ( $\sigma_3$ ) plus rock strength.  $P_{FRAC}$  is commonly estimated in wells by leak-off tests (e.g. Couzens-Schultz and Chan, 2010). The fluids measured can be water, oil or gas, and these can occur in pore spaces and in fractures.

*Overpressure* can develop within sediments that are compacted during burial, as thermal expansion occurs, and as hydrocarbons are generated (e.g. Cobbold et al., 2013; Lahann and Swarbrick, 2011). *Overpressure* can also develop during uplift and erosion events as vertical stress ( $\sigma_v$ ) is reduced but  $P_F$  is maintained (e.g. Doré and Jensen, 1996; Corcoran and Doré, 2002). *Overpressure* is particularly likely to develop within sands that are compartmentalised by faults and impermeable shales (e.g. Bredehoeft et al., 1988).



**Figure 1.** Schematic diagrams of fluid pressure, illustrating some of the different potential uses of *overpressure*. In these examples, the least compressive stress is vertical ( $\sigma_3 = \sigma_v$ ). (a) Schematic cross-section showing a well penetrating two seal units and two hydrocarbon reservoirs. (b) Graph of depth versus pressure for Figure 1(a). In reservoir A,  $P_H < P_F < \sigma_v$ , so the reservoir is overpressured, but is below the fracture pressure ( $P_{FRAC}$ ). In reservoir B,  $P_H < \sigma_v < P_F$ , so it is both overpressured and supra-lithostatically pressured.  $P_F > P_{FRAC}$ , leading to the development of extension fractures. (c) Schematic cross-section showing a well penetrating a seal unit, a hydrocarbon reservoir and a sill. (d) Graph of depth versus pressure for Figure 1(c). In reservoir A,  $P_H < P_F < \sigma_v$ , so is overpressured, but is below the fracture pressure ( $P_{FRAC}$ ). At the sill,  $P_H < \sigma_v < P_M$ , and  $P_M > P_{FRAC}$ , leading to sill propagation.



*Overpressure in volcanology*

Most commonly, magma or related gasses are the fluids of interest in the subject of volcanology, these occurring in magma chambers or other intrusions. In spite of the importance of *overpressure*, the term appears to be used in various different ways in the discipline of volcanology (e.g. within papers published in the Journal of Volcanology and Geothermal Research, including: Fudali and Melson, 1971; Melnik et al., 2005; Davies et al., 2011; Kusumoto et al., 2013a; Elshaafi and Gudmundsson, 2016). For example:

- Kusumoto et al. (2013a) define *overpressure* as the magmatic pressure in a dyke minus the least principal compressive stress ( $\sigma_3$ ) acting on the dyke walls.
- Elshaafi and Gudmundsson (2016) define *magma overpressure* ( $P_O$ ) in a dyke as:

$$P_O = (P_M - \sigma_V) + (\rho_R - \rho_M) g h - \sigma_D$$

where  $P_M$  = magma pressure,  $\rho_R$  = host rock density,  $\rho_M$  = magma density,  $g$  = acceleration due to gravity,  $h$  = depth, and  $\sigma_D$  = differential stress at the level of interest (Table 1). This *appears* to imply the conditions under which the magma exceeds  $\sigma_3$ , leading to sill propagation if  $\sigma_3$  is sub-vertical, or dyke propagation if  $\sigma_3$  is sub-horizontal. This can approximate to  $P_{FRAC}$ , as used in the hydrocarbon industry (Figure 1b).

- *Overpressure* is widely used to mean gas pressures that are high enough to cause explosive volcanic eruptions (e.g. Fudali and Melson, 1971; Melnik et al., 2005; Burgisser et al., 2011), or even trigger earthquakes (Giammanco et al., 2008).
- *Overpressure* is apparently used by Trasatti et al. (2005) to indicate fluid pressures above typical hydrostatic pressures, which would be similar to its usage in the hydrocarbon industry (e.g. Caillet et al., 1997; Swarbrick and Schneider, 1999; Yardley and Swarbrick, 2000; Bowers, 2002; Bjørlykke et al., 2010).

- Some of the literature on mud volcanoes appears to use *overpressure* in the same way as the hydrocarbon industry and structural geology (e.g. Davies et al., 2011), i.e. when  $P_F > P_H$ .
- Some authors use, and even model, *overpressure* without a clear definition (e.g. Hautmann et al., 2009; Mazzini et al., 2009; Shirzaei et al., 2013; Kavanagh et al., 2015).

Use of *overpressure* in volcanology is therefore much less consistent than usage in the hydrocarbon industry.

