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Formation of polygonal fractures systems as a result of hydrodynamic instabilitites in clay-rich deposits.

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Abstract: Fine-grained clay deposits are characterised by the development of polygonal fractures systems. Two different environments are associated with their formation. On continents, dewatering leads to the development of polygonal fractures which have a centimetric to metric sizes. Polygonal fractures are observed in sub-marine sedimentary deposits and can reach hectometric to kilometric sizes. Such giant polygons develop on basins in the absence of tectonic stresses. The two main hypotheses of formation are the syneresis (spontaneous horizontal contraction) [1] and the low coefficient of friction of clay [2]. However, new understandings in the clay rheology and in the hydrodynamical instabilities, controlling the development of compaction in unconsolidated and consolidated clay deposits, permit us to propose an alternative model.

Estimation of the clay viscosity

In clay-rich deposits of oceanic basins, the initial porosity ϕ ranges between 50 and 90% and the material is unconsolidated. Due to the density difference between clays and interstitial fluids, the mud compacts until the porosity decreases to ~30%, when the sediment is consolidated. This porosity value is known as the critical consolidation-deconsolidation threshold value ϕ_c.

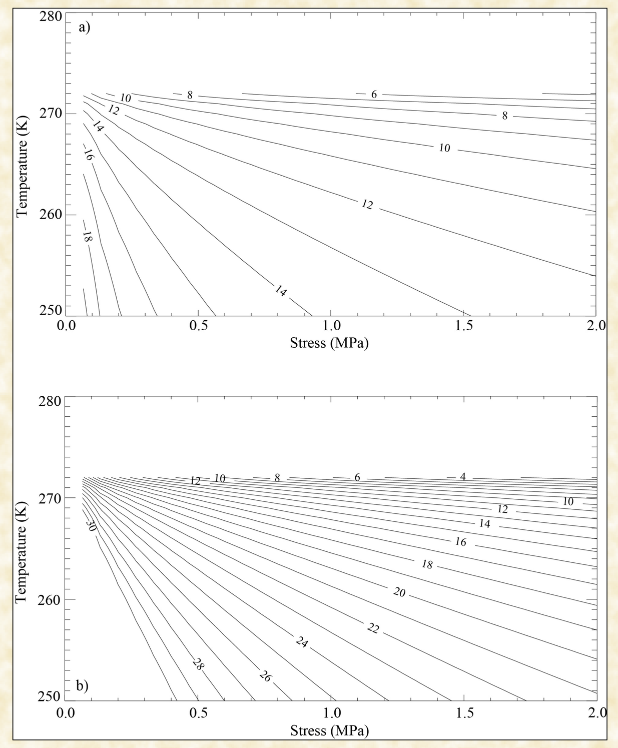
The clay-rich deposit behave as:

- a pure viscous fluid, with an effective viscosity of ~10^4 Pa s, when the fluid concentration < ϕ_c [3],
- a plastic material,with a low tensile strength and with an effective viscosity of ~10^6 Pa s, when the fluid concentration ~ ϕ_c [3],
- a plastic material since the deposit is consituted by a network of connected particles when the fluid concentration > ϕ_c.

→ **Mud rheology is non-linearly related to deviatoric stresses, fluid concentrations and confining pressure [3,4].**

