”Sedimentological characteristics of glaciomarine clays”

Jens Jahren, University of Oslo

Quick clay formation (Torrance 1983):

- Must have a flocculated structure with high void ratio (Rosenqvist 1977)
- Rapid flocculation were silt and clay flocculate together
- High concentration of suspended material entering the water body encourage flocculation (Quigley 1980)
- Flocculated, high void ratio structure essential for later quick clay behaviour (Torrance 1974)
- Quick clay result from: leaching (Rosenqvist 1953), dispersing agents (Söderblom, 1966), cementation (Crawford 1963), rock flour – mechanical weathering (Smalley 1971)

The above show that depositional processes responsible for quick clay formation was not discussed in the quick clay litterature at this time.

This means that sedimentological conditions during deposition potentially affecting extent and distribution of quick clay deposits was not much considered.

Liquefaction is recognized in the litterature but the actual mechanisms responsible for quick clay liquefaction are not much discussed

Quick clay understanding/model

Factors producing high undisturbed strength and high sensitivity

(1) Depositional flocculation
Saline (low zeta potential)
High sediment concentration
Divalent cation adsorption
(2) Slow increase in sediment load
(3) Cementation bonds
Carbonates and sesquioxides (amorphous)

$$S_t = \frac{S_u \text{ undist}}{S_u \text{ remould}}$$

Factors producing low remoulded strength and high sensitivity

(1) High water content ($w_n > w_L$)
Little consolidation or
Decrease in w_L > Decrease in w_n
(2) Low specific surface of soil grains
High silt content or high rock flour in $<2\,\mu$m fraction
High primary mineral ≡ low clay mineral content
(3) High zeta potential
(expanded double layer = high interparticle repulsion = dispersed or peptized state)
Low salinity by leaching (≤ 2 g l^{-1})
Organic dispersants (anion adsorption)
Inorganic dispersants (anion adsorption)
High monovalent cation adsorption relative to divalent cations
(4) Low amorphous content
(5) Low smectite content

Fig. 1. Geochemical and mineralogical controls on sensitivity of clayey soils (from Quigley, 1980).

Table 1. Sensitivity scale (Skempton & Northey, 1952)

Sensitivity	Designation
1	Insensitive clays
1–2	Clays of low sensitivity
2–4	Clays of medium sensitivity
4–8	Sensitive clays
> 8	Extra sensitive clays
> 16	Quick clays

Table 2. Sensitivity scale (Rosenqvist, 1953)

Sensitivity	Designation
1	Insensitive clays
1–2	Slightly sensitive clays
2–4	Medium sensitive clays
4–8	Very sensitive clays
8–16	Slightly quick clays
16–32	Medium quick clays
32–64	Very quick clays
> 64	Extra quick clays

Table 3. Sensitivity scale (Norsk Geoteknisk Forening, 1974)

Sensitivity	Designation
< 8	Low sensitivity
8–30	Medium high sensitivity
> 30	High sensitivity*

*To be called 'quick clay' the remoulded soil must be a fluid i.e. it has a remoulded shear strength < 0·5 kPa.

Factors producing a high undisturbed strength	
Depositional	**Post-depositional**
Flocculation[1,2] salinity divalent cation adsorption high suspension concentration	Cementation bonds rapidly developed slowly developed Slow load increase time for cementation 'thixotropic' processes

Factors producing a low remoulded strength	
Depositional	**Post-depositional**
Material properties low activity minerals dominate[1,2]	Minimal consolidation Leaching[1] decrease in w_L > decrease in w Dispersants[2] decrease in w_L > decrease in w

[1]Essential in marine clays.
[2]Essential in freshwater clays.

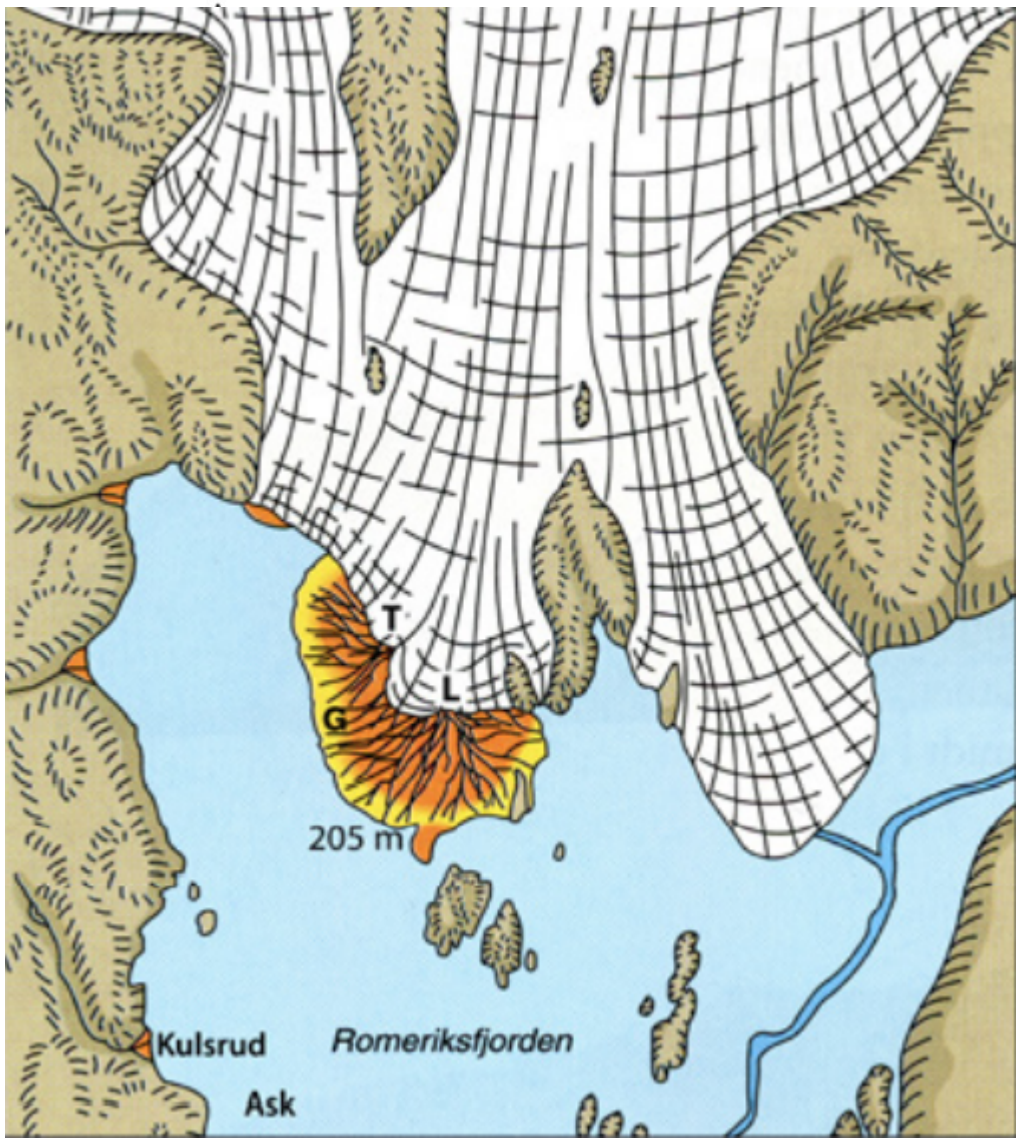
Fig. 2. General model for quick clay development or factors producing high sensitivity in clayey sediments.

Torrance, Sedimentology 1983

Sedimentological perspective:

- Basin configuration,
- Basin infill dynamics,
- Preexisting bedrock topography
- Sediment routing
- Sediment composition,
- Flocculation processes
- Physical changes during deposition,
- Depositional processes,
- Depositional architecture
- Resulting sediment topography
- Sediment texture
- Differential compaction
- Postdepositional processes
- Chemical aspects
- Physical aspects

Example - Gardermoen



NGU rapport 2021 modifisert fra Bargel 2005

Sedimentological modelling of Gardermoen Delta (Tuttle 1998)

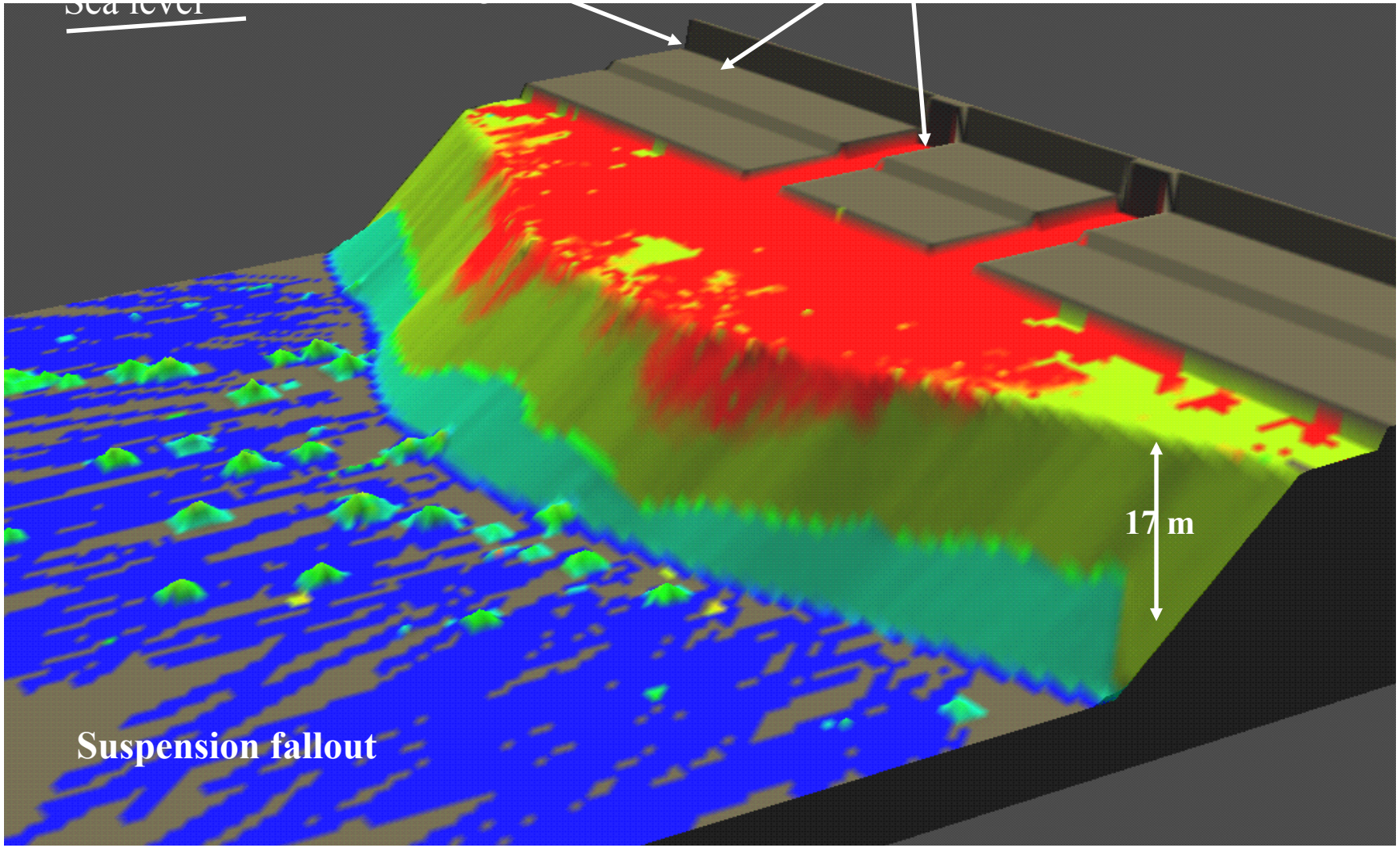
Coarse (pebbles and c. sand),

Medium (m. sand),

Fine (f. sand),

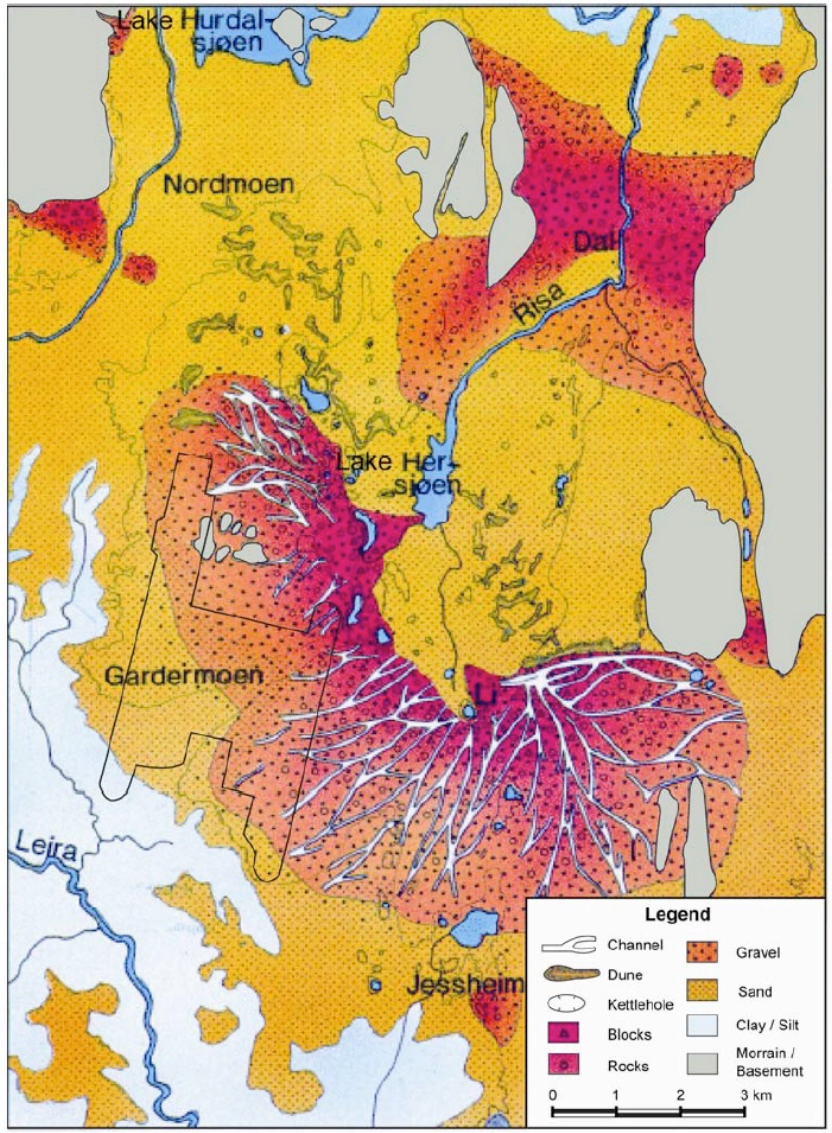
Very Fine (silt and clay)

