Formation of polygonal fracture systems as a result of hydrodynamic instabilities in clay-rich deposits.

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Context

Clay-rich deposits are characterized by the development of polygonal fracture systems (PFS) in continental and marine conditions, with size ranging from tens of centimeters to few kilometres.

Several mechanisms have been proposed to explain their formation as tensile stresses during dehydration on continents and non-tectonic stresses, among others (e.g., syntaxis, downslope sliding, gravitational loading in marine context). None of these mechanisms or combination of mechanisms apply universally to all contexts of PFS. They also have difficulties to explain the range of sizes of PFS. On the other hand, studies of the clay microphysics had develop model of particles agglomeration that may have an influence in the PFS formation.

Unconsolidated domain

In a clay suspension, several forces (as chemical, molecular or magnetic) lead to the formation of aggregates and agglomerates resulting from the collision of smaller grains.

Formation of McKenzie [1]:

The formulations of McKenzie describe the fluid separation in an unconsolidated suspension. If the grain distribution is isotropic in the suspension, the distance of grains is similar to their size. In this case, we can apply the Kozeny-Carman law [4] in order to evaluate the permeability K of the suspension:

$$K = \frac{d^4}{18 \mu \eta \phi}$$

where:

- $d$: mean grain diameter
- $\mu$: bulk viscosity of the suspension
- $\eta$: shear viscosity of the suspension
- $\phi$: solid volume fraction

Figure 1: Kozeny-Carman formula (1)

![Figure 1: Kozeny-Carman formula](image)

$$\eta = \frac{9}{4} \phi \frac{d}{12}$$

When the fluid concentration reaches $\phi_\text{sat}$, the yield strength of the solid framework exceeds the relative weight of the aggregates (~1 Pa to 10 Pa). The solid framework is rigid, implying that the free compaction process stops. To overcome this yield strength, forced compaction is necessary in the consolidated domain.

Consolidated domain

When the permeability $K_\text{sat}$ of the consolidated medium drops at the top of a compacting layer, the growth rate of the compaction waves dramatically increases. First, an initial planar wave of thickness ~2L develops just below the top interface, which eventually splits into several spheres of radius $L$. Then, a second planar wave develops at a depth ~2L below the first one. This wave progressively splits into ~L radius spheres. Finally, other planar compaction waves successively develop at increasing depth but their sizes and growth rates become gradually weaker.

A very complicated problem is to decipher how the strength and the effective viscosity evolve when the porosity is close or greater than $\phi_\text{sat}$. Beyond a deformation rate greater than $\phi_\text{sat}$, interstitial water concentrates into microscopic veins where the grains, aggregates and agglomerates are free to slide [8]. To avoid these sliding effects, [9] have investigated the rheology of frozen saturated clay-rich samples. One of the interpretation we made from their experiment is that the evolution of the rheological law with temperature represents an evolution of the clay rheology as the volume of interstitial fluid decreases first, by freezing large pores then micro-pores. This, thus mimics what may happen in a consolidated medium under forced compaction.

Application to continental context

On continents, between viscosities of $10^6$ to $10^8$ Pa s, consolidation process leads to the development of a size ranging from few centimeters to few kilometres. When evaporation starts, the porosity of the upper layer decreases progressively. When it is close to $\phi_\text{sat}$, it becomes plastic with a yield strength related to the stress due to capillary suction [10]. At this stage, the porosity under the dehydrated cap remains stable and, thus, this layer is bauxite. Consequently, the overlying cap is submitted to a vertical compression and thus to a horizontal tension. This tension overcomes the capillary suction and eventually permits the generation of the desiccation cracks in the cap. The water escape generates a compaction wave in the horizontal direction, which likely triggers cylin-drical waves with a radius proportional to the compaction length $L$ that define the size of the polygons.

Application to marine context

Over a viscosity range of $10^8$ to $10^{10}$ Pa s, the compaction length rises until size of few kilometres, leading to the PFS formation under submarine conditions. They result from the drastic reduction of the permeability at the top of the consolidated clay-rich deposit. The reduction of permeability can be induced by the deposition of fine clay-rich sediment [11; 12] and generates a yield strength of 1 MPa to 3 MPa.

As the consolidated clay-rich deposit becomes isolated, the water pressure increases progressively. This implies that this layer is overpressurized and generates fluid-rich spheres whose radii are proportional to $L$. In continental context, the size of the spheres ranges from 100 m to few kilometres. Conversely, as the walls of the spheres are consolidated, they must break under the 0.1 to 1 MPa stresses due to the buoyancy of the clay suspension contained inside the spheres. Thus, sets of faults are generated inside the walls of the cells which have a polygonal pattern.

Figure 2: Polygons formation in marine conditions.

![Figure 2: Polygons formation](image)

Finally, the buoyancy of the fluid-rich horizons and spheres generates Rayleigh-Taylor instabilities. During that time, fault arrays accumulating the volume of fluid reduction during compaction are generated.

Conclusion

Polygongal fractures systems (PFS) are common in clay-rich deposits in continental and oceanic environments. In non-tectonic contexts, several mechanisms have been proposed to explain their formation and their range of size.

The combination of the microphysics (agglomeration process, mineralogy) with the macrophysics have demonstrated that it controls the size of the PFS that can reach few kilometres in oceanic basins.

Below the consolidation threshold (where the viscosity range from $10^9$ to $10^6$ Pa s), agglomeration occurs in the unconsolidated domain via the compaction process. This is referred as the free compaction. Once the porosity is closed in the consolidation threshold, free compaction stops and to overcome the new yield strength, forced compaction is necessary to overcome the yield strength, forced compaction is necessary in the consolidated domain.

Understanding the generation of vertical permeability in clay-rich horizons can be crucial in non-tectonic zone. Indeed, permeability of clay-rich horizons is considered to be $\leq 10^{-16} \text{m}^2$. However, the presence of the fracturing can dramatically increase the vertical permeability and thus the upward migration of fluids.

References: