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Conference Reports

Glacial Facies Models

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Introduction

A Geological Society of America Penrose Conference on Glacial Facies Models, held in Toronto, 3-8 May 1987, was organized and hosted by N. Eyles, C. Eyles and A.D. Miall. This is a timely theme because glacial sedimentology is a quickly expanding field of study in Canadian and worldwide geoscience with increasing scientific and economic importance.

The conference attracted an impressive line-up of researchers dealing with glacial deposits ranging in age from Precambrian to modern. Participants (65) came from eleven countries (Australia, Brazil, Canada, France, Japan, The Netherlands, Poland, South Africa, Switzerland, United Kingdom and the United States).

The conference was a success in that a wealth of new data and syntheses of existing ideas were presented on many glacial environments. The program highlighted the variety of controls on glacial sedimentation through facies models developed from ancient, Pleistocene and modern settings. This geological cross-section forced participants to consider factors affecting the widest depositional settings (*e.g.*, basin configuration, tectonics, *etc.*). Integrated studies of glaciated basins or along basin transects were proposed to broaden the understanding of controls on sedimentation. Laminated sediments and massive diamictons were identified as difficult facies from which to decipher unequivocal formative processes. Soft sediment deformation structures were presented as important environmental indicators, but they need to be clearly distinguished from glaciotectonic and periglacial structures. The significance of episodic and catastrophic sedimentation, particularly related to decay of the great ice sheets, were highlighted in several presentations and should be the theme of future workshops.

However, a shortcoming of this Penrose was its ambitious program. Too many formal presentations allowed too little time being spent in discussion. Despite a crowded program, several crucial major topics were not covered at all. For example, the sedimentary significance of "deformable beds" (Boulton, 1986) should have at least come up during discussion, but preferably should have been an important part of a presentation on subglacially deposited diamictons.

Four days of sessions covered several broad topics: (1) facies models and facies modelling; (2) continental facies in subglacial/proglacial, eolian and lacustrine settings; (3) glaciomarine facies in fjords, ice marginal environments, temperate and polar continental shelves and slope settings. Thirty-eight oral presentations were made, amounting to a full blown conference rather than the workshop concept that Penrose meetings have embodied in the past. Nevertheless, the organizers are congratulated for bringing together an interesting program.

Facies Models

Walker presented a review of facies models, which attempt to provide a general summary of one or a group of depositional environments. He stressed that second generation models are in use for many non-glacial environments. Second generation models aim to examine the controlling parameters. This contrasts with the first generation glacial facies models. The complexity of glacial environments, particularly the sub-glacial and ice-marginal sub-environments, and their controlling parameters may preclude the establishment of reasonable distillations of all but local models. The use of "basin analysis" techniques has yet to be applied to glaciated terrain.

Crowell introduced an important theme of the conference, which was to integrate our understanding of glacial sequences through time. He emphasized, as did Walker, the importance of event-stratigraphy whereby events may be correlated if the facies differ spatially. However, as some of the examples to follow will show, standard glacial facies summaries were all that could be expected from many areas (*e.g.*, the Proterozoic of Norway); in other examples, facies summaries were not attempted or were not possible given the data available.

Sub-glacial and proglacial and continental facies

Boulton dealt with the large-scale organization of glacial facies. He outlined zones of erosion, deposition, depositional sequences and theoretical dispersal paths on an ice-sheet scale. The significance of isostasy-eustasy was indicated in comparing north-south ice-sheet-scale facies sequences. For example, glaciomarine sequences were predicted to be thicker northward due to greater ice loading and isostatic depression. His target topic of sub-glacial sedimentation was not covered and such major facies components as lodgement and melt-out tills were not systematically described or discussed. However, the range of criteria needed to infer these processes, particularly in ancient rocks, was made clear in subsequent talks. Notable was the absence of discussion on "deformable beds"; their description and importance to ice sheet dynamics and reconstruction. Discussion of "deformation bed" conditions and sediments is probably the "hottest" topic in glaciology related to glacial sedimentology (Alley *et al.*, 1986; Boulton, 1986; Hallet, 1986; Michelson, 1987). Two recent meetings, one on fast glacier flow and a second on deformable beds, highlight recent exciting new glaciological data on rapid flow and sub-glacier bed conditions. Glacial sedimentologists surely should be identifying facies and sedimentary criteria that may help recognize such depositional environments. For example, their recognition has major implications on the reconstruction of the Laurentide Ice Sheet.

