Marine and Petroleum Geology 78 (2016) 883–894

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Overpressure dissipation mechanisms in sedimentary sections consisting of alternating mud-sand layers

Xiaorong Luo [a], [*], Guy Vasseur [b]

[a] *Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*
[b] *Sorbonne Universités, UPMC Univ. Paris 06, CNRS, EPHE, UMR7619 METIS, 4 Place Jussieu, F75005 Paris, France*

ARTICLE INFO

Article history:
Received 6 December 2015
Received in revised form
22 March 2016
Accepted 1 April 2016
Available online 8 April 2016

Keywords:
Numerical modeling
Seal efficiency
Pressure diffusion
Fracturing
Faulting

ABSTRACT

In stable subaqueous environments, sedimentary deposition often results in thick mudstone-rich successions, with mainly argillaceous sediments, containing some intercalated sandstone beds and siltstones laminae. Such depositional sequences are commonly hosting abnormally pressured fluids in some part of their structure. Abnormally pressured compartments – generally overpressured ones – are indicative of effective sealing conditions along their boundaries in order to prevent the dissipation of hydraulic pressure. This work focuses on the various mechanisms of overpressure dissipation in such overpressured mudstone-dominated systems. The study is based on the mathematical and numerical simulation of hydraulic phenomena occurring in various geometries of sandstone-mudstone series. Using 1D models, it is shown that, once overpressure is developed in such a compartment, it can be kept inside for a very long time even if no other pressure process is acting. A basic mechanism is that the mudstone-sandstone succession reacts actively to pressure dissipation: when overpressure is released outward of the compartment, subsequent compaction tends to occur in the neighbouring sediments; this in turn results in a continued pressure generation and tends to maintain the overpressure in the compartment at geological time scale. Natural hydraulic fracturing tends to dissipate overpressure but it does not release the entire overpressure because fracturing is a threshold mechanism which keeps the stress level in the seals at their hydraulic fracturing limit. The opening of faults may modify the pressure pattern through the rapid generation of efficient fluid flow paths; however, its effect is a quasi-instantaneous release of overpressures in sandstones but not in mudstones. 2D numerical simulation suggests that, once the fault is closed, the overpressures remaining in mudstones are rapidly transmitted into adjacent sandstones which then tend to recover their previous high pressure. The most efficient mechanisms of overpressure dissipation in mudstone overpressured compartments are large-scale and long-term tectonic uplift and resulting erosion of overburdens. Studies on the conditions and mechanisms of overpressure dissipation in mudstone-rich successions provide insight into processes of hydrocarbon migration and accumulation processes and the efficiency of cap rock in basins that have experienced multiple episodes of tectonic disturbance.

1. Introduction

For the exploration of hydrocarbon (HC) in sedimentary basins, it is very important to assess the underground distribution of overpressures and to understand their generation and evolution processes. This assessment is crucial for understanding the behavior of HC during their expulsion phase and during their later migration toward eventual traps. For example, the mapping of overpressure distribution and the knowledge of its evolution can give critical indications on the directions and periods of HC expulsion (McAuliffe, 1979; Magara, 1978; Ungerer et al., 1984, 1990). Also the occurrence of overpressure in a mudstone bed implies that this bed is hydraulically effective for sealing (Hunt, 1990); since some of these seals play a major role as effective barriers during the accumulation of HC, the assessment of their sealing efficiency at geological times is also fundamental for HC exploration (Cartwright et al., 2007).

In order to obtain a better understanding of the complex geological phenomena occurring during basin formation and

---

[*] Corresponding author.
E-mail address: luoxr@mail.igcas.ac.cn (X. Luo).

http://dx.doi.org/10.1016/j.marpetgeo.2016.04.001

evolution, many simulation software have been developed in order to model the physico-chemical aspects of this evolution (including mechanical, thermal, hydro-dynamical and chemical phenomena) (Tissot and Welte, 1978, Ungerer et al., 1984, 1990, Luo and Vasseur, 1992, 1996; Hantschell and Kauerauf, 2009). The occurrence and development of overpressures and associated hydrodynamics belong to a specific aspect of such models. In a given formation, the fluid pressure appears as the result of some generating mechanisms which tend to increase the pressure (such as mechanical compaction, tectonic stress, thermal dilation, chemical reaction ….) versus other mechanisms tending to dissipate it (Shi and Wang, 1986; Luo and Vasseur, 1992). If, as assumed in most models, only the compaction mechanism is taken into account for overpressure generation, the pressuring state and evolution (pressure increasing, retaining and dissipating) in a shale layer depend on a relationship between the rate of overburden weight variation on one side and, on the other side, the hydraulic flow through the very tiny pores of the shale which results in a very slow dissipation of the generated overpressure (Neuzil and Pollock, 1983; Audet and McConnell, 1992; Luo and Vasseur, 1995). Rock permeability is therefore a major parameter for overpressure dissipation.

