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

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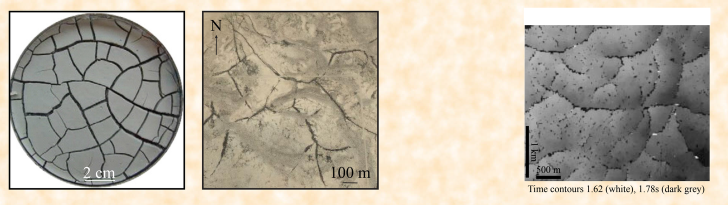
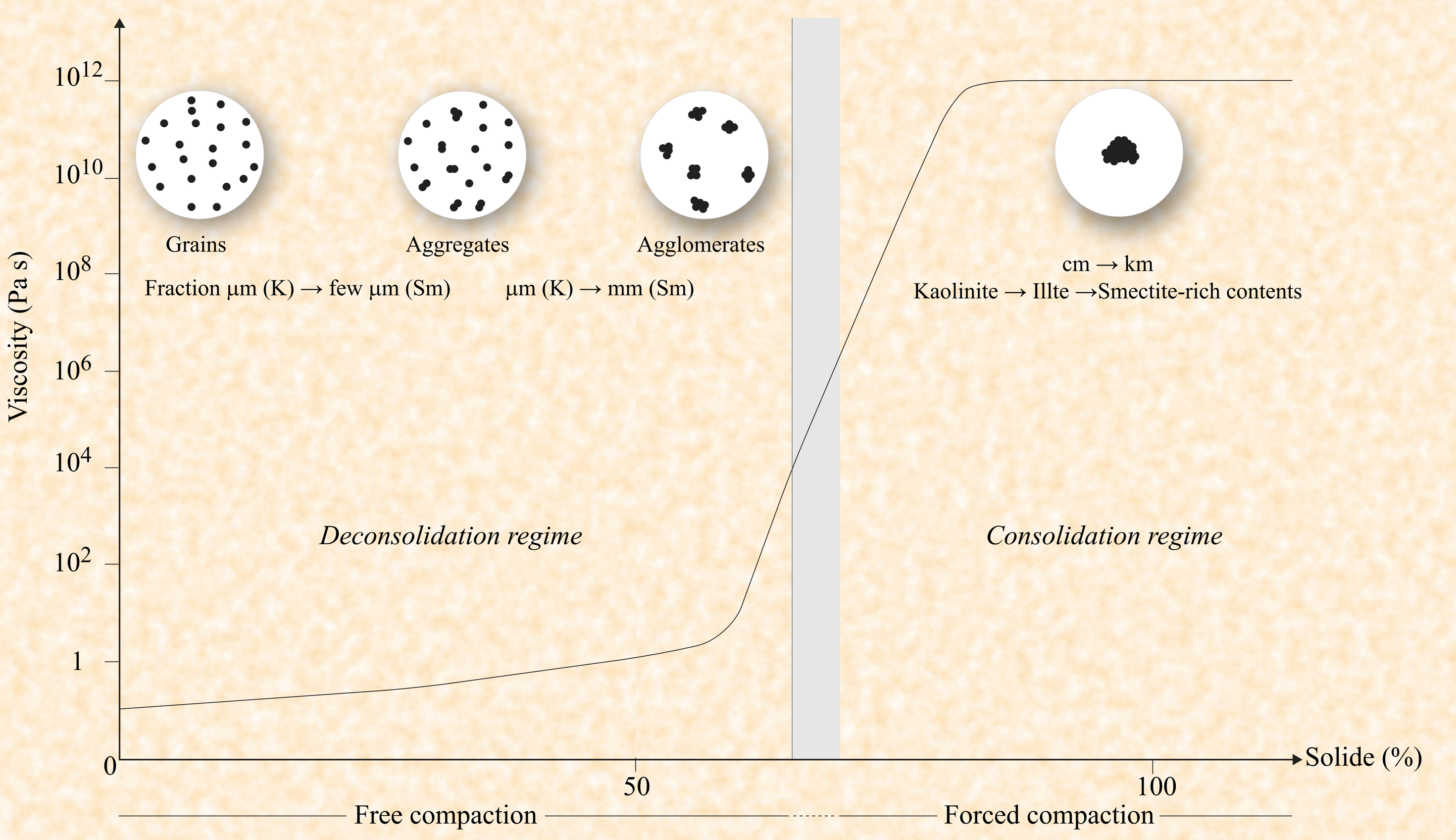
Context

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

	Continents	Oceanic basins
Size of PFS	~30 cm to 300 m	~100 m to 3,000 m



Several mechanisms have been proposed to explain their formation as tensile stresses during dehydration on continents and non-tectonic stresses as e.g., syneresis, downslope sliding, gravitation loading in marine context. None of these mechanisms or combination of mechanisms apply universaly to the diversity of 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.



