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COULD MAGMA TRANSPORT AND ACCUMULATION BE A USEFUL ANALOGUE TO UNDERSTAND HYDROCARBON EXTRACTION?

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The process of magma transport and accumulation is proposed as an analogue for oil and gas extraction from their source rocks and oil shales. Magma accumulation is a highly-dynamic stepwise process, where magma moves inside and with hydrofractures. This may lead to a self-organized critical state, which cannot be described by classical Darcian-type models for flow through intergranular pores or fractures. It was suggested that the same could occur in natural oil and gas extraction, and may perhaps be applied to improve fuel production from oil shales.

Introduction

Segregation, transport and accumulation of a fluid phase are important and common issues in several disciplines in the earth sciences. Extraction of hydrocarbons is of foremost importance to the oil shale industry, while the way oil and gas segregate from their source rocks, move upwards, and accumulate in reservoirs is of primary interest to the general hydrocarbon industry. Probably the most extreme example of segregation and accumulation is the formation of igneous bodies and magma chambers [1, 2]. Melt forms on the micrometer-scale on grain boundaries in rocks at elevated temperatures (roughly >700 °C) in the upper mantle or lower crust. Due to its relative buoyancy, this melt moves upwards and accumulates to form plutons, magma chambers, or volcanic outpourings that can be hundreds of cubic

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kilometers in volume. This process involves a staggering concentration factor of well over twenty orders of magnitude in volume.

As a study object, magma segregation and accumulation has one advantage over other similar geological systems: magma freezes when it cools below its solidus temperature. This allows the geologist to observe frozen-in stages of the process. Examples are migmatites (rocks that were once partially molten and have retained part of their melt) and dykes (magma conduits that now contain solidified magma). In this paper it is therefore proposed that magmatic systems may to some extent be used as analogues to better understand hydrocarbon segregation and accumulation. Magma segregation and accumulation is briefly reviewed, paying special attention to the theoretical approach that is used to explain the process. It is argued that the process is highly dynamical and not well described by classical pore or fracture flow models that are based on Darcy's-law-type continuous differential equations. Some suggestions are presented as to where the insight from magmatic systems and their dynamics could perhaps be applied to hydrocarbon and oil shale research.

Magma Transport and Accumulation

The theory on magma segregation, transport and accumulation is currently dominated by porous flow through intergranular porosity (e.g. [3–5]) or fracture networks (e.g. [6, 7]). Although intergranular flow may be significant in the mantle, transport through fractures or dykes is usually favored for the crust (e.g. [8–12]). The emphasis in most research lies on transport properties of a single dyke, at the neglect of accumulation required to feed a dyke, as pointed out by Weinberg [7]. Although much is written on magma transport, still little is known about accumulation. Where accumulation is considered in more detail, Darcian porous flow theory is generally used [3, 7, 13].

The "Diffusional Regime"

Darcian porous flow theory is essentially based on the basic Darcian law that states that the flux (Q) is proportional to the gradient in hydraulic head ($\nabla\varphi$):

$$Q = k \cdot \nabla\varphi, \tag{1}$$

where k is a proportionality constant, which describes the transport properties of the system (Fig. 1).

Darcy's law is essentially similar to Fick's law for diffusion, which describes the flux (J) of a diffuse species as a function of a proportionality constant, the diffusivity (D), and the gradient in concentration of the species (∇C):

$$J = D \cdot \nabla C \tag{2}$$

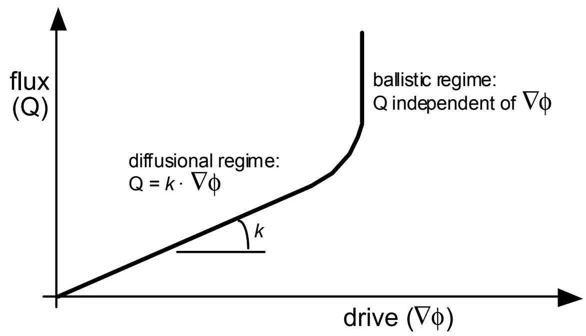

Fig. 1. Graph illustrating the relationship between flux (Q) and drive (gradient in hydraulic head, $\nabla\varphi$) in the diffusional regime and in the ballistic regime. At a low drive (diffusional regime), the relationship can be described with a linear function (Darcy's or Fick's law, Eq. (1)). At a high drive (ballistic regime) this relationship breaks down and the flux becomes independent of the drive