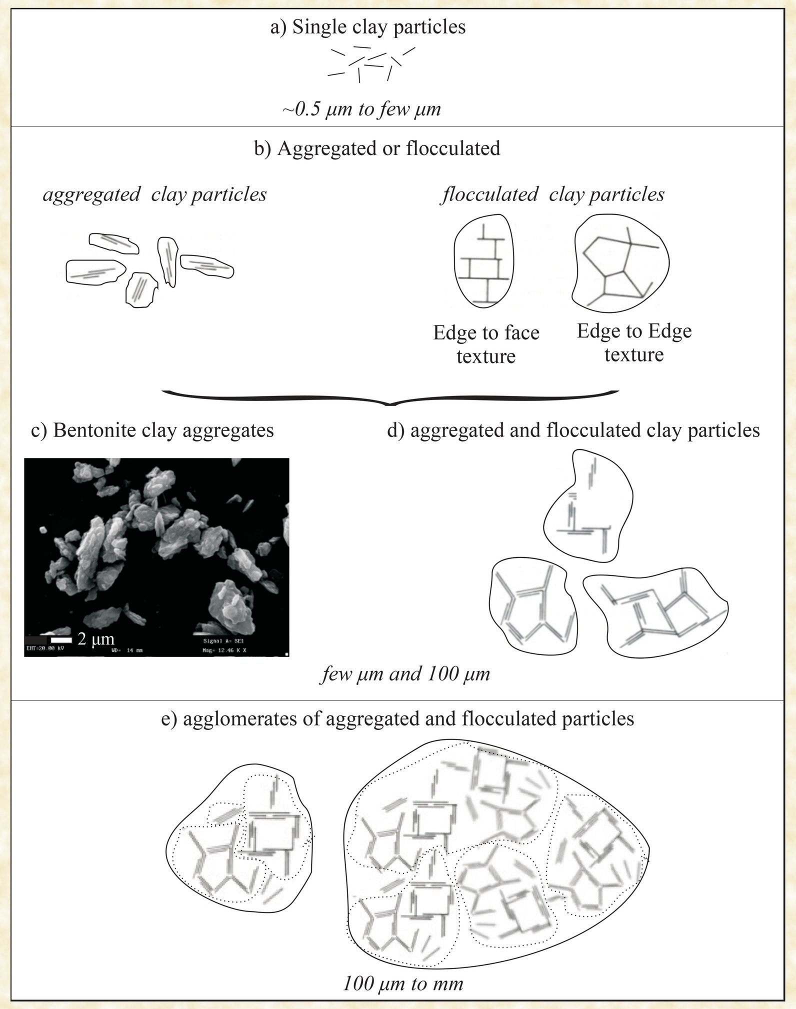
During deformation and just before the volume of fluid is normally totally squeezed during the compaction of the consolidated mud, interstitial water concentrates in microscopic veins where the clay grains are free to slide. To avoid this sliding effet, [6] investigated the rheology of saturated clay-rich soils below the temperature of freezing of the interstitial water. The estimation of the effective viscosity μ of the clay (Pa s) is related to the temperature T (K), its strength σ (MPa) and its density ρ (kg m^{-3}):

$$\mu = 10^6 \frac{(2.677 - 0.840\,10^{-4}\rho)\mathrm{x}(273-T)^{\frac{1}{0.470 - 0.212\,10^{-4}\rho}}}{\sigma^{\frac{1}{0.470 - 0.212\,10^{-4}\rho} - 1}}$$



Clay viscosity variation in logarithm scale (obtained from above equation) for a density of 1380 kg m^{-3} (a) and 1880 kg m^{-3} (b), as a function of the applied stress and the temperature. The variation of viscosity results from the decrease of the interstitial fluid volume with increasing densities. These results show that clays require a stress of a few hundreds of kPa to be deformable at 271 K (μ= 10^9 Pa s - 10^{12} Pa s) whereas clays deform at 258 K when the stress exceeds several MPa and then, the effective viscosity exceed 10^{12} Pa s.

Early compaction



In a suspension, indivicual clay grains aggregate themselves in fresh water or flocculate in salt water. These newly clay aggregates aggregate again and forms aggregation of aggregates or also referred as agglomerates.