Objectives

→ Explain the range of sizes of observed PFS in continental and oceanic contexts.

→ Study the influence of the grain agglomeration, at microscopic scale, on the formation of PFS in using two-phase flow formalisms.

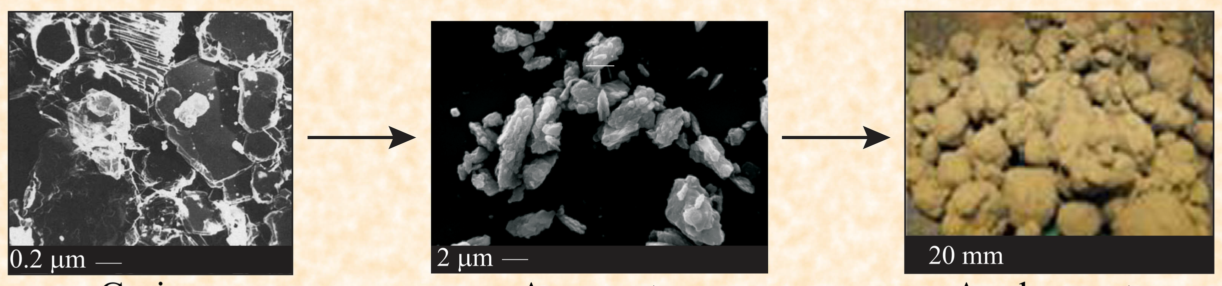
Two-phase flow formalisms (McKenzie and Bercovici) were devoted to the modelling of fluid-rock separation during compaction in partially molten intrusions. These two formalisms are used to describe:

1) the fluid separation in a unconsolidated medium [1],
2) the compaction process in a consolidated solid-liquid medium [2].

The fluid concentration of an unconsolidated/consolidated medium is designated as the porosity ϕ. When the fluid concentration reaches ϕ_{cons}, grains form a connected solid framework tied at their contact by chemical forces. Porosity ϕ_{cons} at which the medium is consolidated stands between ~26 to 47 % and is considered here as the consolidation treshold.

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.



Grains → Aggregates → Agglomerates

[3] have shown that the size of agglomerates d depends on their mineralogy:

	Kaolinite (K)	Illite (Ill)	Smectite (Sm)	Mixed agglomerates
Agglomerates size d	≤ 10 µm	~50 µm	~100 µm	~1 mm

To explain this range of size, we consider that above several µm, agglomeration is determined by the collision of grains on a viscous fluid, with a viscosity close to 10^4 to 10^6 Pa s. The collision results from the difference in Stokes velocities of the grains. This hypothesis permit us to apply the formalism of McKenzie to explain the range of size of the agglomerates.

Formalism of McKenzie [1]:

The fomalism 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:

$$K = \frac{\phi^3 d^2}{(1-\phi)^2\, 172.8}$$

Application of this equation explains plug measurements which reveal a permeability of 10^{-17} and 10^{-15} m² for clay suspensions essentially composed of aggregates with a size d of ~10^{-7} and 10^{-6} m, respectively [5]. The formalism of McKenzie demonstrated that the fluid motion during compaction presents two distinct regimes:

1) if the initial porosity ϕ increases with height, ϕ evolves with a rate proportional to the compaction length L:

$$L = \sqrt{\frac{K(\xi + 4/3\eta)}{\phi\mu}}$$

ξ: bulk viscosity of the suspension,
η: shear viscosity of the suspension,
μ: water viscosity.

2) Alternatively, if the height is >> to L and some vertical variations of fluid concentration is present, individual compaction spheres with radii proportional to L develop [6]. Their core porosity is greater than the initial porosity.