Transport modes that are governed by equations similar to Fick's basic diffusion equation can be termed diffusional. The diffusional description of transport is strongly deterministic: all relevant aspects of the system through which transport takes place are described by the proportionality constant k, which is the conductivity in case of porous flow. k can be a function of fluid amount or porosity in case of the Carman-Kozeney law [3], which relates permeability to porosity by a power-law. However, the description of the system is not a function of the flux or changes in flux in time. Knowing k, one can completely describe the flux at any value of $\nabla\varphi$. Another important aspect of the diffusional description is the assumption of a certain homogenization scale, above which one can treat a volume of rock as a continuum with homogeneous properties, such as k.

Problems with the Diffusional Approach

Hydrofractures are fractures that are propped open by the pressure of the fluid (magma, oil, gas, water) inside the fracture. If the containing fluid is buoyant and the hydrofracture is steep, a hydrofracture becomes unstable above a certain critical length [8]. The critical length is in the order of tens of meters for water, and may be a few hundreds of meters for more viscous magma [14]. When a tectonic stress gradient is applied normal to the hydrofracture, it may become unstable at much smaller lengths. Above the critical length, the front and rear tip of the hydrofracture start to propagate in the same direction. The hydrofracture does not expand, but moves together with its containing fluid. This is well illustrated in analogue experiments of Maaløe [15], Takada [16], Dahm [17] and Bons *et al.* [18]. Movement, interaction, and mergers of such mobile hydrofractures [19] lead to a stepwise accumulation in ever-larger mobile hydrofractures or dykes [20, 21].

Then transport described above cannot be described well with the diffusion model. Overall conductivity of the system is zero, because through-going connected fracture paths do not develop. The predicted flux would be zero. Small parts of the system, however, do develop transient connectivity when mobile hydrofractures connect. This causes intermittent local transport and accumulation. The effective conductivity is non-zero, but only while transport takes place. Bons and van Milligen [22] modelled stepwise accumulation in analogue experiments (Fig. 2) and with a stochastic computer model. They showed that the systems developed to a state that is known as self-organized critical one [23–25]. This state is best known by its analogy with a critical sand pile.

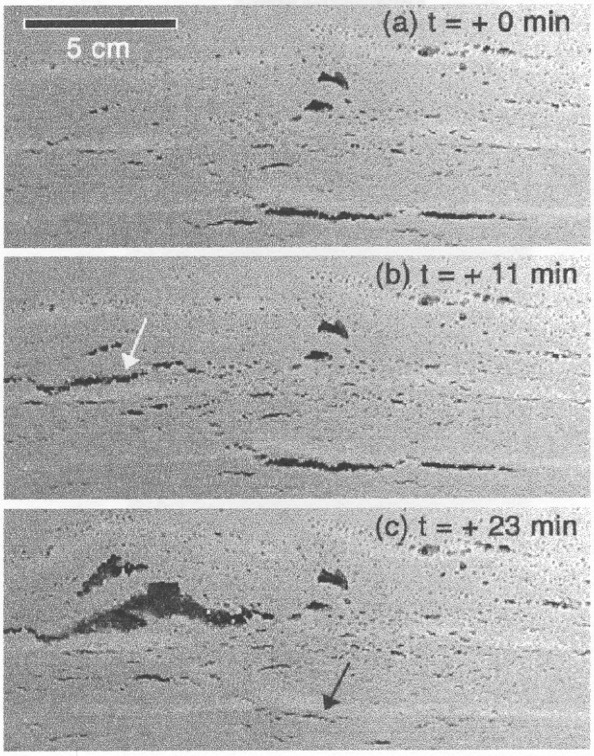

Fig. 2. Images from the analogue experiment described by Bons and van Milligen [22] to illustrate stepwise escape of a mobile phase in hydrofractures. The image shows sand immersed in sugar water with yeast (grey). Fermentation of the sugar produced CO_2 gas, which accumulates in hydrofractures and bubbles (black). Hydrofractures are continuously being created and destroyed. Image (*a*) was taken two hours after start of fermentation; (*b*) 11 min later, a new hydrofracture developed at the left (white arrow); (*c*) 23 min later, the hydrofracture at the bottom has almost completely drained and closed (black arrow)