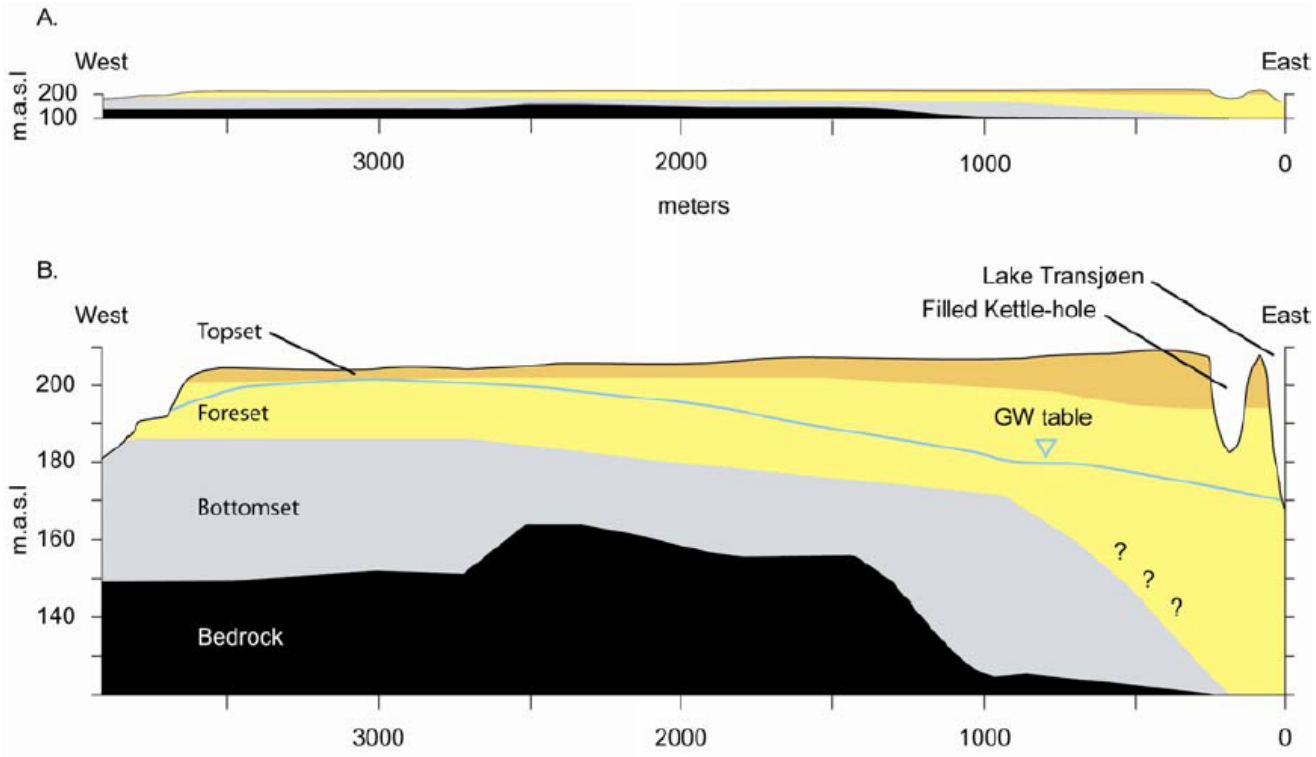
Grid spacing = 4 m, Area = 640 X 640 m, Vertical exaggeration = 3,
One melt season (150 days)



