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Differentiating hyperpycnal, hypopycnal and turbidity current deposits in a fine-grained Pleistocene-Holocene glaciogenic system

Omar Al-Mufti and Bill Arnott, Department of Earth and Environmental Sciences, University of Ottawa

Introduction

The fate of sediment-laden density flows, whether flowing into the depositional basin or sourced from within it, are strongly controlled by the density contrast between the flow and the basin fluid, which in turn fundamentally influences the character of the sedimentary deposit. However, differentiating the deposits of hyperpycnal and hypopycnal flows, respectively inflow density greater and less than the basin fluid, in addition to turbidity currents, namely flows initiated by slope failure in the basin, remains a source of much debate. In part this can be attributed to the difficulty in determining the density of the fluid in an ancient depositional basin, which then is often assumed. Here, based on a variety of geochemical and biological attributes in an almost modern succession of glaciogenic deposits, basin fluid conditions are well constrained and shown to have varied from freshwater to seawater – a change that occurred in as little as several years. Since sediment texture and mineralogy remained constant, and sediment flux incrementally constant, observed changes in depositional characteristics can be attributed to changes in the composition of the basin fluid, and thereby its control on the character and trajectory of sediment-laden density flows.

Study area and methods

During melting of the Laurentide Ice Sheet and northward migration of the ice front a glaciolacustine basin formed in the isostatically depressed Lake Champlain, St. Lawrence and Ottawa River valleys forming glacial Lake Candona (Parent & Occhietti, 1988). Later as the ice front retreated north of Québec City, marine water from the Atlantic Ocean entered the glacio-isostatically depressed basin (Cronin, 1977) and converted Lake Candona into the Champlain Sea (Fig. 1A) – a transition that occurred in as little as several years (Al-Mufti et al., 2024). Deposition of fine-grained sediment, mostly silt and clay, blanketed the Ottawa area with a thick succession (up to ca 100 m) of "mud" that commonly is termed the 'Champlain Sea mud/sediment' or 'Leda Clay'. In terms of geotechnical properties, these sediments are considered 'sensitive clays' and prone to failure when stressed and therein represents a significant concern for substrate stability, particularly in urbanized areas like Ottawa.

Fine-grained strata were studied at four locations (Fig. 1B) — specifically, outcrop exposures at Pinecrest Creek in west Ottawa and an excavation site in east Ottawa, and two cored boreholes (66 m and 47 m long) 2.75 km apart in east Ottawa. Previous work by Al-Mufti et al. (2022) subdivided the stratigraphic succession into four informal mud-dominated lithostratigraphic units, which from base to top are mud rhythmites (Unit 1), bioturbated mud (Unit 2), banded mud (Unit 3), diffusely stratified or structureless mud intercalated with well-stratified mud and deformed mud (Unit 4) — Unit 1 was deposited in glaciolacustrine Lake Candona whereas units 2 to 4 were deposited in the glaciomarine Champlain Sea.

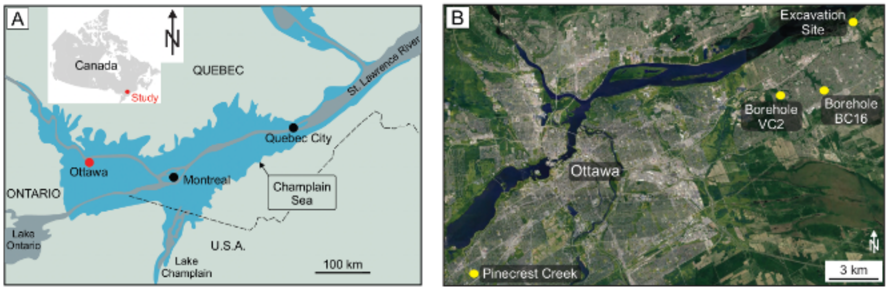

Fig. 1(A) Extent of the Pleistocene-Holocene Champlain Sea and (B) study sites in the Ottawa area

Due to their fine grain size and macroscopic textural uniformity cores were first scanned using X-ray computed tomography (CT). Although CT can effectively discriminate sedimentological features like laminae, bedding, and trace fossils, data resolution was limited to a vertical resolution of ~ 0.6 mm. Therefore, to identify details of texture and grain fabric at the sub-0.6-mm-scale sediment samples from core and outcrop were made into thin sections and then analyzed using conventional optical and scanning electron microscopy. These analyses showed that strata comprise two distinct lithotypes: Microfacies A and B, which are summarized next.

Results

X-ray computed tomography (CT) showed that all strata are characterized by a several cm- to few-dm-thick pattern of upward increase followed by decrease in stratal bulk density (measured in Hounsfield units, HU). This rhythmic pattern in bed-scale HU corresponds to differences in silt abundance and was interpreted by Al-Mufti et al. (2022) to record the waxing followed by waning of annual glacial meltwater discharge. More detailed petrographic and scanning electron microscopy showed that units 2, 3 and most of unit 4 consist of structureless mud with dispersed laterally discontinuous well-sorted silt lens (Microfacies A, see next), whereas units 1 and intercalated beds in Unit 4 consist of well-stratified mud (Microfacies B, see next). Interestingly, the change from well-stratified mud in Unit 1 to mostly structureless mud in the overlying stratigraphic succession coincides with a change from freshwater conditions in Lake Candona to seawater in the Champlain Sea suggesting a relationship between basin fluid composition and the character of sedimentation, which as discussed below involves a change in both sediment transport and deposition.

Microfacies A – Structureless mud with dispersed silt lenses

Microfacies A (MFA) consists of structureless mud made up of clay-size particles with varying abundance of dispersed, laterally discontinuous lenses of well-sorted silt. Strata are ungraded, inverse or normally graded, the latter two being defined by upward changes in silt abundance and grain size. MFA is dominated by mud particles that are < 1 micron in size and show no noticeable particle fabric. Additionally, clay minerals contribute negligibly to the clay size fraction. Where present, silt lenses occur as laterally discontinuous features composed of moderately to well-sorted, medium to coarse silt with uncommon fine silt-size grains (Fig. 2A) and a notable absence of clay particles (Fig. 2B). Silt lenses range from a single silt grain up to ca 100 μm thick and 50 μm to 1000 μm wide.

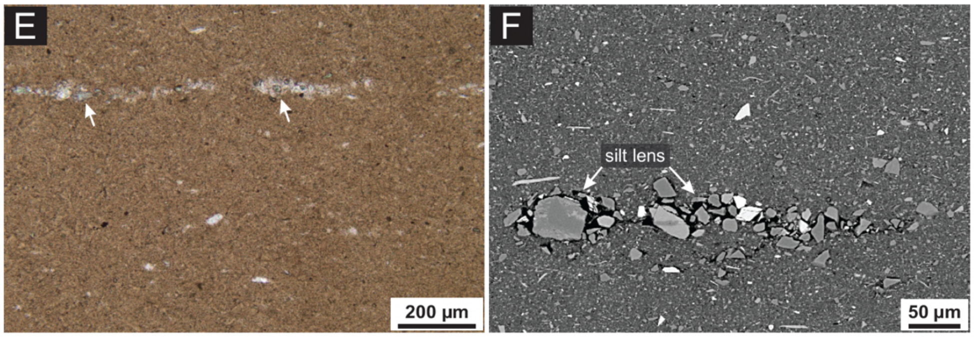

Figure 4 – Microfacies A: structureless mud with dispersed silt lenses (A) plane-polarized light photomicrograph (A) and (B) backscattered micrographs

Microfacies B – Planar-laminated mud

Microfacies B (MFB) is characterised by a distinctive pinstripe motif of laterally continuous, sharply alternating silt-rich and clay-rich layers, each ranging from a few tens of micrometres up to ca 500 µm thick (Fig. 3A, B). The base of MFB is sharp and planar except where loaded (Fig. 6A). Laterally continuous silt-rich layers consist of moderately to well-sorted, mostly medium to coarse silt and uncommon silt-size mud intraclasts (Fig. 3B, C). Clay-rich layers are comparatively more poorly sorted and composed of a mixture of clay and dispersed very fine to medium silt-size grains. Unit 4a strata also contain common to abundant silt to medium sand-size mud intraclasts (Fig. 3C, D), although intraclasts are dominantly coarse silt to very fine sand-size.

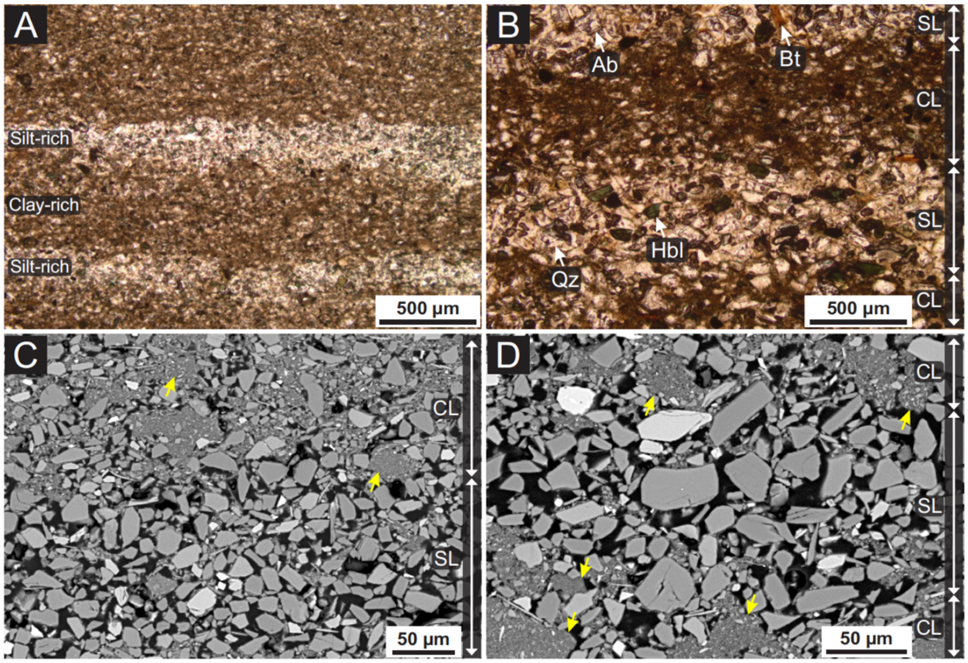

Figure 3 –Microfacies B: planar-laminated mud. (A, B) Plane-polarized light photomicrographs showing laterally continuous, pinstripe planar-laminae consisting of sharply alternating silt-rich (SL) and clay-rich (CL) layers. Albite – Ab, Hornblende – Hbl, biotite – Bt, Quartz - Qtz. (C, D) Backscattered electron micrographs showing microtextural detail of the silt-rich and clay-rich layers. Note the well-sorted texture and negligible clay-size particles in the silt-rich layers and the comparatively more poorly sorted texture, mixture of clay-size and silt-size particles, and preferential occurrence of mud clasts (arrows) in the clay-rich layers.

Discussion

The trajectory of glacial meltwater, or similarly a river, upon entering a body of standing water is controlled largely by the density difference between the inflowing fluid and the ambient basin fluid. Where the density of the inflow exceeds that in the basin, like conditions in freshwater Lake Candona, and the pressure force (Kassem and Imran, 2001) and basin depth (Lamb et al., 2010) sufficient, the inflow will plunge and evolve into a density- +/- gravity-driven turbidity current (Mulder et al., 2003). Being tied directly to river or glacial meltwater outflow, the entire flow, including the end-product turbidity current, is commonly termed a hyperpycnal flow (Bates, 1953). In contrast, if the basin fluid is denser than the inflow, for example the Champlain Sea, the inflow will separate from the seabed and form a buoyant hypopycnal surface plume. Particle settling from the plume is controlled by particle weight (i.e. Stokes settling), potentially augmented by particle flocculation and convective instabilities that collectively serve to accelerate the transfer of sediment from the surface toward the seabed. The build-up of settling particles in the near-bed region may form a suspension whose density exceeds that of the ambient fluid thereby creating a secondary density- +/- gravity-driven bottom-hugging turbidity current (Parsons et al., 2001).

Model

Glaciolacustrine strata of Unit 1 (Lake Candona) were deposited by bottom- hugging hyperpycnal flows and consist of a distinctive alternating pattern of silt-rich and clay-rich laminae (Microfacies B) attributed to the rhythmic alternation of shear-thinning and shear-thickening processes in the non-Newtonian very-near-bed region. A similar pattern, both texturally and dimensionally, is observed in the similarly well-stratified interbeds in Unit 4. Being associated with slump deposits and uniquely containing abundant mud intraclasts derived from an at least partly compacted muddy substrate, these strata are interpreted to be turbidites initiated in the basin rather than hyperpycnites. This suggests that differentiating fine-grained deposits of hyperpycnal flows from turbidity currents based solely on physical stratal attributes may in fact be a challenge. Glaciomarine deposits of units 2, 3 and most of the strata making up Unit 4 were deposited in the Champlain Sea by hypopycnal flows that formed buoyant plumes from which sediment settled spawning bottom-hugging secondary turbidity currents. In these flows insufficient sediment concentration and shear stress inhibits shear-thinning and -thickening processes from operating and instead entropic Brownian motion within the fluid results in a unstratified deposit with a disorganized particle fabric (Microfacies A). Additionally, Microfacies A strata contain irregularly spaced, well-sorted silt lenses that range from a single silt grain to a few silt grains thick and record outer flow disturbances that reworked the previously deposited disorganized silt and clay. Whereas differentiating fine-grained hypopycnal flow deposits from hyperpycnal flows or turbidity currents may be straightforward, differentiating them from pure suspension fallout would appear to rely on the recognition of the thin, well-sorted silt lenses indicating advection rather than pure particle settling.

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