If we applied this formalism and the results obtained by [6], we propose that the agglomeration process leads to the concentration of grains into spheres. The size of the spheres are proportional to the compaction length *L*. For example, if we consider K = 10^{-17} and 10^{-15} m², η and ξ = 10^6 Pa s, we deduce that *L* is ~100 µm and 1 mm, respectively. Thus, during the compaction of the clay suspension, the agglomeration process leads to the formation of compaction spheres with a 100 µm to 1 mm size, range of size observed by [3].

When the fluid concentrations reaches ϕ_{cons}, the yield strength of the solid framework exceeds the relative weight of the agglomerates (~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.

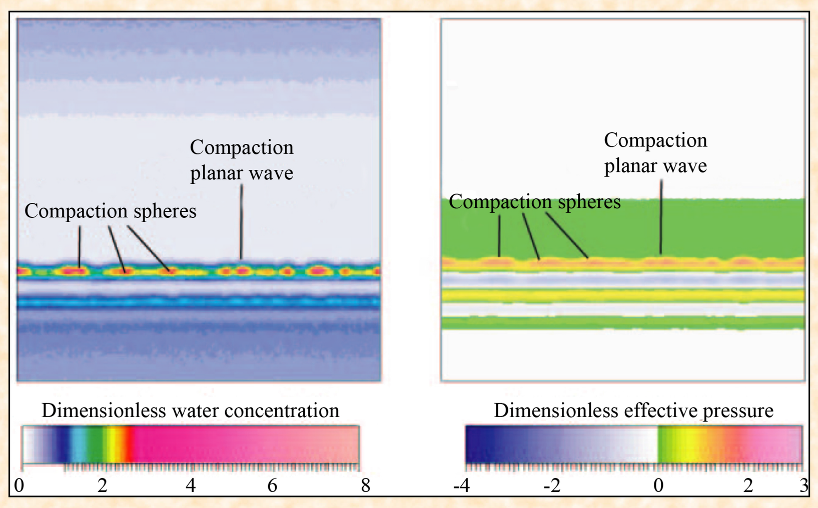
Consolidated domain

Formalism of Bercovici [2]:

The fomalism of Bercovici [2] described the compaction in a consolidated liquid medium. Here, the solid framework deforms like a viscous material with an effective viscosity representing the intrinsic shear viscosity η of the grains. Studies [7] have demonstrated that as in an unconsolidated medium, the compaction process in a consolidated medium generates individual compaction spheres where their radii are proportional to the compaction length L:

$$L = \sqrt{\frac{K\eta}{\phi\mu}}$$

When the permeability K(ϕ) 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.



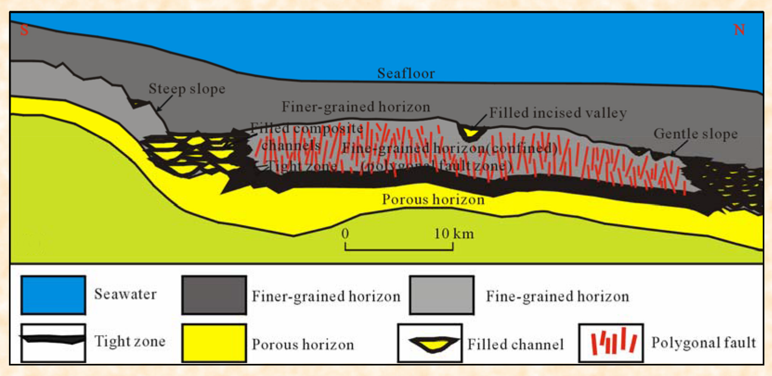
A very complicated problem is to decipher how the strength and the effective viscosity evolve when the porosity is close or greater than ϕ_{cons}. Beyond a deformation rate greater than ~0.3, interstitial water concentrates into microscopic veins where the grains, aggregates and agglomerates are free 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. Thus, this mimics what may happen in a consolidated medium under forced compaction.