Tuttle, 1998

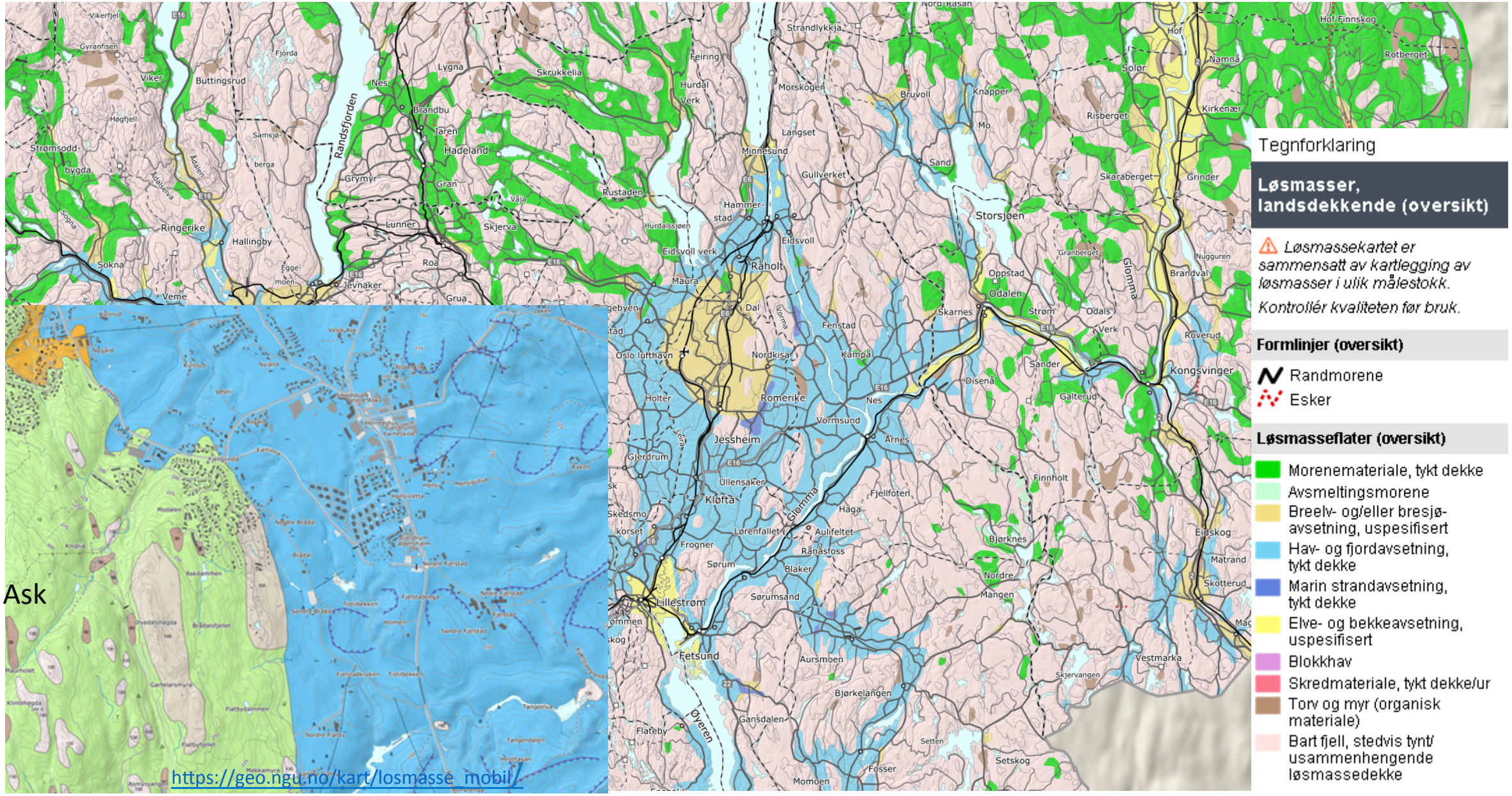
Gardermoen



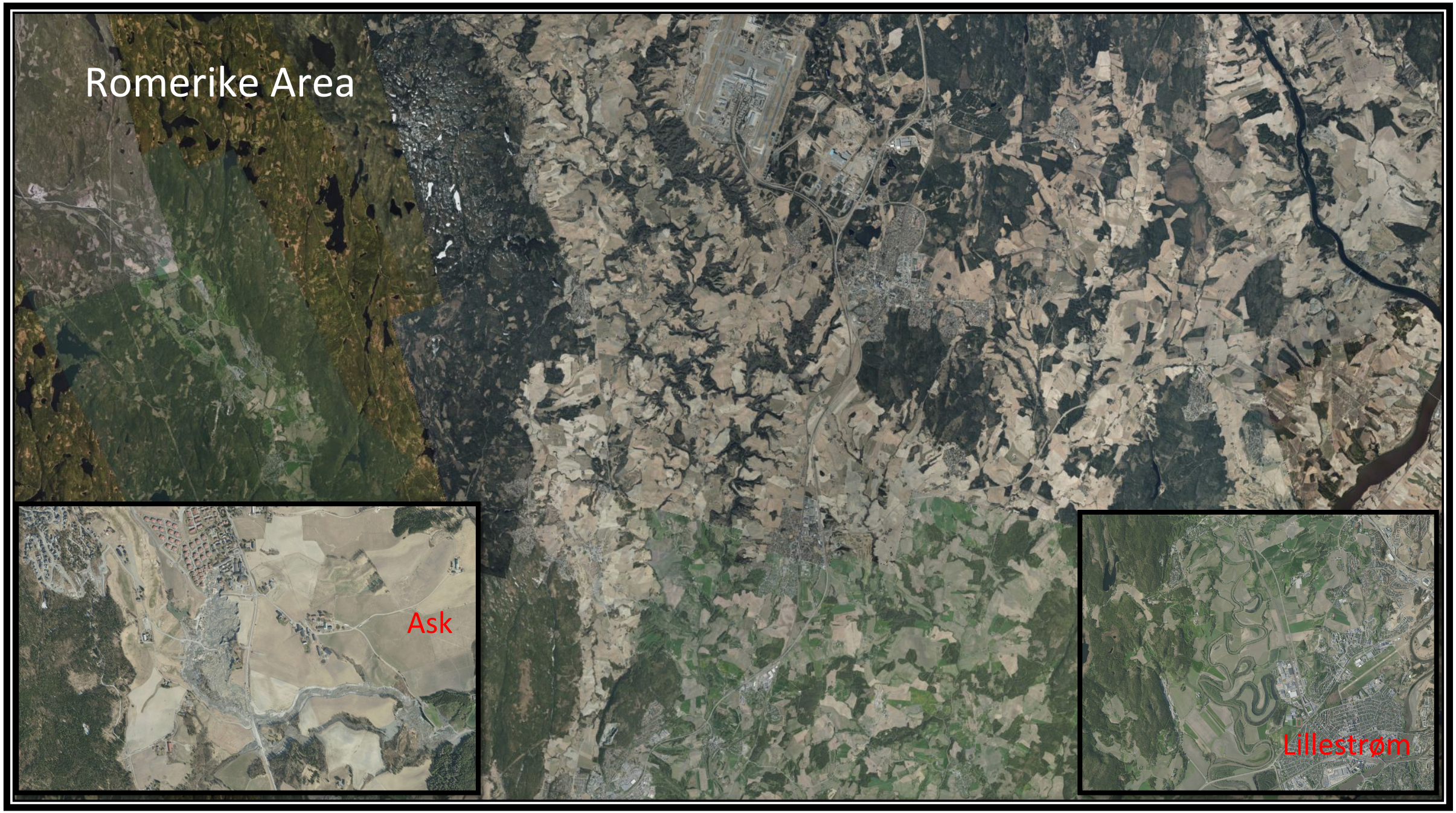


Jørgensen and Østmo 1990, Tuttle 1997, Sundal, et al 2019

Romerike Area

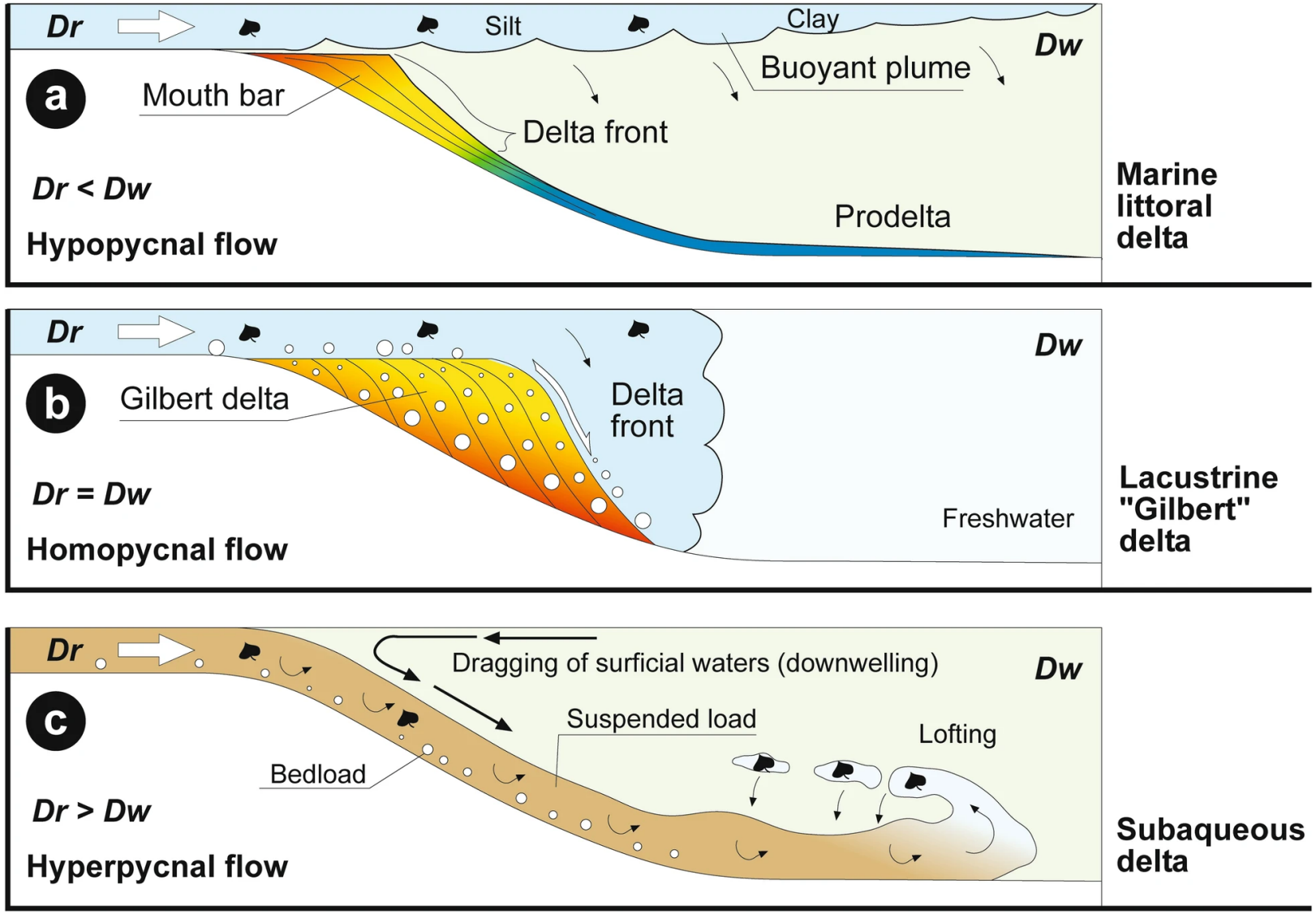


https://geo.ngu.no/kart/losmasse_mobil/


Romerike Area
Ask
Lillestrøm

Density derived modes of flow

Origin of hypopycnal (a), homopycnal (b) and hyperpycnal (c) flows as a result of the density contrast between river discharge and basin waters. Note in c that the excess in density is provided by sediments in turbulent suspension. Modified from Zavala and Pan 2018

