Ascent and movement of buoyant fluids in the lithosphere

How buoyant hydraulic fractures emerge, propagate, and interact with the environment

1 Abstract

Hydraulic fractures are driven by an internal fluid pressure exceeding the minimum compressive stress, propagating in a direction perpendicular to the latter. This class of tensile fractures has gained interest over the last fifty years due to the development of multiple engineering applications. Among these industrial applications are well-stimulation treatments by hydraulic fracturing used in the oil and gas industry to enhance the permeability of tight reservoirs. The same technique is used in geothermal systems to increase production. It has become of increased interest recently in the discussion about the energy transition thanks to the idea of orange hydrogen production, carbon capture and sequestration, and the use of the underground for fracture thermal or elastic energy storage. But buoyant hydraulic fractures occur not only due to anthropogenic actions but also naturally. The most dramatic manifestation of such fractures is the process of magma migration at a large scale in so-called dikes and sills. Generally, the ascent of geothermal fluids in subduction zones or at hot spots can also be related to such processes.

Most anthropogenic applications are performed in sedimentary basins. In these geological formations, the minimum compressive stress is usually horizontal and increases with depth. As a result, hydraulic fractures grow along vertical planes. Because the density of the fluid and solid are generally different, a buoyant force between the hydrostatic pressure gradient and the background stress emerges. This force causes the fracture to deviate from its initially radial propagation towards an elongated growth in the direction of gravitational acceleration. Once initiated, it is essential to note that this propagation is self-sustained, meaning that with no further source of external energy, the fracture will continue to propagate. Such propagation is notably dangerous if directed upwards, as potentially sensitive aquifers could be infiltrated. In our work, we quantify this elongated propagation and study how this relates to the dominant energy dissipation mechanisms (viscous flow of the fluid in the fracture against the energy used for fracture surface creation.

In the first part, we have studied the emergence and propagation of such fractures from a linear elastic fracture mechanics (LEFM) viewpoint using scaling analysis and numerical simulations. We could notably show that the entire history of such fractures can be related to only two dimensionless numbers combining the properties of the solid (density, elasticity, fracture resistance), the fracturing fluid (density, viscosity), and the fluid release (rate, release time). We could characterize the possible emergence and the various self-similar solutions of buoyant hydraulic fractures. Lately, we have started investigating the effects of heterogeneities and other mechanisms, like fluid mass changes, on the propagation of hydraulic fractures. At the current state of our research, we continue to investigate various aspects to increase the comparability of our results and findings with industrial and natural occurrences of buoyant hydraulic fractures.

Keywords: Hydraulic fracture, buoyant hydraulic fractures, self-sustained buoyant growth, dike intrusions

2 Biography

Andreas Möri is currently a post-doc in the Geo-Energy Laboratory (GEL) in the Civil Engineering Department at EPFL. He obtained his Bachelor's and Master's degrees in Civil engineering from EPFL with a specialization in geotechnical construction and equivalent credits in structural engineering. During his studies, his interest was directed toward the localization of deformation, respectively fracturing, of geomaterials coupled with fluid flow inside localized fractures and the bulk. During his Master's project, he focused on shear localization as the initiation mechanisms of landslides and investigated a creeping landslide in the Swiss pre-alps. He performed early work on hydraulic shear fractures, studying the remote nucleation of aseismic slip due to the stress transfer caused by an aseismic shear fracture. In his Ph.D., he shifted towards opening mode hydraulic fractures and notably investigated the influence of gravitational forces on their propagation, emergence, and arrest. During his thesis in the GEL lab, he became an expert on buoyant hydraulic fractures. He could relate previously existing late-time and two-dimensional solutions to such fractures' full, three-dimensional planar propagation. Thanks to his expertise in the scaling analysis and numerical validation of fundamental physical processes in fully coupled hydromechanical problems, he further laid the basis for studying various additional mechanisms related to different occurrences of such fractures. These mechanisms include heterogeneities, size-dependent effects, and fluid mass losses. Additionally, he has been passionate about studying poroelastic effects on hydraulic fracture propagation, where he is currently finishing some projects started during his thesis. He obtained his Ph.D. from EPFL in September 2023 before switching to a post-doc position in the same lab. This project-based position is sought to validate the feasibility of fracture thermal energy storage through lab experiments. He currently performs experiments with circulating high-temperature fluids in previously created hydraulic fractures in large-scale rock specimens. In the project's further development, he will try to create multiple fractures in such samples, including a subsequent charge and discharge of the designed thermal battery.