Paul addressed sub-glacial sedimentation. He questioned the likelihood of widespread sub-glacial melt-out till units because consolidation, widespread dewatering, deformation and failure of sediment would be more significant and would limit the preservation of melt-out facies. These processes were considered by Paul to affect fine-grained sediments in particular, and some of the classical work on postulated melt-out sequences was carried by Harrison (1957) on fine-grained sediments and many others have adopted his interpretation. Clearly, there is a discrepancy between those conclusions drawn from a consideration of the theory of thaw consolidation and those based on interpretation of sediment properties. Discrepancies such as this should have been discussed at length, but the time was not available, and also the broad range of specialties of the participants perhaps precluded such detailed discussions.

Lawson described the ice marginal environment as very complex, with many controlling parameters ranging from sediment source to meltwater supply. He questioned whether the well-studied deposits of the Matanuska Glacier, Alaska, provide good analogs for Pleistocene sequences. For example he noted that sediment flows are generally <1 m thick whereas many units interpreted as sediment flow deposits are 10-15 m thick as seen in Pleistocene sequences from Iowa.

Shaw and Rust outlined the importance of deposition by sub-glacial and ice-marginal meltwater. Shaw presented evidence that catastrophic meltwater erosion and deposition may be widespread. Bedrock erosion marks record evidence for former tunnel and sheet floods involving up to 14 km³ of meltwater. Supraglacial to sub-glacial drainage events may rapidly produce complex sub-glacial stratigraphies similar to those interpreted to represent multiple advances, *e.g.*, interbedded sequences of gravel and till. In a second example, northern Saskatchewan drumlins were portrayed as resulting from large sub-glacial cavities eroded into the overlying ice and subsequently infilled during the waning stages of catastrophic sub-glacial flooding. Event stratigraphy may be possible by tracing the deposits of such catastrophic floods in proglacial fluvial, lacustrine and glaciomarine sequences.

Rust compared subaerial and the more prevalent subaqueous outwash (fan) deposits. Subaqueous fans are distinguished by characteristic linear bodies, rapid lateral facies change, fining-upward (gravel to clay) successions, massive sand in channels with steep margins intraclasts, and truncation by littoral erosion. Subaqueous fans are very common in Pleistocene sequences (mainly in Laurentide drift sequences) and they are being recognized in older sequences (*e.g.*, Gowganda Formation, see Mustard and Donaldson, 1987). Evenson discussed inwash sediments that are lithologically different from associated sub-glacial sediment.

O'Brien observed sedimentary features that he interpreted to be sub-glacial in Australian, Permian "tillites". These included boulder pavements, drainage blankets and deformation features such as fractured sand fills attributed to brittle failure and tension.

Periglacial features (Worsley) and soft sediment deformation structures (Brodzikowski) are important in defining detailed environments. Ice wedge structure was best portrayed by vertical fabric; however, care is needed in interpretation of such structures because water-escape fissures may have similar vertical bedding (Burbidge, poster display).

Continental periglacial eolian and lacustrine facies were well covered. Lea emphasized Alaskan coastal sand sequences (ballistic ripples, low angle cross-strata, coarse lags, and dust/saltation couplets) interbedded with organic material. These interbedded sequences bear little or no relationship to waxing or waning of glaciers. Lea also pointed out that water-escape features (rather than ice wedges) distinguish upfolding adjacent to vertical bedding.

Deynoux provided another example of periglacial eolian deposits, in this case, from late Precambrian strata, West Africa. Gustavson (in addition to Lawson) provided one of the few reports from a modern glacial setting (Malaspina Glacier, Alaska). He emphasized the high water input (7 m total per year *e.g.*, 3 m·a⁻¹ precipitation and 4 m·a⁻¹ ice melted in the marginal zone) to the ice margin. Limited surface drainage on this glacier results in a dense sub-glacial drainage network with high sediment load discharges from subaquatic sources into the ice-marginal, Malaspina Lake. Underflows are common as are overflows and interflows in Malaspina Lake.