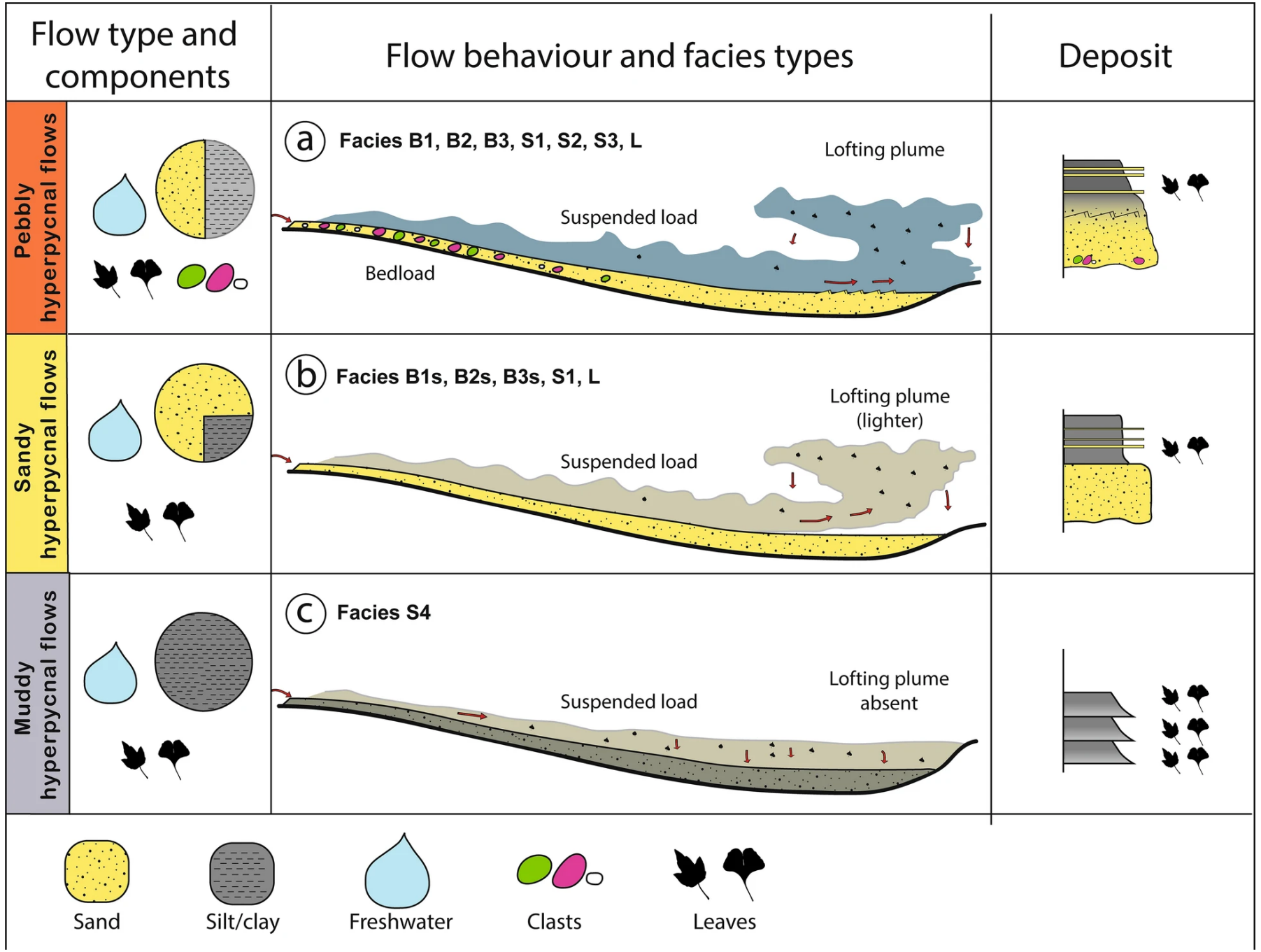


Hyperpycnal flow

"A hyperpycnal flow forms when a relatively dense land-derived gravity flow enters into a marine or lacustrine water reservoir. As a consequence a highly dynamic and often long-lived dense underflow develops. Depending on the characteristics of the parent flow the resulting deposits (hyperpycnites) can be very variable".

"Muddy SLTF. Due to the excess of density provided by the silt/ clay suspension, the flow will be always attached to the basin bottom until the final deposition, and consequently lofting is not possible".

(Zavala 2020)



Modified from Zavala and Arcuri 2016

Fine grained hyperpycnal deposits: Schieber, Southard, Thaisen (2007) Accretion of Mudstone Beds from Migrating Floccule Ripples. Science

It appears that irrespective of what drives flocculation in a given experiment, flocculation provides deposition-prone particles without fail over a wide range of experimental conditions. Formation of floccule ripples from a variety of clay-size materials (kaolinite, montmorillonite, and lake mud), and over a range of sediment concentrations and salinities (distilled, fresh, and salt water) strongly suggests a universal process at work.

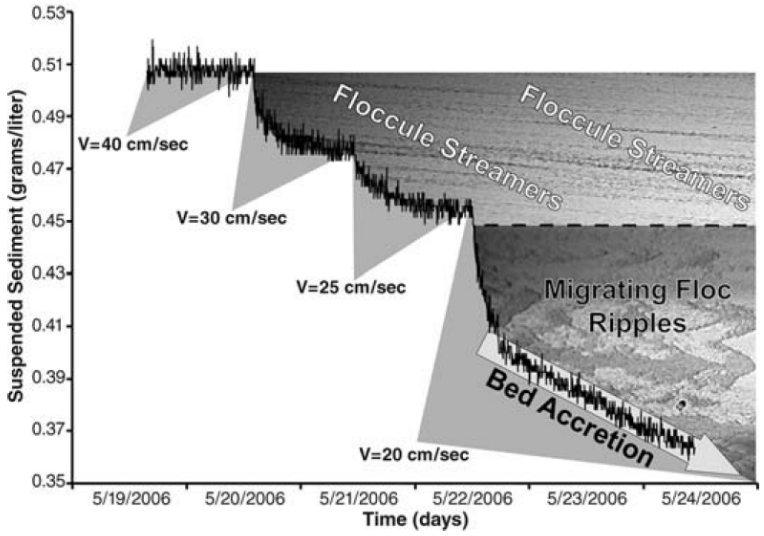


Fig. 2. Example of changes in suspended sediment in the course of an experiment. Vertical axis shows continuously logged suspended sediment concentration, and horizontal axis shows time elapsed (tick marks separate successive days). The critical velocity of sedimentation lies between 25 cm/s and 20 cm/s and coincides with the onset of development of floccule ripples. Its exact determination requires the use of smaller velocity steps.

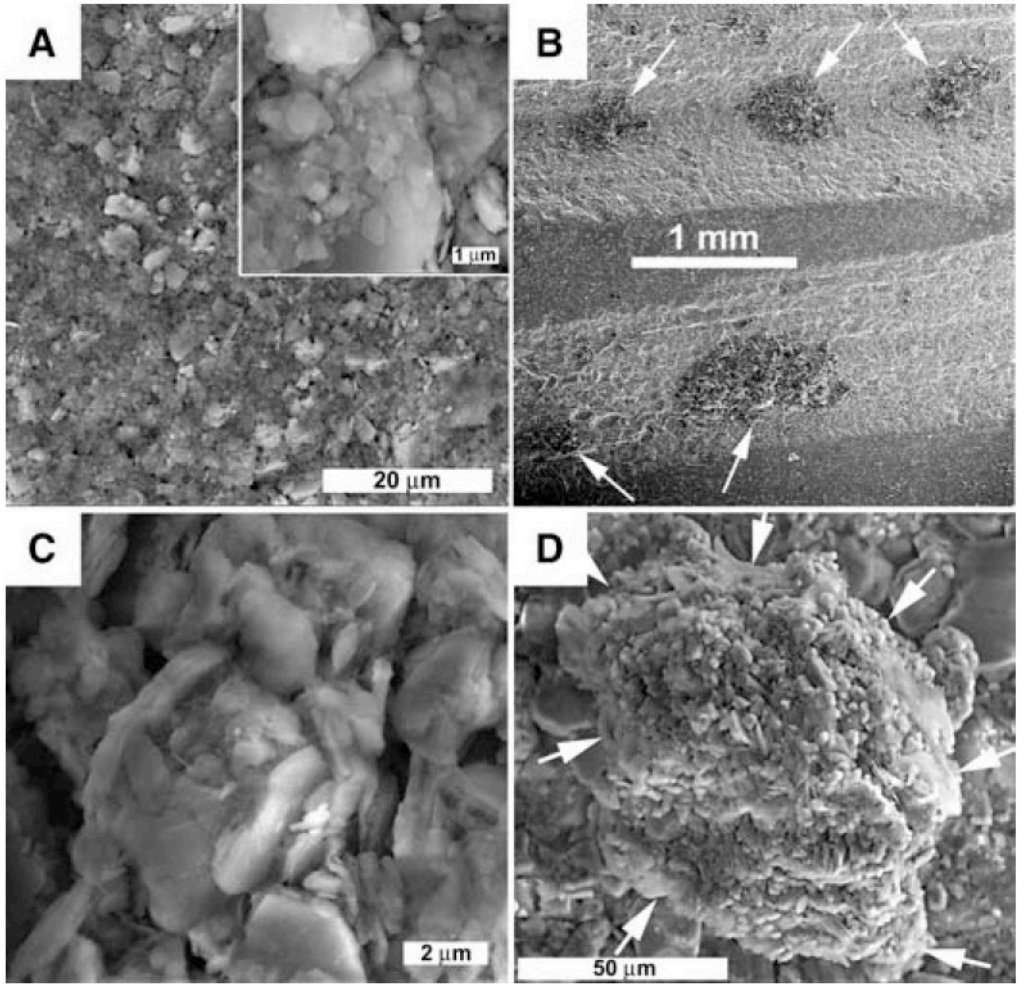


Fig. 1. Flume feed and floccules. (**A**) SEM image of typical kaolinite clay used in the majority of experiments. Inset shows size and morphology of clay flakes. (**B**) SEM image of floccules (pointed out by arrows) that were trapped at the flume bottom with a grooved glass slide. (**C**) Close-up of floccules in (B). (**D**) SEM image of a floccule (outline marked with white arrows). This floccule measures 0.12 mm along the long axis.

Schieber, Southard, Thaisen (2007) Accretion of Mudstone Beds from Migrating Floccule Ripples. Science

Our observations do not support the notion that muds can only be deposited in quiet environments with only intermittent weak currents (*8*). Instead, bedload transport of flocculated mud and deposition occurs at current velocities that would also transport and deposit sand (*21*). Clay beds can accrete from migrating floccule ripples under swiftly moving currents in the 10 cm/s to 26 cm/s velocity range, a range likely to expand as flows with larger sediment concentrations are explored. Whereas the

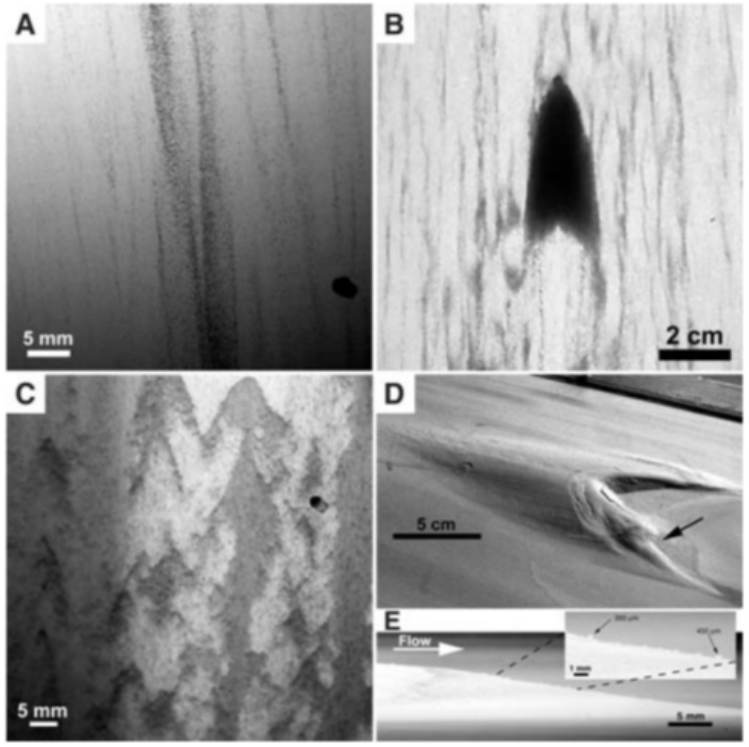


Fig. 3. (**A**) Floccule streamers photographed through the flume bottom (flow velocity 48 cm/s, initial sediment concentration 0.72 g/liter, lake mud in tap water). (**B**) Streamlined floccule ripple and floccule streamers. (**C**) Multiple floccule ripples begin to coalesce. Flow is from top to bottom in images (A), (B), and (C). (**D**) Oblique view of large barchan-shaped migrating floccule ripple. Flow is toward the right. (**E**) Side view of the left horn of this ripple [pointed out by black arrow in (D)]. Inset shows that the surface is covered with small, round bodies, the clay floccules that moved across the ripple during current activity. Numbers indicate floccule size.