In mudstone-dominated formations, the mudstone layers are relatively very low permeability compared to coarse grains ones and appear to control the overpressure in surrounding rocks. The sealing effect of these fine-grains formations seems to prevent any fluid flow from the formations themselves and from other neighbouring ones. They would therefore act as “pressure-seals” and explain the present occurrence of overpressure in the so-called overpressured compartment (Hunt, 1990; Surdam et al., 1994) which are presently observed.

This relatively tough explanation has been leading to an interesting discussion at the end of the last century on the conditions required to prevent fluid flow at geological time scales. Deming (1994) argued that, in order to maintain overpressure beneath a sealing layer of 100–1000 m thickness for more than 1 Ma, its permeability should be as small as 1.0×10^{-21}~$l.0 \times 10^{-23}$ m^2, i.e. somewhat smaller than most values measured in the laboratories for shales. He and Corrigan (1995) pointed out that boundary conditions of Deming's model are not relevant to actual geological problems and that his inferred specific storage coefficient is too small. Using relevant conditions, the overpressures may in fact be maintained up to near 10My. This was confirmed by Luo and Vasseur (1997) through an analytical model of pressure evolution in a complex composed of a compartment sealed by an upper shale layer and show that a shale layer of several tens of meters with a reasonable permeability (about 10^{-15} m^2) is able to maintain overpressure. The underlying permeable layer does contributes to the maintenance of overpressure because it is submitted to ongoing compaction (Luo and Vasseur, 1997; Borge, 2002). Muggeridge et al. (2004, 2005) further confirm this conclusion by designing more complex models composed of alternated mud - sand layers in the vertical as well as in the lateral directions.

Most overpressures observed in basins actually occur in compartments consisting of low permeability mudstone beds with coarse-grains sediments within these seals (Surdam et al., 1994; Luo and Vasseur, 1997; Luo et al., 2007; Kukla et al., 2011). Since the seals are not absolutely impervious, overpressured compartments are leaking and the general trend is pressure relaxation. However the geological time evolution of the physical properties of these mudstone beds and/or the modification of their integrity may affect the evolution of pressure and may increase or decrease the rate of overpressure dissipation. For example the occurrence of oil or/and gas in a compartment is expected to increase the sealing effect of the shale due to the relative permeability effect (Surdam et al., 1994); this would result in a delayed overpressure dissipation. Alternatively when fractures and opening faults affect the seal, an increased dissipation rate seems unavoidable (Kukla et al., 2011; Czauner and Mádl-Szőnyi, 2013). However, the work of Luo (2004a) suggests that the time evolution of a fault is such that it does not remain open for long enough to release the entire overpressure. The same ubiquitous effect seems to characterize natural hydraulic cracking: it acts as a threshold process which keeps the pressure at the fracturing limit under relaxed stress conditions (Luo and Vasseur, 2002).

There remain many questions on overpressure generation, maintenance and dissipation during basin development. Although simple analytical or numerical models are useful, it is important to replace these geological phenomena in the general context of the dynamical coupled factors and processes occurring during basin evolution. Only numerical models can tackle these highly non linear phenomena and emphasize the associated feedback effects. Therefore quantitative numerical basin modeling appears as an indispensable quantitative tool to analyze and to calibrate the pressuring processes, and to evaluate the pressuring effect of possible mechanisms during basin evolution (Luo, 1994).

The present paper aims to give an overview of the major mechanisms of overpressure dissipation in alternated mudstone sandy beds and to discuss their efficiencies. These mechanisms are simulated with the help of a numerical basin simulator developed in previous studies (Luo and Vasseur, 1992, 1995, 1997, 2002). A set of simple models of sediment beds with similar initial and boundary conditions are presented for evaluating the overpressure occurrence and for focusing on their dissipation. The effect of various dissipating processes is then systematically evaluated.

2. Methods

In this paper, a numerical basin modeling software called TPC-MOD (Luo and Vasseur, 1992, 1995, 2002; Luo et al., 2007) is used as a quantitative analyzing tool to simulate the overpressure dissipating processes in an overpressured sedimentary section consisting of alternating mud-sand layers.

TPC-MOD is a 2-D numerical basin modeling simulator that was developed to assess the importance of fluid pressure generation/dissipation mechanisms in actual basins and in synthetic sedimentary sections (Luo and Vasseur, 1992, 1995, 2002; Luo, 2004a,b). It is based on a finite element discretization of space and uses isoparametric quadrilateral elements. In the model, the fields of temperature, pressure and stress-strain, are computed as numerical solutions of the basic non linear equations for heat exchange and for fluid flow through an iterative loop process (Luo, 1994). Most coefficients of the differential equations of transfer derive from two fundamental empirical relations characterizing the hydro-mechanical behaviors of the sediments and intervening directly in the fluid flow equation.

The law for porosity is derived from the well known Athy's law (Athy, 1930). For historical reasons, the Athy's law is generally expressed as a function of depth z for the case where the fluid pressure is hydrostatic:

$$\phi(z) = \phi_0 \exp(-cz) \tag{1}$$

where ϕ_0 is the surface porosity and c a compaction coefficient with dimension m^{-1}, both of which being characteristic of the medium. On the basis of soil mechanics this relation is generalized to the case of non hydrostatic pressure under the form: