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Introduction
The Laurentide Ice Sheet and its Significance
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Résumé de l'article

Au cours de la dernière glaciation, l'inlandsis laurentidien a recouvert de vastes étendues de l'est, du centre et du nord de l'Amérique du Nord. L'inlandsis a causé un affaissement d'au moins 300 m de l'écorce terrestre et a emmagasiné une telle quantité d'eau que le niveau marin s'est abaissé de 40-50 m. On a d'abord considéré l'inlandsis comme un complexe de glaciers fondamentalement indépendants; plus tard, on a cru qu'il s'agissait d'une seule nappe glaciaire centrée sur la baie d'Hudson; on a récemment démontré qu'il était formé d'au moins trois grandes masses coalescentes. L'inlandsis a également été la cause de modifications de la circulation atmosphérique et de la migration des biozones vers le sud; il a érodé les roches déjà altérées et recouvert de vastes étendues de dépôts fraîchement érodés. L'explication de l'évolution et de la dynamique de l'inlandsis a des répercussions sur la prospection des gîtes minéraux, la prévision des effets des pluies acides, la compréhension de la nature et de la distribution des sols, la localisation de matériaux pour la construction, la prévision des variations du niveau de la mer, la modélisation des changements climatiques et la prévision de changements majeurs dans le régime d'écoulement des glaciers modernes.

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Introduction

THE LAURENTIDE ICE SHEET AND ITS SIGNIFICANCE*

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ABSTRACT The Laurentide Ice Sheet is a glacier complex that covered large parts of eastern, central and northern North America during the last glaciation. The Ice Sheet depressed the crust by at least 300 m and it held enough water to lower sea level 40-50 m. The Laurentide Ice Sheet was first viewed as a complex of essentially independent glaciers; later it was considered a single sheet centred on Hudson Bay; and recently the Laurentide Ice Sheet has been shown to have been made up of at least 3 major coalescent ice masses. In addition to lowering sea level and depressing the land surface, it changed atmospheric circulation, caused southward movement of biozones, eroded the weathered mantle, and deposited extensive areas of freshly eroded materials. Understanding the history and dynamics of the Ice Sheet is important in prospecting for ore deposits, predicting effects of acid rain, understanding the nature and distribution of soils, locating granular aggregate, predicting sea level change, modelling climatic change and predicting major changes in flow patterns of modern ice sheets.

RÉSUMÉ *La calotte glaciaire laurentidienne et ses effets*. Au cours de la dernière glaciation, l'inlandsis laurentidien a recouvert de vastes étendues de l'est, du centre et du nord de l'Amérique du Nord. L'inlandsis a causé un affaissement d'au moins 300 m de l'écorce terrestre et a emmagasiné une telle quantité d'eau que le niveau marin s'est abaissé de 40-50 m. On a d'abord considéré l'inlandsis comme un complexe de glaciers fondamentalement indépendants; plus tard, on a cru qu'il s'agissait d'une seule nappe glaciaire centrée sur la baie d'Hudson; on a récemment démontré qu'il était formé d'au moins trois grandes masses coalescentes. L'inlandsis a également été la cause de modifications de la circulation atmosphérique et de la migration des biozones vers le sud; il a érodé les roches déjà altérées et recouvert de vastes étendues de dépôts fraîchement érodés. L'explication de l'évolution et de la dynamique de l'inlandsis a des répercussions sur la prospection des gîtes minéraux, la prévision des effets des pluies acides, la compréhension de la nature et de la distribution des sols, la localisation de matériaux pour la construction, la prévision des variations du niveau de la mer, la modélisation des changements climatiques et la prévision de changements majeurs dans le régime d'écoulement des glaciers modernes.

INTRODUCTION

The Laurentide Ice Sheet was the glacier complex that occupied much of northern North America during the last 100 ka. It stretched from the eastern margin of the Canadian Cordillera on the west to the Atlantic seaboard and continental shelf on the east; from the channels at the southern margin of the Queen Elizabeth Islands on the north, south to at least 40° in the mid-western United States (Fig. 1). Models constructed by HUGHES *et al.* (1981) suggest a maximum ice volume of 34.8 x 106 km^3 whereas those constructed by FISHER *et al.* (1985) proposed a minimum volume of 18.0 x 106 km^3. It may have made up about 35 % of the worlds ice volume at the Late Wisconsinan maximum and accounted for 60 to 70 % of the ice which melted at the end of the Wisconsinan.

It is important to note that the term "Laurentide Ice Sheet" as a capitalized proper noun is used only for the ice that occupied northern North America during the last or Wisconsin Glaciation. We know that ice sheets occupied this same general area during earlier phases of the Pleistocene but our knowledge of the extent and timing of these earlier features is too incomplete to warrant referring to them by precise names.

TERMINOLOGY

It is necessary to spell-out the terminology that will be used in the papers concerning the Laurentide Ice Sheet which follow. Figure 2 presents the Quaternary time classification that is slowly being adopted in Canada. The Quaternary is considered to have begun 1.65 Ma ago, at the end of the Olduvai Normal-Polarity Subchron. The Quaternary is subdivided into the Pleistocene and the Holocene epochs with the Holocene beginning at 10 ka. In line with what is becoming standard international practice, the Pleistocene is divided into early, middle and late subdivisions with the Early-Middle boundary at 790 ka (boundary between the Brunhes Normal and the Matuyama Reversed-Polarity Chronos as indicated by the chronology of JOHNSON, 1982), and the Middle-Late boundary at 130 ka (the approximate beginning of the last interglaciation as suggested by oxygen isotope curves for deep sea cores). The Late Pleistocene is divided into two