#### *Overpressure in structural geology*

Any fluid in rock may be of interest in structural geology, including water, hydrocarbons, CO<sub>2</sub> and magma. These fluids may occur in pore spaces, fractures or in other spaces in rock. *Overpressure* is predominantly used within structural geology (e.g. as published in Tectonophysics and the Journal of Structural Geology) in the same way as in the hydrocarbon industry. *Overpressure* is thus defined as the condition in which  $P_F > P_H$ , i.e. it exceeds the hydrostatic pressure of an equivalent free column of water (e.g. Bolton et al., 1998; Sibson, 2004; Mourgues and Cobbold, 2006; Mazzarini and Isola, 2007; Lacoste et al., 2011, fig. 1; Lacoste et al., 2012; Cobbold et al. 2013; Suppe, 2014; Mourgues et al., 2016) (Figure 1a). Less formally, however, structural geologists may *infer* that *overpressure* existed during deformation by the occurrence of such structures as horizontal veins, which form when  $P_F$  exceeds the vertical stress ( $\sigma_V$ ), showing that  $P_F > P_H$  (e.g. Stoneley, 1983; Hillier and Cosgrove, 2002; Tavarnelli et al., 2004). This inference does not, however, mean that *overpressure* is actually defined as the condition in which  $P_F > \sigma_V$ . Some authors use the term “driving pressure” to mean  $P_{FRAC}$  (e.g. Pollard and Johnson, 1973; Renshaw and Pollard, 1994), and the importance of differential stress is acknowledged (e.g. Cox. 2010)...

Definitions used in volcanology (e.g. Kusumoto et al., 2013a) sometimes get used in the structural geology literature. For example, Gudmundsson et al. (2012) define *overpressure* as “the difference between the total fluid pressure inside the fracture and the normal stress at that point” (also apparently used by Kusumoto et al., 2013b).

#### *Two fundamental uses of the term “overpressure”*

There therefore appear to be two fundamental differences in the usage of the term *overpressure*:

1. As a limit or threshold above which some physical change takes place, such as dyke opening or explosive volcanism.
2. As a measure of how much a pressure (stress) exceeds a standard value, such as hydrostatic or lithostatic stresses.

In both cases, there is a need to define the usage precisely and to use more precise, less ambiguous terms (see below).

#### **Geothermal energy as an example of the need for precise terminology**

The exploitation of geothermal energy in volcanic regions means that reservoir engineers, volcanologists and structural geologists will tend to need to collaborate. As with the hydrocarbon industry, safe and successful drilling of geothermal wells requires prediction and measurement of  $P_F$ , but in this case perhaps including  $P_M$ , so scientists from the different disciplines require a common understanding of what is meant by *overpressure*. Reservoir engineers and modellers working on geothermal energy appear to use *overpressure* in the same sense as in the hydrocarbon industry. For example, Dempsey et al. (2015) define *overpressure* as “pressure in excess of undisturbed formation pressure”. Whilst this is

compatible with the predominant usage in structural geology, it is different from several of the definitions in volcanology.

Figure 1(c) illustrates the potential differences between different definitions of *overpressure* in a geothermal reservoir.  $P_F$  for the water in a hydrothermal system may exceed  $P_H$  but be less than  $P_{FRAC}$ , whilst  $P_M$  may exceed  $P_{FRAC}$ , leading the emplacement of igneous intrusions. To limit confusion, there is a need for clear, unambiguous definitions that all scientists working together will understand.

### **Suggested alternative terms**

It would be advantageous to use unambiguous terms to avoid the potential for confusion. For example, *fracture pressure* (e.g. Morgenstern, 1962; Swarbrick and Lahann, 2016) may be used when  $P_F$  is high enough to generate fractures. Similar terms that have been used in relation to volcanic activity include *opening pressure* (e.g. Ida, 1992) or *eruption pressure* (e.g. Morrissey et al., 2010). Similarly, *supra-hydrostatic fluid pressure* may be used when fluid pressure exceeds that expected in a column of water at that depth (e.g. Sibson, 1990), and *supra-lithostatic fluid pressure* (Sibson, 1992) may be used when  $P_F > \sigma_v$  (Figure 1d).

### **Conclusions**

*Overpressure* has been cited as being important in a wide variety of processes in the geosciences, including hydrocarbon production, volcanism, faulting and seismic activity. The term *overpressure* is, however, a polyseme, being used in different ways by different researchers. For example, several different uses appear in the volcanology literature. This diversity of usage may cause confusion, especially where people from different disciplines have to collaborate, as in the exploitation of geothermal energy. It is therefore important that

each usage of *overpressure* is precisely defined and carefully explained in relation to other stress components. We suggest that use of the following terms and definitions will give greater precision:

- *Overpressure* should be confined to the condition in which  $P_F$  exceeds the value that would be expected for that depth in a water column (hydrostatic pressure), i.e. in the same way as is used in the hydrocarbon industry (e.g. Fertl and Chilingarian, 1989) and predominantly in structural geology (e.g. Bolton et al., 1998). Alternatively, *supra-hydrostatic fluid pressure* could be used when fluid pressure exceeds that expected in a column of water at that depth (e.g. Sibson, 1990).
- *Fracture pressure* ( $P_{FRAC}$ ) should be used for the condition in which  $P_F$  is strong enough to cause fracturing. For example, extension fractures (including dykes and sills) will form when  $P_F$  exceeds  $\sigma_3$  and the rock strength (e.g. Swarbrick and Lahann, 2016).
- *Supra-lithostatic fluid pressure* should be used for the condition in which  $P_F$  exceeds  $\sigma_V$  (Sibson, 1992). Sills will tend to develop under these conditions if the fluid is magma.

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## Highlights for “The interdisciplinary use of *overpressure*”

- *Overpressure* is used in variety of different ways in the geosciences.
- We suggest that the term should be carefully defined whenever used.
- Other, less ambiguous terms could be used, such as *supra-hydrostatic fluid pressure* and *supra-lithostatic fluid pressure*.

ACCEPTED MANUSCRIPT