Ashley outlined depositional models for ice-contact and distal glacier-fed lakes. Thick summer and winter units relate to direct underflow deposition with no thermocline effects close to the ice margin. Distal rhythmites show winter suspension units of equal thickness derived from a thermocline separation. Summer and winter units of equal thickness relate to subaqueous source inputs. Surge deposits (slump turbidities) may be similar to varves. Later, however, Hein suggested that large slump failures should be followed by smaller retrogressive failures, which should lead to multiple graded units that thin (and fine) upward.

Gustavson discussed the hydrology and sedimentology of the temperate Malaspina Glacier, Alaska, stressing the importance of non-rhythmic sedimentation in an ice-contact lake. This has important implications regarding the distinction of non-glacial deposits and fine-grained, massive glaciolacustrine sediment. Sedimentation and landform construction in these lakes (and subaerial streams) results from sub-glacial fluvial erosion and deposition from fountains or tunnels. A related poster suggested a comparison with Pleistocene ice-marginal landforms at the southeastern margin of the Laurentide Ice Sheet that were probably formed by mainly sub-glacial processes.

Shilts outlined the significance of ice contact (stagnant masses) sedimentation in late glacial lakes by use of sonar sub-bottom profiling. N. Eyles suggested that seasonal controls have been overemphasized in studies of glaciolacustrine environments and resedimentation processes, such as slumps and turbidity flows, have been under-emphasized. However, to evaluate this claim, we are faced with the difficult problem of being able to separate turbidites originating as mass flows and those deposited from hyper-concentrated meltwater. Once more, this could have been the subject of profitable discussion that time did not permit.

Grass demonstrated, on video, the significance of ice scours produced in large, shallow lakes, such as Lake Erie. He used a plate tectonic model involving piling and thrusting of ice sheets to portray ice-ridging that may create scours 4 km long and 60 m wide. Woodworth-Lynas reported on Pleistocene and modern sea ice scours and emphasized the need for sedimentary descriptions that can be recognized in the geologic record.

Glaciomarine environments

Glaciomarine environments were covered in the final two days. Topics included: fjords/ice proximal, temperate continental shelves, temperate-polar continental shelves and continental slope environments.

Quaternary glaciomarine environments. Powell reviewed sedimentary systems in temperate fjords. He emphasized summer sedimentation as rhythmic, short-period (several/day) sedimentation pulses involving fine-grained sediment (cyclopels) and sandy sediment (cyclosams). Bergstone mud and homogeneous mud were noted as important deposits during winter sedimentation. Hein emphasized the role of mass-flow sedimentation in sandy fjord sediments. Arcuate step-faults are common, but are overwhelmed by high rates of sedimentation. Associated muds appear massive as a result of ubiquitous bioturbation. Molnia discussed glacially influenced structureless deposits in the Gulf of Alaska, arguing that high sedimentation rates relate to storm events (wind and rain). A tectonically controlled glacier basin is important for high glacial loads. Anderson discussed Antarctic glaciomarine sedimentation and stressed high sedimentation inputs especially of stony muds close to the grounding line. Laminated silts deposited beyond the grounding line were interpreted as ice shelf deposits.

Pre-Quaternary glaciomarine sequences. Lagoe discussed foraminifer biofacies in Yakataga Formation, Gulf of Alaska. He reported that depth and particularly substrata are controlling factors on modern foram distributions.

Boyd presented perhaps the most interesting findings at the conference in reporting offshore stratigraphy on the outer Scotian Shelf. He reported tunnel valleys with fjord-like dimensions (300-200 m depth and 3-5 km across) relating to enormous discharges of meltwater at the margin of the Laurentide Ice Sheet. Extensive sand deposits identified on the continental slope may be related to the large flushing events which created the tunnel valleys.

Miall's report on the Gowganda Formation stressed the large channels that may be associated with sediment gravity flows (turbidites, liquid or fluid flows) and minor subaqueous outwash on an Early Proterozoic continental margin. Discussion of such mechanisms of transport to the continental shelf as by ice shelfs, meltwater or icebergs were debated.

Edwards discussed upper Proterozoic glaciomarine deposits from Norway. He suggested that uncouplings of ice from the bed produced laminated sediment with little coarse sediment from meltwater underflows. He raised the problem of distinguishing massive dropstone diamictons with stratification from tectonic layering.

Socci presented late Precambrian/Cambrian sediments from the Boston Basin that had tectonic control, rifting, and volcanic activity. Diamictites pinched out abruptly, and are channellized and interbedded with shaly sands; all are interpreted as downslope debris flow deposits.

