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John T. Andrews

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Résumé de l'article

Malgré les progrès importants accomplis dans l'étude de plusieurs questions touchant la calotte glaciaire laurentidienne, certains problèmes majeurs devront être abordés au cours de la prochaine décennie. Ainsi, la collaboration entre les chercheurs qui élaborent les modèles et ceux qui fournissent les données de terrain sera primordiale. Même si on poursuivra l'élaboration de reconstitutions davantage raffinées fondées sur l'isostasie glaciaire, la glaciologie, la climatologie ou la géologie glaciaire, on devra en arriver à réaliser une reconstitution de la calotte glaciaire où les données climatiques, glaciologiques et isostatiques seront intégrées. Cette reconstitution servira à fournir des extrapolations d'ensemble sur les paysages glaciaires, glacio-marins et périglaciaires, sur les sédiments et les chronologies. Ses extrapolations serviront à leur tour à orienter les recherches de terrain sur la forme des lits glaciaires et sur les sédiments associés à l'inlandsis. Un tel projet de reconstitution du modèle glaciaire et de vérifications sur le terrain ne pourra être accompli sans une meilleure compréhension des processus de mise en place des sédiments glaciaires et sans la mise sur pied d'un programme détaillé de prises d'échantillons pour fins de datation afin d'augmenter nos connaissances sur la chronologie des événements.

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Postface

THE LAURENTIDE ICE SHEET: RESEARCH PROBLEMS

John T. ANDREWS, Department of Geological Sciences, and Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado 80309, U.S.A.

ABSTRACT Although major progress has been made in several research topics on the Laurentide Ice Sheet, there are still substantial problems that require investigation over the next decade. Of particular importance will be the active participation between modelers and those who provide the "ground truth". Although individual reconstructions of the ice sheet, based on glacial isostasy, glaciology, climatology, and glacial geology, will continue to be developed and refined the next important step should be the development of an integrated climate/glaciology/isostatic ice sheet reconstruction that will serve to provide a holistic series of predictions about glacial, glacial marine, and periglacial landforms, sediments, and chronologies. These predictions can then serve as the basis for guiding field programs to examine bedforms and sediments associated with this ice sheet. This program of model reconstruction and verification will require a more complete understanding of glacial depositional processes than is currently available and, in addition, will be heavily dependant on a detailed dating program to improve our knowledge of the chronology of events.

RÉSUMÉ *La calotte glaciaire laurentidienne: les recherches à venir.* Malgré les progrès importants accomplis dans l'étude de plusieurs questions touchant la calotte glaciaire laurentidienne, certains problèmes majeurs devront être abordés au cours de la prochaine décennie. Ainsi, la collaboration entre les chercheurs qui élaborent les modèles et ceux qui fournissent les données de terrain sera primordiale. Même si on poursuivra l'élaboration de reconstitutions davantage raffinées fondées sur l'isostasie glaciaire, la glaciologie, la climatologie ou la géologie glaciaire, on devra en arriver à réaliser une reconstitution de la calotte glaciaire où les données climatiques, glaciologiques et isostatiques seront intégrées. Cette reconstitution servira à fournir des extrapolations d'ensemble sur les paysages glaciaires, glaciomarins et périglaciaires, sur les sédiments et les chronologies. Ses extrapolations serviront à leur tour à orienter les recherches de terrain sur la forme des lits glaciaires et sur les sédiments associés à l'inlandsis. Un tel projet de reconstitution du modèle glaciaire et de vérifications sur le terrain ne pourra être accompli sans une meilleure compréhension des processus de mise en place des sédiments glaciaires et sans la mise sur pied d'un programme détaillé de prises d'échantillons pour fins de datation afin d'augmenter nos connaissances sur la chronologie des événements.

INTRODUCTION

The papers in this special volume are only part of what will be presented at the 1987 INQUA Symposium on the Laurentide Ice Sheet. Nevertheless, they include the key elements in our continued attempts to better understand the main problems associated with the history of this massive ice sheet which developed after the height of the last interglaciation (since *ca.* 125 ka), and underwent final deglaciation within the last 5 to 8 ka, and which is still occurring today on places like Baffin Island.

This postface addresses what I consider to be some of the major research requirements for the years ahead. Many of these are self-evident, but this does not diminish their importance.

FUTURE RESEARCH TOPICS

In general I feel that progress in our understanding of the dynamics of the Laurentide Ice Sheet and of its effect on the global system will most profitably arise from interactions between researchers from several fields. No matter what the basis of the reconstruction, new models of the Laurentide Ice Sheet must be accompanied by specific statements as to the key elements that provide valid tests for the falsification of a particular reconstruction. This request is founded on the philosophical premise that hypotheses can be proven false but cannot be uniquely verified.

