Vertical and conical hydrofractures induced by pore fluid pressure in sedimentary basins

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Abstract

The understanding and the quantitative evaluation of fluid migrations in sedimentary basins are of major environmental and economical interests. Sub-horizontal fluid flows are mainly driven by highly permeable formations and are well described by diffusion based (Darcy) models. At the opposite, it is more awkward to quantify vertical movements of fluids through very low permeability sediments (shale) because migrations mainly occur along faults of tectonic origins or along seepage structures that result from hydraulic fracturing or fluidization processes. Such "Focused" fluid flows form in response to overpressurizing of fluid within the sediment. They are manifested in a range of structures such as sand intrusions (injectites), mud volcanoes or pipes (and associated craters and pockmarks on the seafloor) that have strong consequences on the hydrodynamics of basins because they are pathways for hydrothermal pore fluids, hydrocarbons and gas (Berndt, 2005).

The most recent research advances concerning focused fluid flow (F.F.F.) structures have been due to the progresses in 3D seismic surveys that allow a better detection and a finer geometrical definition of the structures (Cartwright, 2007). Among the various morphologies observed on seismic line, vertical pipes and conical structures are frequent. Pipes are subvertical columnar zones of seismic disturbance that are interpreted as hydrofractured zones of focused migration of fluids through low permeable sediments. The pipes often connect to localized sources of fluids or pressure such as sandy reservoirs or faults that conducts fluids (fig.a). Pipes often terminate in seafloor pockmarks or conical structures (fig.a). Conical structures are also observed for sand injectites (Cartwright et al., 2008)(fig.b) that result from the remobilization and injection of sand into fractures. Morphologies of sand injectites observed in sedimentary basins are broadly similar to magmatic intrusions. Nevertheless, the hydraulic fracturing processes are slightly different. For igneous intrusions, magma can't migrate through pore space and the fluid (magmatic) pressure remains confined in the intrusive body. At the opposite, fluids responsible for the formation of sand injectites, mud volcanoes or pipes are water or gas. These fluids percolate through pore space and modify the effective stress field in the vicinity of the structure.

In order to understand the effects of this pressure diffusion on the formation of F.F.F. structures and conical morphologies, we conducted 2D analogue experiments in a Hele-Shaw like cell. F.F.F. structures were formed by hydraulic fracturing a cohesive and permeable granular material. The fracturing fluid was air and was injected at a central injector. A second injection of air at the base of the apparatus allowed us to simulate the effect of fluid overpressure already present in the sediment (λbasin). We did a series of more than 30 tests of hydro-fracturation (fig.c). For the finest models (e < 10cm), two hydraulic fractures initiated at the injector and formed a conical structure. For experiments not subjected to basal air injection (no initial fluid overpressure, λbasin = 0), the fractures were steep. At the opposite, when the model was initially overpressured (λbasin > 0), the cone flattened. The dip of the fractures decreased when the fluid overpressure increased. For highly overpressured models (λbasin > 1), hydrofractures formed horizontally. For experiments where the model was thick enough and was not submitted to initial fluid overpressure (λbasin = 0), a single hydraulic fracture propagated vertically up to a critical depth where a cone formed. This critical depth increased when the fluid overpressure increased. The pore pressure required to initiate the hydraulic fractures at the injector (λfract) were deduced from analytical solutions (abstract ""Basin scale" versus "localized" pore pressure stress coupling – implications for trap integrity evaluation") and compared to experimental data. Figure e shows the relationship between the dip of the experimental hydrofractures and parameter $R = \frac{\lambda_{fract}}{\lambda_{basin}}$ that measures the amount of localized fluid overpressure required to initiate the fractures. In the vicinity of the injector, the local pore pressure field is responsible for stress deviations due to
seepage forces (Mourgues and Cobbold, 2003). This stress deviation was calculated with numerical (F.E.M.) elastic models (fig.d) and the dip of the principal stress (a few centimeters far from the injector) was plotted on figure e. The good correlation between the dips of fractures and principal stresses demonstrates that the angle of the cone is controlled by stress deviation induced by the pore pressure field. This phenomenon occurs preferentially for high fracturing pressure (for highly cohesive material) and for moderate effective vertical stresses (close to the surface or when the sediments are highly overpressured). At great depth, in normally pressurized sediment the deviation is too small to generate conical structures and the fractures propagate vertically.

figure: (a.) Vertical pipe in the Lower Congo Basin. It takes root on a paleo-channel and terminates in a Giant pockmark with a conical shape (from Gay et al. 2006). (b.) Conical sand injectites from the Faeroe-Shetland
Basin (from Cartwright et al., 2008). (c.) Experiments of hydraulic fractures for various initial fluid overpressure ($\lambda_{basin}$). (d.) Numerical calculation of stress orientation close to the injector. (e.) Correlation between the conical shape and the dip of the principal stresses. The stress rotation induced by the pore pressure field around the injector is responsible for the conical structures.

References