Visser presented the most comprehensive facies reconstruction of glaciogenic deposits in discussing the Karoo Basin sediments. He highlighted, in part, the significance of subaqueous fan and esker deposits interbedded with diamictons in the Permo-Carboniferous Dwyka Formation, South Africa. Subaqueous fans and esker deposits required sub-glacial drainage and hence, warm-based grounded ice-sheets. Visser's reconstruction incorporated a large floating ice-sheet adjacent to terrestrially grounded ice, but within his mapped distribution of fan deposits. Known large ice sheets are usually subtended by polar ice sheets without little sub-glacial drainage. The need to explain thick massive diamictites forced an expansion of the depositional model to include more observations that cannot be readily explained by knowledge existing of glaciated basins.

Miller offered a classical advance-retreat cycle to explain Permian successions in Antarctica. She interpreted sub-glacial facies defined by imbricate sand lenses. Ojakangas reported siliciclastic basin fills consisting of thick massive diamictons and thick interbeds of stratified sand in the Proterozoic of Antarctica.

Summary of formal sessions

The program included a total of 38 speakers and discussion of a variety of styles of glaciogenic sedimentation as a foundation for discussion. Although time to accomplish the synthesis was short, some important concepts were forthcoming.

(1) Transect studies should be encouraged in order to integrate data from offshore and terrestrial environments by tracing facies laterally or more likely matching stratigraphy by linking events from one environment to another. For example, the recognition by Boyd of large offshore (Scotian Shelf) tunnel valleys bordered by thick sand sequences presumably relates to major drainage events at the margin of the Laurentide Ice Sheet. Such former, larger drainage events should have produced clear geomorphic and sedimentologic evidence. Transect studies will also have to incorporate geophysical, drilling and paleontologic studies.

(2) There is a pressing need to understand the processes that operate in glaciogenic environments: this is clear from our lack of understanding regarding the origin of massive diamictons. The familiar concepts of lodgement, melt-out, and deformation processes are too ill-defined and insufficiently studied to explain the complex sequences being recorded. Other processes need better understanding, for example, the significance of wind in glacial-eolian sediments. Eolian deposits can be confused with plane-bedded sand of aqueous origin that are also interbedded in glaciogenic sequences. A detailed understanding of the mechanisms of deposition will allow very specific depositional conditions to be inferred such as may be suggested from adhesion ripples, translatant ripples, *etc.*

Similar, detailed, environmental inferences are being drawn from identification of hummocky or swaley cross-stratification in glaciogenic sequences, examples of which were illustrated on the field trip.

(3) There were no glaciologists at the meeting to report on the exciting new instrumentation and recording of modern processes on rapidly moving glaciers, *e.g.*, Variegated Glacier, Alaska (Kamb *et al.*, 1985) and Ice stream B (Antarctica, Alley *et al.*, 1986). As a result, there was no discussion of possible former ice-stream deposits or erosion that may have related to the former presence of widespread deformable beds beneath Laurentide Ice Sheet (Boulton, 1986).

(4) The role of meltwater storage and catastrophic discharge from major ice-sheets is a potential important working theme for a conference considering the significance meltwater was to the majority of facies reported.

(5) The studies from tidewater glaciers in Alaska (Powell) highlighted the importance of rapid, episodic and possibly catastrophic sedimentation and the radical changes in depositional environment. It is possible that catastrophic events may be the most significant and best preserved events recorded in many glacial environments (Smith, 1985).

(6) The role of biota in glaciogenic sediments was neglected and needs more evaluation. The significance of biota was well illustrated on the field trip where ostracodes were found within the Sunnybrook unit and trace fossils were regularly located within rhythmic (varved) couplets.

Field Trip

A field trip to examine the local Scarborough Bluffs sections produced a welcome change of pace to the busy program. The Scarborough Bluffs sections are controversial (Eyles and Eyles, 1983; Sharpe, 1987) and the field trip produced some of the best discussion, particularly debates regarding the origin of massive diamicton and adjacent rhythmic sediment. Debate on these topics crystallized the discussion of these themes from the sessions.

The Scarborough Formation comprises raised glaciolacustrine deltaic deposits, which were used in evaluation of ice-proximal environments and particularly the importance of seasonal hydrologic control. Lower laminated Scarborough clay beds (silt, clay and minor sand) have a cumulative thickness of 28 m. They consist of multiple-graded units interbedded with cross-laminated sets, ripple formsets and massive beds. Burrow traces are common. The beds are thought to be multiple, thin (1-15 cm) underflow deposits, possibly derived from an ice-marginal and/or slump events. They are perhaps delta foreslope turbidites. Their regular rhythmic arrangement is suggestive of an annual control on sedimentation. They cannot, however, be confidently identified as classical varves, but relatively thick clay layers in a known glacial environment point to seasonal control on discharge and to a seasonal ice cover. The rhythmites contrast with large massive silty sand facies interpreted as subaqueous slumps, possibly from an ice-margin (Kelly and Martini, 1986).

The point of this example is that glaciolacustrine sequences in an ice-dammed lake show rhythmic sedimentation that was argued by many to lack an annual control. However, thick clay caps (1-2 cm) in rhythmic sediment imply periods without appreciable inflow or wave-generated currents. The simplest explanation is that clays are winter or late fall deposits in a quiescent lake. This calls for careful evaluation of rhythmic sequences in fine-grained deposits of glacial lakes that have been interpreted as non-varved.

The overlying Scarborough sands were briefly discussed, and they consist of ripple cross-laminated units passing upward to trough and planar cross-stratified sands. They were interpreted as upper delta slope deposits, and the whole sequence represents a prograding delta.

The Sunnybrook diamicton (Sunnybrook Till of Karrow, 1967) was examined next. This is a clay-rich massive to stratified diamicton with a low clast volume. It has a conformable to interbedded contact with sand and mud below, but occasionally has a striated boulder pavement at its base (Sharpe and Barnett, 1985). The guidebook reports low frequencies of freshwater ostracodes which are considered to be *in situ*. The faunal aspect was not emphasized on the trip, rather discussion centered on evidence for or against a glacial origin for the diamictons. Some participants considered the massive diamictons to represent a sub-ice deforming layers; others considered the diamictons to present subaqueous debris flows from a nearby glacier. The majority view that the massive diamictons appeared to be distinct from rain-out deposits contrasted with the guidebook report of *in situ* ostracodes and magnetic fabrics (A.M.S.) with little or no preferred orientation (compare Gravenor and Wong, 1987). The range of interpretations of these well-exposed Pleistocene sediments for which the paleogeography is well known, underlines the difficulty of interpreting similar diamictons in ancient sequences.

Adjacent overlying beds (Bloor Member beds, Karrow, 1967) consist of regular rhythmically laminated silt and clay couplets, and minor fine sand. The regular occurrence of the well-displayed bioturbation near the top of each silt member strongly suggests annual sedimentation. The alternative is that the couplets represent episodic turbidity flows, of approximately the same magnitude (clay member of couplets thin progressively upward).

The question raised here is not whether rhythmic units are varves or turbidites. Many varves are composed mainly of turbidity current deposits as was demonstrated by Kuenen over thirty years ago. We are concerned with the cause of the rhythmicity in glaciolacustrine deposits. To what extent does it relate to episodic, turbidity currents generated by lake bed failure or by meltwater flow events on a relatively short time scale (hours, days or weeks)? Or, to what extent does it depend on seasonal cycles that must have an effect on wave processes through the formation of lake ice and an inflow discharge through their influence on surface melting? Obviously, most glacial lake fine-grained sediments will include the influence of both controls and the trick, which does not seem to have been mastered yet, is to separate them.

If this type of controversy results from spectacular, well-exposed sections, then general agreement on older glaciogenic deposits that may have complex provenance, structural and tectonic histories seems unlikely.

Conclusions

Emphasis was placed on description of glacial and glaciogenic sediments and their environments with the aim of identifying characteristic facies and facies assemblages. A goal of producing a meeting of minds regarding a process approach and a "products" (deposits) approach did not materialize because few process studies were presented or discussed. Processes in environments that are adjacent to glaciers (rivers, lakes, deltas, fans) are better known than glacial processes and thus glacial facies models have a weaker actualistic base. Most modern glacial studies are in glacial environments that may not be representative of the large Pleistocene ice sheets. These process studies serve to underline the remarkable complexity of glaciogenic environments. Where so many factors affect sedimentation, one may even question the use of facies models. However, facies summaries are useful in identifying depositional environments and reconstructing the processes that occurred within them.

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