The "Ballistic Regime"

The self-organized critical (SOC) state typically develops in strongly driven systems that are far from equilibrium [26]. The SOC state has some particular characteristics:

1. The response of the system to an increase in the drive is not to increase the gradient, but to open up alternative transport channels. In our case this means than an increase in melting does not lead to a higher gradient in hydraulic head ($\nabla\varphi$ in Eq. (1)) to increase the drainage flux (Q in Eq. (1)), but to activate more (mobile) hydrofractures, which also increases the drainage. In terms of Darcy's law, we then have an apparent conductivity (k) of infinity. This is however misleading, as k is in fact always just sufficient to accommodate the imposed flux (see Fig. 1).
2. Transport is highly irregular or intermittent and occurs in bursts or avalanches. This intermittent dissipation of the drive is best known from the dissipation of elastic energy in the crust, which occurs by earthquakes. The flux is thus highly irregular over time, but does not display random noise. Instead, the power of the noise is inversely proportional to the frequency of the noise; a phenomenon known as a $1/f$ signal or pink noise (Bak *et al.* 1987). The dominance of fast transport events gives this regime the name "ballistic".
3. The SOC state is both robust and highly unstable. The system is robust, because it always draws back to the critical state, even though large deviations may occur due to avalanches. It is at the same time very unstable: even small perturbations may lead to far-reaching chains of events or avalanches.
4. The system develops self-similarity or fractal properties. Typically, the avalanches (earthquakes, flow pulses) show a power-law size distribution [24]. The analogue experiments of Bons and van Milligen [22] and numerical modeling (Bons, unpublished) show that both the hydrofracture volumes and the volumes of escaping fluid batches follow such a power-law:

$$N_{>V} = c \cdot V^{-m} \tag{3}$$

where $N_{>V}$ is the number of volumes larger than volume V;
c is the number of volumes larger than unity;
m is the power-law exponent.

This means that there is no typical length scale for the volumes and there is therefore also no homogenization scale as used in the diffusional continuum approach. The exponent m essentially describes the efficiency of accumulation. At m = 1, the same amount of volume or mass resides in each volume category. This is the boundary between dispersion (m>1) and concentration (m<1). Maximum concentration is reached when 50% of all volume or mass resides in the single largest batch at m = 2/3. The exponent m

must lie between the end-member cases m = 1 and m = 2/3 in case of accumulation in power-law distributed batches.

Power law distributions and fractal properties, consistent with the above, are commonly found in magmatic and non-magmatic fracture systems [27–29]. We analyzed outcrop and drill core sections through stromatic migmatites (with parallel melt veins) in South Finland, Labrador, and the Estonian crystalline basement and found power law distributions in all cases (see Fig. 3 for an example).

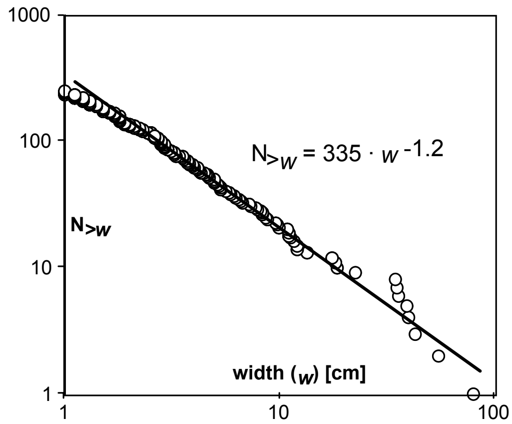

Fig. 3. Graph showing the number of melt veins wider than a width w as a function of w. The vein widths have a power-law distribution. Outcrop of Palaeoproterozoic migmatites at the Masku “Riviera”, north of Turku, south Finland

Differences between Diffusional and Ballistic Regime

Many systems show diffusional behavior at a low drive and ballistic behavior at a high drive. It is tempting, but incorrect, to describe such systems with a non-linear conductivity parameter (e.g. [30]). Avalanches or ballistic events are typically dependent on the system size, implying that the effective coefficient derived for one system is not valid in another, larger or smaller, system. This renders the use of Eq. (1) with an effective non-linear conductivity parameter useless as a predictive tool [31]. The ballistic state is essentially a state where all excess drive is immediately dissipated. In case of fluid transport, this means that all fluid in excess of the critical fraction is quickly transported out of the system.