GLACIAL PROCESSES

Ice sheet reconstruction that is based on geological data requires a valid understanding of the glaciological significance of glacial deposits and glacial erosional landforms. By-and-large until the middle of the 1970's, glacial geological research efforts concentrated on glacial stratigraphy and chronology, with interpretations based on an incomplete understanding of glacial processes. Over the last decade there has been a pronounced shift in research such that glacial sedimentology is now an active and exciting field (DREWRY, 1986). The net result of this effort has been to question the interpretation of several pre-existing stratigraphic schemes, an example being the discussion on the origin of the sediments exposed in wave-cut bluffs along Lake Ontario (EYLES and EYLES, 1983).

The suggestion by BOULTON and JONES (1979) (also BOULTON *et al.*, 1985; FISHER *et al.*, 1985) that ice sheets may be affected by deformable beds is an important concept that is bringing together glaciologists and glacial geologists in a number of workshops and meetings (EOS, 1986). The recent suggestion that ice streams in West Antarctica may be lying on deformable sediments (BLANKENSHIP *et al.*, 1986) requires that glacial geologists critically evaluate whether evidence for such processes are preserved in the sediments that underlay the Laurentide Ice Sheet (*e.g.* SHARPE, 1986; CLARK, 1986; MICKELSON, 1986). Indeed these questions were addressed in the abstracts cited and further elaborations can be expected in the near future.

Of particular importance in the context of the Laurentide Ice Sheet, and high latitude ice sheets in general, is the role of "cold ice". The discussion on the extent of glaciation during the Wisconsinan Stage (DENTON and HUGHES, 1981; DYKE *et al.*, 1982; ENGLAND and BEDNARKSI (in press); FUNDER, in press) frequently comes down to the interpretation of "old" landforms. In some views (*i.e.* GROSSWALD, 1984) it is argued that "cold ice" can passively extend across previously deposited glacial and marine sediments without leaving any deposits. There is little doubt that cold ice did cover, and preserve, extensive upland areas in northern Canada (SUGDEN, 1977; ANDREWS *et al.*, 1985a), but whether this applies to deposits at, or close to sea level, is more difficult to justify as in these position the ice would normally be flowing faster. Note that ECHELMEYER (1986) argues that frozen sediments can deform if overlain by glacier ice.

Thus the role of cold ice in glacial geological processes, and the effect of glacial overriding of deformable sediments are two examples of critical questions that require investigations around and under existing ice masses, as well as studies of older glacial sediments and landscapes. Continued research into glaciology and glacial geological processes are necessary to solve these, and other problems, that impact on our ability to reconstruct paleo-glaciological environments.

DATING OF GLACIAL AND NONGLACIAL EVENTS

Glacial stratigraphers can frequently do no more than "count backwards" in attempting to establish a chronology for glacial events. Because of the limits of radiocarbon dating (*ca.* < 40 ka) we have a fair knowledge of the late glacial history of the ice sheet back to about 20 ka; an imperfect knowledge of events between 20 and 40 ka; and sketchy knowledge of the events that led to the development of the ice sheet during marine isotope stages 5 through 4. Indeed, although the most extensive glaciation of the northeastern sector of the ice sheet appears to have occurred at this time (*e.g.* ANDREWS *et al.*, 1985b) we are not at all sure whether the Laurentide Ice Sheet approached its southern limit during the Early Wisconsinan (CLARK and LEA, 1986; VINCENT and PREST, 1987).

Amino acid racemization of marine carbonates offers a possible approach to grouping deposits of similar age in the <125 and >30 ka interval, but shows little promise of providing accurate numeric ages (MILLER, 1985). Thermoluminescence (TL) and Electron Spin Resonance (ESR) (BERGER, 1984; LINKE *et al.*, 1985) are being increasingly used, with some success, to date glacial and associated nonglacial sediments (*i.e.* loesses, glacial marine silts, etc).

If these methods can indeed be demonstrated to produce reasonable numeric ages in the >30 and <125 ka interval then there exists the strong possibility that, for the first time, we will be able to speak with assurance about the extent and history of glaciation throughout the entire Wisconsinan Stage (*e.g.* SHILTS, 1985).

Radiocarbon dating has provided the most complete body of information on late glacial events. However, even the use of this invaluable tool was often restricted by the small size of critical samples. The development of mass spectrometry as a method for dating small (<30 mg) samples indicates that many more radiocarbon dates will be forthcoming from important sections, both onshore and offshore (*cf.* PRAEG *et al.*, 1986).

There is little doubt that probably the severest restriction on ice sheet history is connected with problems of acquiring reliable numeric ages for particular events. AMS, amino acid racemization, TL and ERS methods all have specific problems and limitations. However, these problems may be reduced by the use of multiple methods that provide a degree of cross-checking.