During compaction until consolidation, the fluid-aggregates separation form pocket-like structures also called compaction spheres [7]. The development of spheres requires an unique condition: a strong obstruction to the upward free percolation of the interstitial fluid [5]. The size of these spheres are proportioanl to the compaction length L [8]:

$$L = \sqrt{(K\mu_s / \phi\mu_w)}$$

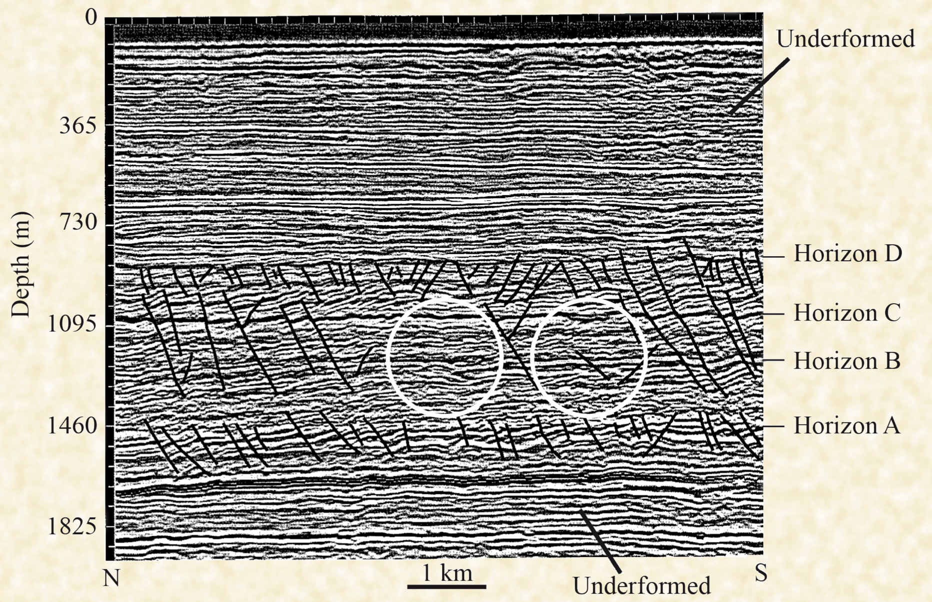
where K is the permeability (m²) and μ_s and μ_w are the viscosity of the suspension and of the water, respectively

Permeability depends on the porosity ϕ and the size of the agglomerates d. It is deduced from the Kozeny - Carman's law:

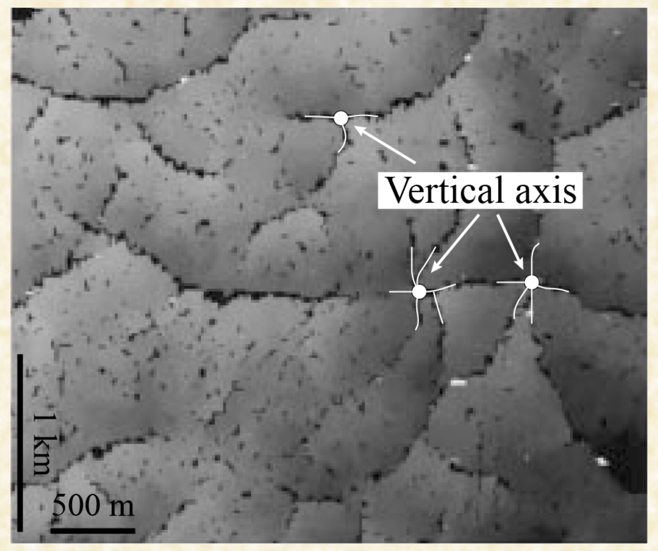
$$K = \frac{\phi^3 d^2}{(1-\phi)^2\ 172.8}$$

	Fresh water	Salt water
Permeability K	~10^{-17} m^2	~10^{-15} m^2
Compaction length L	100 µm	1 mm

Formation of the North Sea giant polygons



Seismic cross-section survey from the Central North Sea Basin. Four distinct horizons (A to D) are visible. Horizons A and D have a thickness of ~150 m and a dense network of conjugated steep faults. Horizons B-C have a tickness of ~500 m and some conjugated steep faults [Modified from 9]



Time contours 1.62 (white), 1.78s (dark grey)

Map showing the fractures in layer B, which is located at ~1.5 km depth. Note that the traces of the fractures delimit polygonal networks with characteristic lengths of ~500 m and ~1 km, respectively. Two to six fault planes (in white) are emitted from a hub (white dot) corresponding to a vertical axis [Modified from 9].