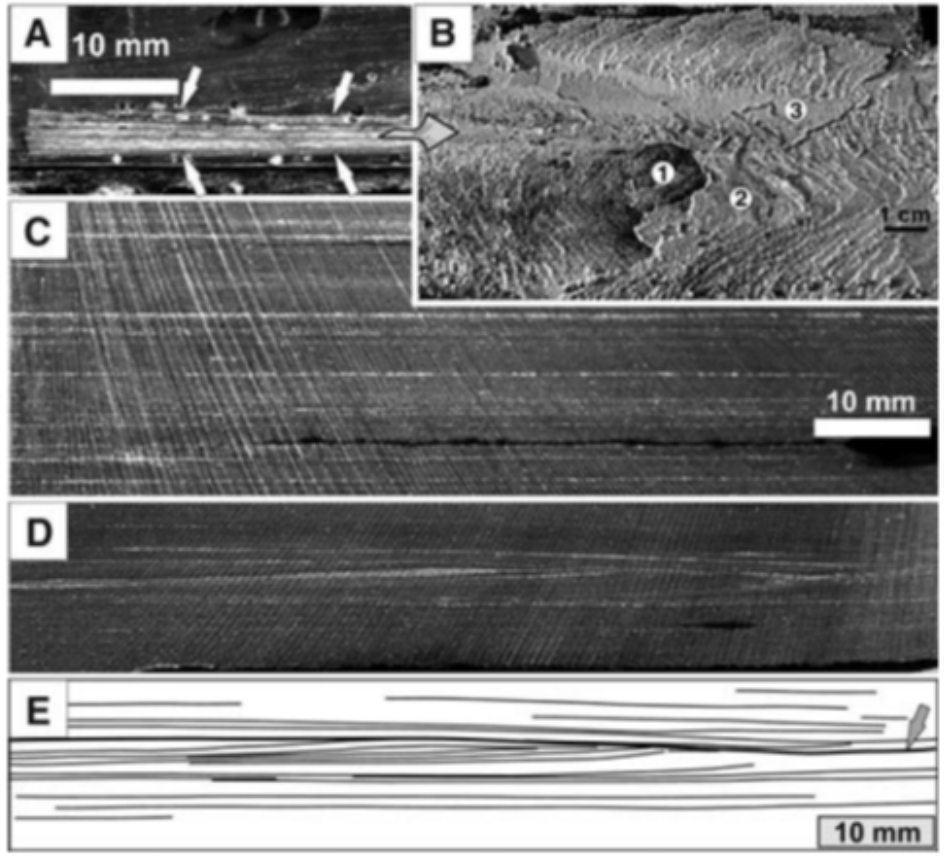


Fig. 4. (**A**) Laminated flume sediment (between white arrows) that was deposited during an experiment with continuous current flow. Sample was embedded in epoxy and cut perpendicular to bedding. Sample is curved due to desiccation. The darker internal laminae are hematite markers. (**B**) Textural detail from the interior of the clay layer in (A) (top view, arrow indicates 90° twist). As the layer dried out, its upper portion formed concave desiccation polygons, whereas its lower portion remained attached to the flume bottom. Removing the upper portion exposes a bottom-parallel surface through the clay layer. The curved lines are the upper terminations of broken foreset laminae of floccule ripples. The foreset laminae are inclined to the right, and the circled numbers indicate a succession of overriding ripples (see also fig. S4). The overall texture resembles "rib and furrow" structures as known from current rippled sandstones (*24*). (**C**) Parallel-laminated black shale, New Albany Shale, Devonian, Indiana. Lighter laminae are silt-enriched. (**D**) Cross-laminated shale collected from the same core box as (C). (**E**) Tracing of silt laminae visible in (D). Arrow marks an internal erosion surface. In the center are inclined (to the left) truncated laminae, forming the outline of a compacted and mud-dominated ripple. The synoptic relief of this ripple is 3 mm, but its original relief would have been ~20 mm (assuming 85% water content), the same magnitude as observed in our experiments.

Some references/oral communications:

"Charles Nittrouer, UNIVERSITY OF WASHINGTON, faculty member in both the School of Oceanography and the Department of Earth and Space Sciences, is a geological oceanographer who studies the ways that sediment behaves in various marine environments".

Charles Nittrouer (communicating with Per Aagaard):

"I include these [*references below*] to give you a sense of the type work we did. Although interested in sediment transport and deposition, we never investigated the floc character of the particles. However, in temperate tide-water systems with extremely rapid sediment accumulation rates (Alaska, Patagonia), the flat surfaces of the fjord deposits are likely demonstration of hyperpycnal flows being dominant".

"I'm sure you have seen rapidly accumulating flat-bottomed fjords that I mentioned. As an example, below is some rough data from Jorge Montt fjord at the northern end of the Southern Patagonia ice field. These sedimentary strata have accumulated in about 10 years, since the ice front started retreating past a choke point. Sediment accumulation rates are many meters per year, and almost impossible to be supplied to the bed by pelagic sedimentation (i.e., settling from suspension)."

J.M. Jaeger and C.A. Nittrouer, Sediment deposition in an Alaskan fjord: controls on the formation and preservation of sedimentary structures in Icy Bay, J. Sed. Res., 69, 1011-1026 (1999).

K.V. Boldt, C.A. Nittrouer, B. Hallet, M.N. Koppes, B.K. Forrest, J.S. Wellner, and J.B. Anderson, Modern rates of glacial sediment accumulation along a 15o S-N transect: in fjords of the Antarctic Peninsula and southern Chile, Jour. Geophys. Res. Earth Surface, 118, 2072-2088, doi:10.1002/jgrf.20145 (2013).

E.F.Eidam, C.A. Nittrouer, Ø. Lundesgaard, K.K. Homolka, and C.R. Smith, Variability of sediment accumulation rates in an Antarctic fjord. Geophys. Res. Letts., 46, 13271-13280, doi.org/10.1029/2019GL084499 <https://doi.org/10.1029/2019GL084499> (2019).

O'BRIEN, N. R., NAKAZAWA*, K. E. I. J. I., & TOKUHASHI*, S. H. U. I. C. H. I. (1980). Use of clay fabric to distinguish turbiditic and hemipelagic siltstones and silts. *Sedimentology*, *27*(1), 47-61.

"… Clay fabric differences are pronounced. Random clay flake orientation prevails in the turbiditic interval while the hemipelagic unit has more preferred orientation. The fabric reflects different conditions of sedimentation. The turbiditic clay was deposited more rapidly in the flocculated state while the interturbidite hemipelagic clay may have formed from more slowly sedimented dominantly dispersed clay. Results suggest that clay fabric may be useful in combination with other sedimentary features in the study of mud-turbidite sedimentation."

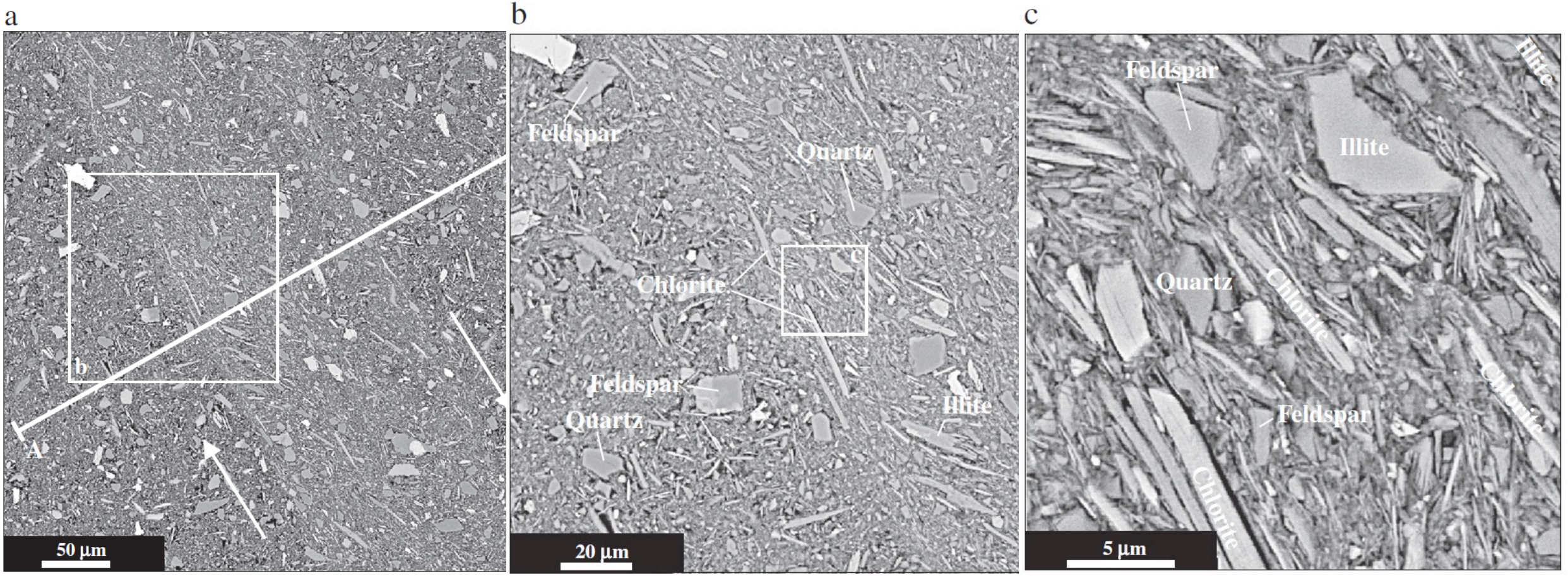
O'Brien, N. R. (1971). Fabric of kaolinite and illite floccules. Clays and Clay Minerals, 19(6), 353-359.

"Clays were flocculated in the laboratory in both distilled water and slightly saline (1 g/l. NaCl) water using various clay concentrations."

"Illite floccules in distilled water also consist of abundant face-face oriented overlapping flakes. However, in salt water there is a more even mixture of fabrics-edge-to-face flocculation of individual platelets and also stepped clusters of face-to-face oriented flakes, the latter being more abundant."

"It is suggested that under the experimental conditions the double layer of each clay particle is compressed resulting in an increase in the importance of van der Waals forces of attraction. As a result flakes approach each other and rotate into a parallel or subparallel position. The resultant dominant fabric is that of a stepped cluster of overlapping flakes."

Texture, mineralogy

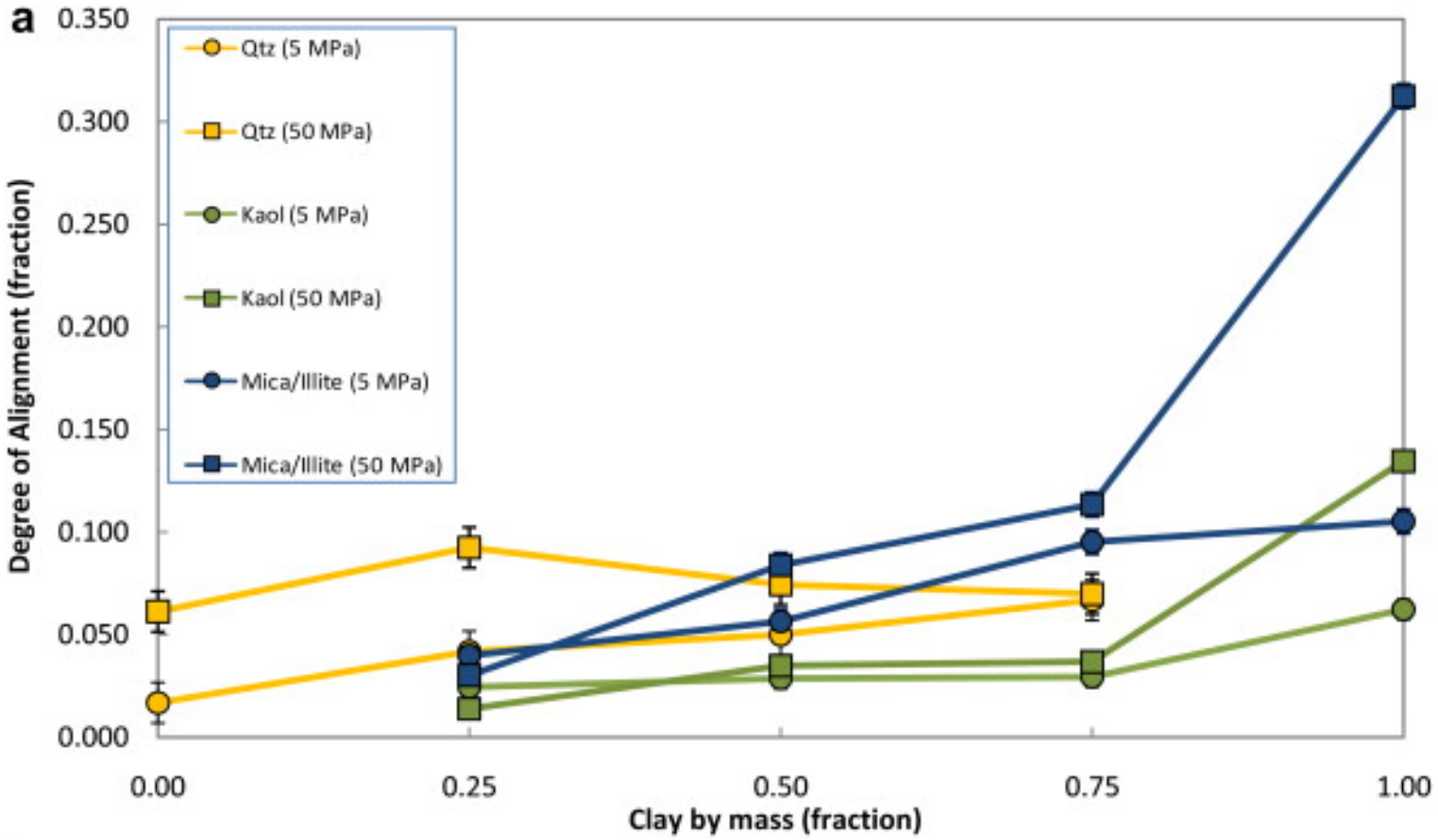


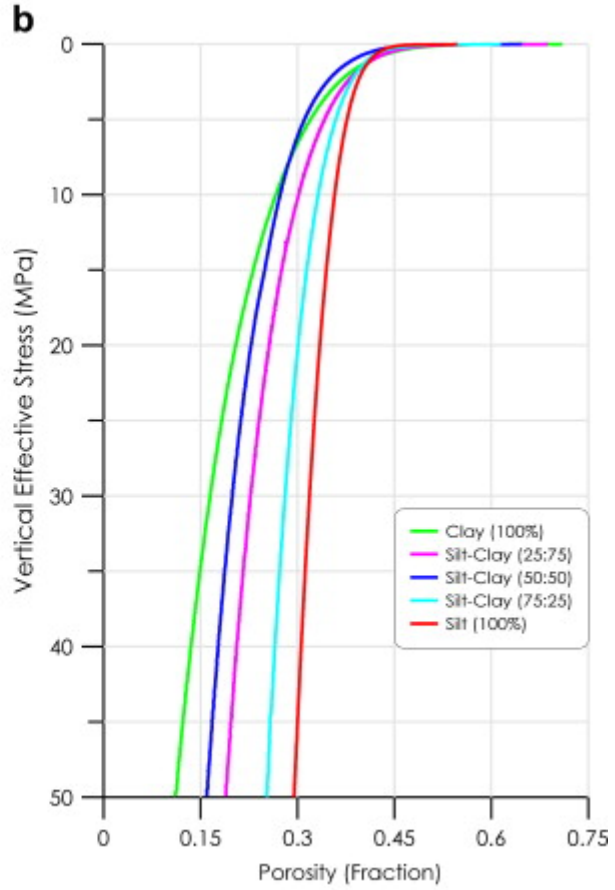
Microstructural observations of shear zones in sensitive clay

Gylland et al (2013)

Compaction alignment in clay – silt aggregates from uniaxial compaction experiments:

a) Degree of alignment (DOA) of quartz, mica/illite and kaolinite plotted against clay content in silt-clay mixture. It is evident that addition of clay content in a silt-clay mixture generally increases degree of mineral alignment. Mica/ illite fabric alignment is systematically higher than that of kaolinite. b) Porosity change in silt-clay mixtures as a function of vertical stress





Fawad et al 2010

Possible implications (practical and academic) of better understanding of quick clay depositional processes

- Architecture of possible quick clay deposit (3D)
- Better control on hydrogeology/permeability contrasts/leaching
- The importance of flocculation, mineralogy, grain size distribution, grain types, grain fractions, grain packing and texture (resulting in an interlocked clay-silt structure – preventing compaction – essential for quick clay formation?)
- Possible natural stabilizing mechanisms (amount and depth of shearing during differential compaction, effect of ravine formation)
- Quick clay fluidization/liquefaction process – why are some layers more "quick" than others



Way forward? Some geology related quick clay issues:

- Is delineating quick clay architecture feasible?
- Better understanding of textural prerequisits and practical detection of quick clay?
- Rock physics template development for reliable quick clay detection (density-resistivity)?
- Role of hydrogeology

Flooding Drammenselva 2013

Bilde tatt fra NASAs satellitt Terra på formiddagen søndag 26. mai 2013. (Foto: (NASA Terra MODIS))