ICE SHEET/OCEAN INTERACTIONS

Some of the major advances in our information base will come from the nearshore and adjacent deep sea basins that fringe the eastern and northern margin of the Laurentide Ice Sheet. In addition, events that occurred at the southern flank of the ice sheet can be monitored by looking at changes which took place in more distal areas, such as the Gulf of Mexico (KENNETT and SHACKELTON, 1975; LEVENTER *et al.*, 1982).

Traditionally the concept of "glaciation" was developed from terrestrial glacial sequences, but in the last two decades research on deep sea cores has led to a revolution in our concepts of the number and style of Quaternary glaciations (SHACKELTON and OPDYKE, 1973; HAYS *et al.*, 1976). However, there is still a substantial leap of faith in correlation between these two widely different and separate areas. The critical areas for research are thus the basins and troughs that extend along the continental margin of Canada from the Maritimes to the Arctic (*e.q.* SCOTT *et al.*, 1984; FILLON and HARMES, 1982; OSTERMAN *et al.*, 1985; JOSENHANS *et al.*, 1986; PRAEG *et al.*, 1986; MACLEAN, 1985; KING and FADER, 1986). Such ice proximal environments contain potential high resolution records of continental glaciation (SCOTT *et al.*, 1984; ANDREWS *et al.*, in press), although reworking of sediments and microfossils will always be a problem in these areas (*e.g.* MUDIE and SHORT, 1985). As records become available from these ice proximal to ice distal shelf localities, researchers will be able to more accurately reconstruct terrestrial→shelf→deep sea transects (AKSU, 1985; MUDIE and SHORT, 1985; AKSU and MUDIE, 1985).

The links between the terrestrial glacial sequence and the postulated response of the oceans to the ice sheet forcing have largely been implicit because of the limited studies on the glaciated continental margins. The eastern and northern margins of the Laurentide Ice Sheet terminated, to a greater or lesser degree, in the sea and hence additional studies on the offshore glacial marine sequences will most likely produce exciting results.

MODELS AND ICE SHEET RECONSTRUCTIONS

The Laurentide Ice Sheet has been reconstructed on the basis of glacial geology, glaciology, and glacial isostatic information (PREST, 1984; DYKE *et al.*, 1982; DENTON and HUGHES, 1981; PELTIER and ANDREWS, 1983; BOULTON *et al.*, 1985; DYKE and PREST, 1987). Some of the models are static representations of average conditions, others are dynamic and change through time. Other types of models take a particular ice sheet reconstruction and examine the effects of the ice sheet on climate (*e.g.* KUTZBACH and WRIGHT, 1985; BROCCOLI and MANABE, 1987).

It is in the modeling effort that greatest attention must be directed toward establishing lines of communication between the various disciplinary groups. Ideally a complex ice sheet model is required to take into account various feed-backs between climate, ice physics, earth rheology, and oceanography. The information available to constrain such reconstructions are: glacial and periglacial landforms and sediments, elevation and rate of change of relative sea level, and proxy climate and ocean records (*i.e.* pollen, foraminifera, stable isotopic signals, etc).

The ice sheet reconstructions must be viewed as operating in two directions. In the first instance, models of the ice sheet can serve to pinpoint particularly sensitive geographic areas where research should be directed. In the second instance, mismatches between "ground truth" and a model will refine fundamental properties of the input properties which are important in other research fields, such as earth rheology and ocean circulation.

CONCLUSIONS

The history of the growth, development, and retreat of the Laurentide Ice Sheet during all or parts of marine isotope stages 5 through 1 is a topic of profound global importance. In the last 20 to 30 years Canadian research has dramatically expanded our knowledge of the Wisconsinan Stage and, in particular, have documented events in the northern sectors of the ice sheet. This has provided a balance to the traditional emphasis of the glacial sequences along the southern margin of the ice sheet. These topics are covered by the papers in this issue, particularly the contributions by DYKE and PREST, DREDGE and THORLEIFSON, VINCENT and PREST and ST-ONGE. The change in detail between the $<$ 20 ka record and those $>$ 20 ka is aptly illustrated in a comparison between the temporal treatments of the ice sheet. Although maps can be drawn of the Late Wisconsinan marginal fluctuations, with intervals of between 1 and 2 ka, the problems of dating events $>$ 20 ka is significantly more complex and interpretation is thus more subjective (see DREDGE and THORLEIFSON, 1987).

How large ice sheets react to changes in climate is of current societal concern because of the possible changes in the Antarctic Ice Sheet associated with a predicted climate warming driven by increased CO_2 production (U.S. DEPARTMENT OF ENERGY, 1985). The current slight rise in global sea level is having a profound economic impact along many coastlines of the world. Thus the potential changes of mass of the Greenland and Antarctic ice sheets, which may be either positive or negative due to these effects, may well be modeled in some fashion, after we have a more complete understanding of the history of the Laurentide Ice Sheet. Rather than "forcast" we should attempt to "backcast" using "our" ice sheet as an analogue.

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