Diffusional systems show variations and fluctuations in flux at the small scale, below the homogenization scale. Going up in scale, the small-scale fluctuations average out and the observed flux becomes ever more constant or smooth. This is different in the ballistic regime, where an increase in scale permits larger events or avalanches to occur. Fluctuations in flux therefore do not average out when going up in scale, but become ever larger.

Conclusions and Implications

The stepwise transport and accumulation mechanism that is described above forms a highly dynamic, ballistic system. It is capable of disposing of any magma in excess of a critical fraction in the partially molten rock. Such a system cannot be described adequately with the classical Darcian approach. There is no reason to assume that the same may not apply to source rocks of hydrocarbons. Oil and gas are buoyant fluids that may induce the necessary overpressure to produce hydrofractures. Such hydrofractures would be more mobile than magma-filled ones, owing to the low viscosity of oil and gas. To understand hydrocarbon reservoir generation, it may be useful to study magmatic systems and the properties of ballistic or SOC systems.

As the oil shale industry has extraction of hydrocarbon as one of its main aims, it may also be useful to consider SOC state in this discipline. Systems with dynamic fracturing (the possibility of creating, propagating and closing of fractures) are prone to become SOC, if a high enough drive is imposed. Such systems may develop in oil shales where hydrocarbons are being released and become mobile fluid (including gas) phases. If such situations are created it is of crucial importance to describe the system in a physically correct way. Describing a ballistic system as diffusional may be wrong, or at the least misleading.

One special and possible useful characteristic of a SOC system is its ability to efficiently dispose of any excess drive without increasing the gradient. This would imply that once a SOC system is established during progressive fluid hydrocarbon release, any further fluid that is produced can be efficiently recovered. We cannot propose how to make the hydrocarbons mobile in oil shale. However, it is possible to envisage that "controlled SOC" accumulation may improve extraction efficiency and perhaps even reduce negative environmental side effects.

Questions remain whether SOC systems occur in oil shales, whether they can be induced, and if so, whether they can be harnessed to improve fuel production. We hope that this paper will encourage the oil shale community to consider these questions.

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REFERENCES

1. *Brown, M.* The generation, segregation, ascent and emplacement of granitic magma: The migmatite-to-crustally-derived granite connection in thickened orogens // Earth Sci. Reviews. 1994. Vol. 83. P. 83–130.
2. *Petford, N., Cruden, A.R., McCaffrey, K.J.W., Vigneresse, J.-L.* Granite formation, transport and emplacement in the Earth's crust // Nature. 2000. Vol. 408, P. 669–673.
3. *McKenzie, D.* The generation and compaction of partially molten rocks // J. Petrol. 1984. Vol. 25, P. 713–765.
4. *Khodakovskii, G., Rabinowicz, M., Genthon, P., Ceulenceer, G.* 2D modelling of melt percolation in the mantle: the role of melt dependent mush viscosity // Earth and Planetary Science Letters. 1995. Vol. 134, P. 267–281.
5. *Aharanov, E., Spiegelman, M., Coleman, P.* Three-dimensional flow and reaction in porous media: implications for the Earth's mantle and sedimentary basins // J. Geophys. Res. 1997. Vol. 102, P. 14,821–14,834.
6. *Nicolas, A., Jackson, M.* High-temperature dikes in peridotites: origin by hydraulic fracturing // J. Petrol. 1982. Vol. 23, P. 568–582.
7. *Weinberg, R.F.* Mesoscale pervasive felsic magma migration: alternatives to dyking // Lithos. 1999. Vol. 46, P. 393–410.
8. *Weertman, J.* Theory of water-filled crevasses in glaciers applied to vertical magma transport beneath ocean ridges // J. Geophys. Res. 1971. Vol. 76, P. 1171–1183.
9. *Emerman, S.H., Marrett, R.* Why dykes? Geology. 1990. Vol. 18, P. 231–233.
10. *Clemens, J.D., Mawer, C.K.* Granitic magma transport by fracture propagation // Tectonophysics. 1992. Vol. 204, P. 339–360.
11. *Petford, N., Kerr, R.C., Lister, J.R.* Dike transport of granitoid magmas // Geology. 1993. Vol. 21, P. 845–848.
12. *Rubin, A.M.* Propagation of magma-filled cracks // Annual Rev. Earth Planet. Sci. 1995. Vol. 23, P. 287–336.
13. *Connolly, J.A.D., Podladchikov, Yu. Yu.* Compaction-driven fluid flow in viscoelastic rock // Geodinamica Acta. 1998. Vol. 11, P. 55–84.
14. *Secor, D.T., Pollard, D.D.* On the stability of open hydrofractures in the Earth's crust // Geophys. Res. Letters. 1975. Vol. 2, P. 510–513.
15. *Maaløe, S.,* 1987. The generation and shape of feeder dykes from mantle sources // Contribs. Mineral. Petrol. 1987. Vol. 96, P. 47–55.
16. *Takada, A.* Experimental study on propagation of liquid-filled crack in gelatin: shape and velocity in hydrostatic stress condition // J. Geophys. Res. 1990. Vol. 95, P. 8471–8481.
17. *Dahm, T.* On the shape and velocity of fluid-filled fractures in the earth // Geophys. J. Int. 2000. Vol. 142, P. 181–192.
18. *Bons, P.D., Dougherty-Page, J., Elburg, M.A.* Analogue modelling of segregation and ascent of magma // (on-line) J. Virtual Explorer. 2001. Vol. 4: Animations in Geology – visualising the Earth. http://virtualexplorer.earth.monash.edu.au/VEjournal/

19. *Bons, P.D.* The formation of large quartz veins by rapid ascent of fluids in mobile hydrofractures // Tectonophysics. 2001. Vol. 336, P. 1–17.
20. *Sleep, N.H.* Tapping of melt by veins and dikes // J. Geophys. Res. 1988. Vol. 93, P. 10,255–10,272.
21. *Bons, P.D., Dougherty-Page, J., Elburg, M.A.* Stepwise accumulation and ascent of magmas // J. Metamorphic Geol. Vol. 19, P. 625–631.
22. *Bons, P.D., van Milligen, B.P.* New experiment to model self-organized critical transport and accumulation of melt and hydrocarbons from their source rocks // Geology. 2001. Vol. 29, P. 919–922.
23. *Bak, P., Tang, C., Wiesenfeld, K.* Self-organized criticality: An explanation of 1/f noise // Phys. Rev. Letters. 1987. Vol. 59, P. 381–384.
24. *Bak, P.* How Nature Works: The Science of Self-Organized Criticality. – Oxford, Oxford University Press, 1996.
25. *Jensen, H.J.* Self-Organized Criticality. – Cambridge, University Press, 1998.
26. *Bak, P., Tang, C. Wiesenfeld, K.* Self-organized criticality // Physical Review A. 1988. Vol. 38, P. 364–374.
27. *Tanner, D.C.* The scale-invariant nature of migmatite from the Oberpfaltz, NE Bavaria and ist significance for melt transport // Tectonophysics. 1999. Vol. 302. P. 297–305.
28. *Bonnet, E., Bour, O., Odling, N.E., Davy, P., Main, I., Cowie, P., Berkowitz, B.* Scaling of fracture systems in geological media // Reviews Geophys. 2001. Vol. 39, P. 347–383.
29. *Johnston, J.D., McCaffrey, K.J.W.* Fractal geometries of vein systems and the variation of scaling relationships with mechanism // J. Struct. Geol. 1996. Vol. 18, P. 349–358.
30. *Roering, J.J., Kirchner, J.W., Sklar, L.S., Dietrich, W.E.* Hillslope evolution by nonlinear creep and landsliding: An experimental study // Geology. 2001. Vol. 29, P. 143–146.
31. *van Milligen, B.P., Bons, P.D.* Comment on “Roering et al. Hillslope evolution by nonlinear creep and landsliding: An experimental study” // Geology. 2002. Vol. 30. P. 481–482.