Application to continental context

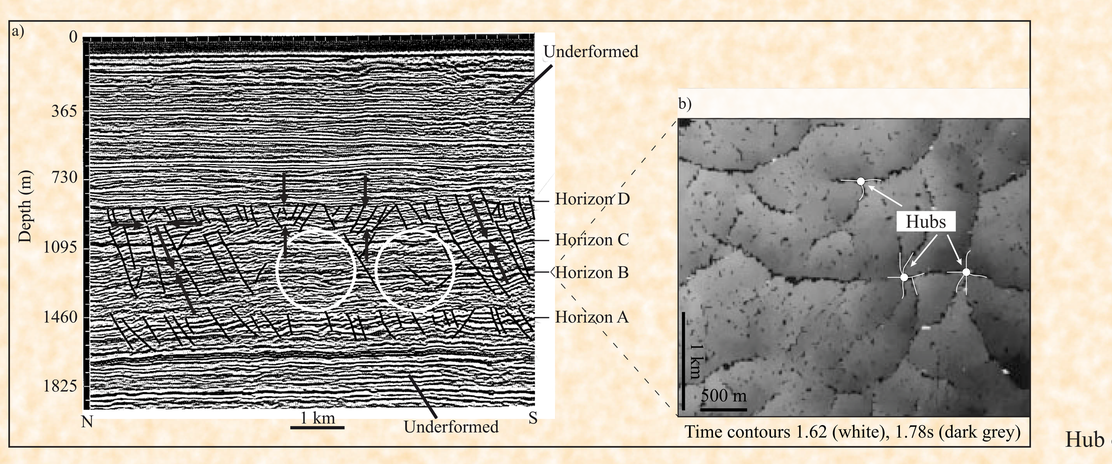
On continents, between viscosities of 10^4-10^8 Pa s, consolidation process leads to desiccation cracks with a size ranging from few centimetres (K) to hectometre (Sm). When evaporation starts, the porosity of the upper layer decreases progressively. When it is close to ϕ_{cons}, it becomes plastic with a yield strength related to the strength due to capillary suction [10]. At the contrary, the porosity under the dehydrated cap remains stable and thus, this layer is buoyant. 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 cylindrical waves with a radius proportional to the compaction length *L* that define the size of the polygons.

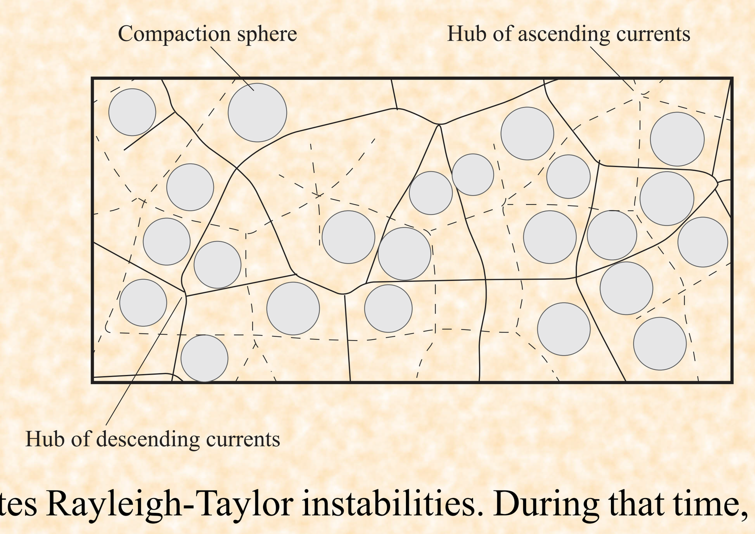
Application to marine context

Over a viscosity range of 10^4-10^8 Pa s, the compaction length rises until size of few kilometres, leading tho 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 finer clay-rich sediment [11; 12] and generates a yield strength of 0.1 MPa to 1 MPa.



As the consolidated clay-rich deposit becomes isolated, the water pressure increases progressively. This implies that this layer is overpressured and generates fluid-rich spheres whose radii are proportional to *L*. In submarine 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 planform





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

Conclusion

Polygonal 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 treshold (where the viscosity ranges from 10^4 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 to the consolidation treshold, free compaction stops and to overcome the new yield strength, forced compaction is necessary. It can be generated by dehydration on continents, top sealing and/or Rayleigh-Taylor instabilites in oceanic basins. To conclude, the formation of PFS can be explain compaction process that develops at different scales.

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 ≤ 10^{-16} m². However, the presence of the fracturing can dramatically increase the vertical permeability and thus the upward migration of fluids.

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