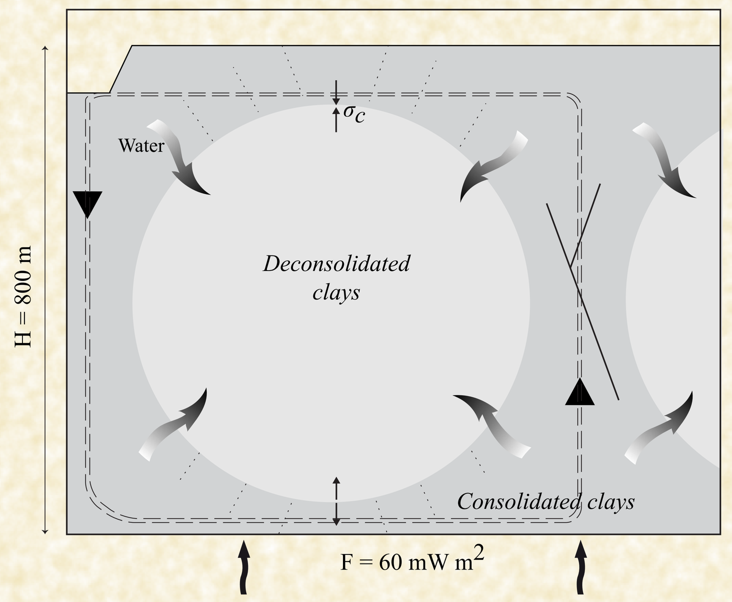
The effective viscosity depends on porosity and on the deviatoric stresses acting on the consolidated clay-rich deposit. In North Sea, the main process that generate deviatoric stresses is the compaction. In the B-C horizons, the rather circular region (white circles) devoid of fractures may represent paleo-cores of compaction spheres with a diameter h ~500 m. We deduce that the density contrast between spheres, constituted by deconsolidated clays, and the consolidated clay deposit is ~55 kg m^{-3}. The vertical compressive stress σ acting at the top and bottom of the compaction sphere is ~0.3 MPa.

Thus the effective viscosity μ of the clay deposit is ~2 10^{10} Pa s. Its permeability K is 10^{-11} m^2 or 10^{-9} m^2 and L is 25 m or 250 m, respectively. Compaction spheres generated during compaction have a size exceeding 2L. Thus, the compaction spheres with a diameter of ~800 m are representative of a deposit with a compaction length L closer to 250 m. It is consistent with a consolidated deposit with an initial permeability Kc of ~10^{-9} m^2. Such a high value of the permeability is only possible if the agglomerates produced during the consolidation of the clay have a size of ~1 mm, thus consistent with agglomerates produced during the early compaction of flocculated particles.

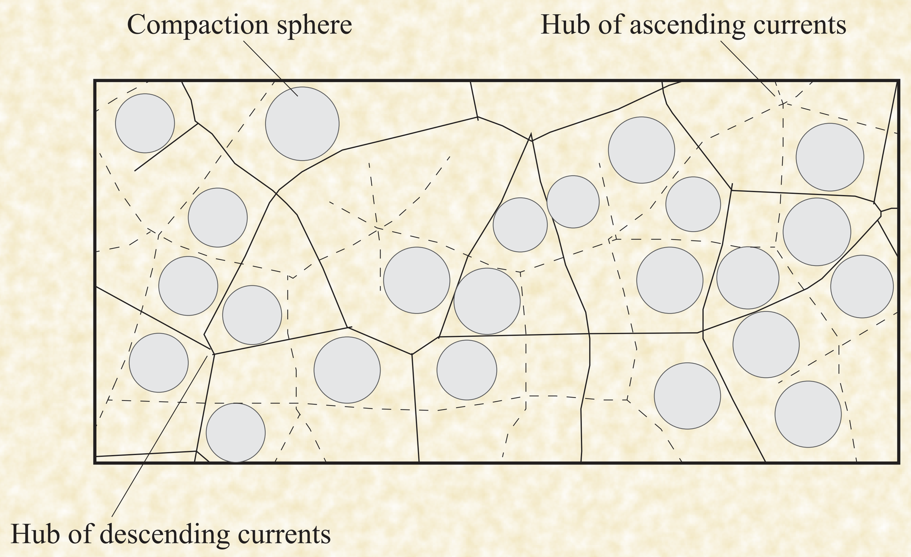
The presence of hubs in plan view from where three to six faults are emitted is characteristic of a spoke-pattern convection. The development of these hubs are specific to thermal convections or Rayleigh-Taylor overturns [9]. The polygonal geometry associated to the development of compaction spheres generates hubs with only at maximum 3 or 4 fractures. The only plausible explanation for the development of the hubs is to assume that at the same time that the compaction spheres grow, plastic flow convection develops. The plastic Rayleigh number is:

$$Ra_p = \frac{\rho g \alpha_p \Delta T H^3}{\mu_c \kappa_c}$$

Model parameters:
H = 800 m
F = 60 mW m^{-2}
ΔT = 40 K
σ = 0.3 MPa
μ ~10^9 Pa s
K ~ 10^{-9} m^2
L ~ 250 m
Ra_p ~ 10^6



Sketch representing the development of the North Sea giant polygons during the steady state of the model. Spherical compaction waves are generated in the consolidated layers and have a diameter of ~800 m.They induce horizontal fluid variation (grey arrows). The σ of 0.3 MPa creates fractures at their bottoms and tops.

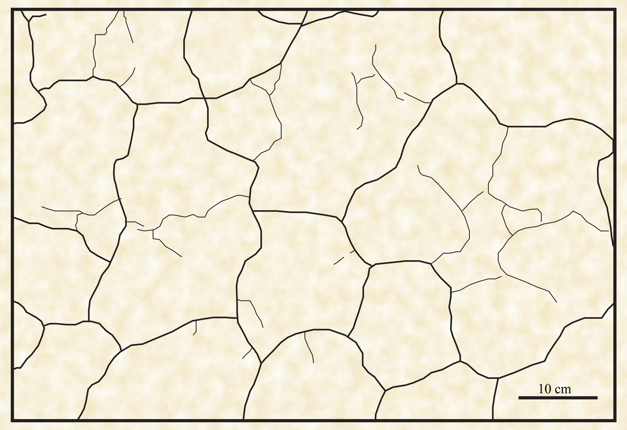


The polygonal features observed at the top of horizon B result from the plastic convection that occur at the same time than the compaction process. Thus, the ascending and descending currents of the plastic convection, represented by black lines and located below troughs, lead to the development of polygons.

Terrestrial polygons

At the surface, the top dewatering induces a porosity reduction which leads to a drastic reduction of its permeability. That obstruction provides the condition for the development of compaction spheres. However, the porosity reduction in the clay slurry was not important enough to fully consolidate it. The compaction length of the fluid-rich horizon is found to reach several cm.

The geometry of the polygonal fractures and the marine giant polygons in plan view is very different. We propose that this difference of geometry is due to the fact that in the case of marine giant polygons, hydrothermal and plastic convections develop at the same time than the compaction spheres.



Conclusion:

Recent understanding of consolidated clays rheology permit to propose new hypotheses for the development of giant polygons. We consider that the development of giant polygons results from the superposition of hydrodynamical instabilities leading to the formation of (i) mm-size agglomerates of clay particles while the deposit is unconsolidated, followed after by the consolidation of this layer, then (ii) hectometric to kilometric compaction spheres develop and (iii) finally ends with the occurrence of plastic convections. Two conditions are essential for the development of hectometric to kilometric size polygonal fractures systems: 1) high permeability of the clay deposit composed of mm-size agglomerates and 2) dramatic increase of the clay strength as the deposit consolidates.

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