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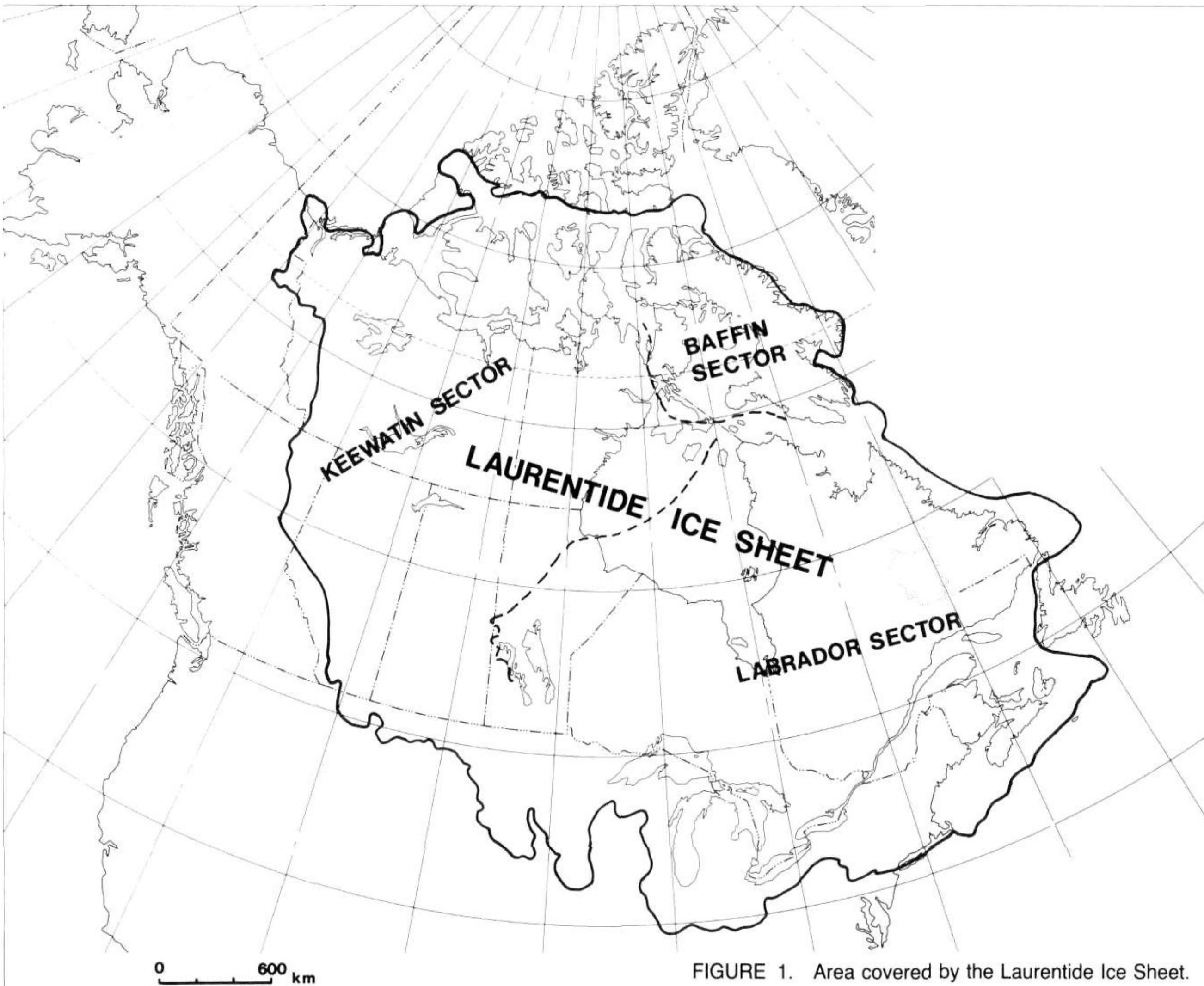

FIGURE 1. Area covered by the Laurentide Ice Sheet.
Région recouverte par la calotte glaciaire laurentidienne.

stages, the Sangamonian and the Wisconsinan with the boundary between them set at 80 ka (the approximate time when deep sea oxygen isotope curves suggest we were entering the main part of the last glacial phase). The Wisconsinan is itself divided into early, middle and late substages with 65 and 23 ka as the separating ages.

One further convention of usage should be pointed out. The chronostratigraphic terms "Sangamonian" and "Wisconsinan" are used for the periods between 130 and 80 ka and 80 and 10 ka respectively. The terms Sangamon Interglaciation and Wisconsin Glaciation are used for the time transgressive geologic-climate or event units that occurred during Late Pleistocene.

The Laurentide Ice Sheet has been subdivided into three sectors, the Labrador, Keewatin and Baffin sectors, each named after a main area of inception (PREST, 1970 and DYKE *et al.*, in press; Fig. 1). Each sector was at times made up of more than one major ice flow component which was marked by a primary ice divide or ice divide system. These are simply referred to as "Ice". For example during the Late Wisconsinan the Keewatin Sector included Plains Ice, and Keewatin Ice; the Labrador Sector included Hudson Ice and Labrador Ice and the Baffin Sector included Foxe, Amadjuak, and Penny Ice as dynamically distinct components (DYKE *et al.*, in press). Other terms used are ice divide — a topographic ridge on an ice mass; saddle — a low area on an ice divide; and ice dome — a high area on an ice mass that induces radially divergent flow lines.

REGION COVERED BY THE LAURENTIDE ICE SHEET

The position of the limit of the Laurentide Ice Sheet at various times is discussed in several of the papers that follow. Consequently this subject will not be discussed further here. However, much of the discussion on inception, growth and decay requires an elementary knowledge of the nature of the area overridden by the ice sheet complex.

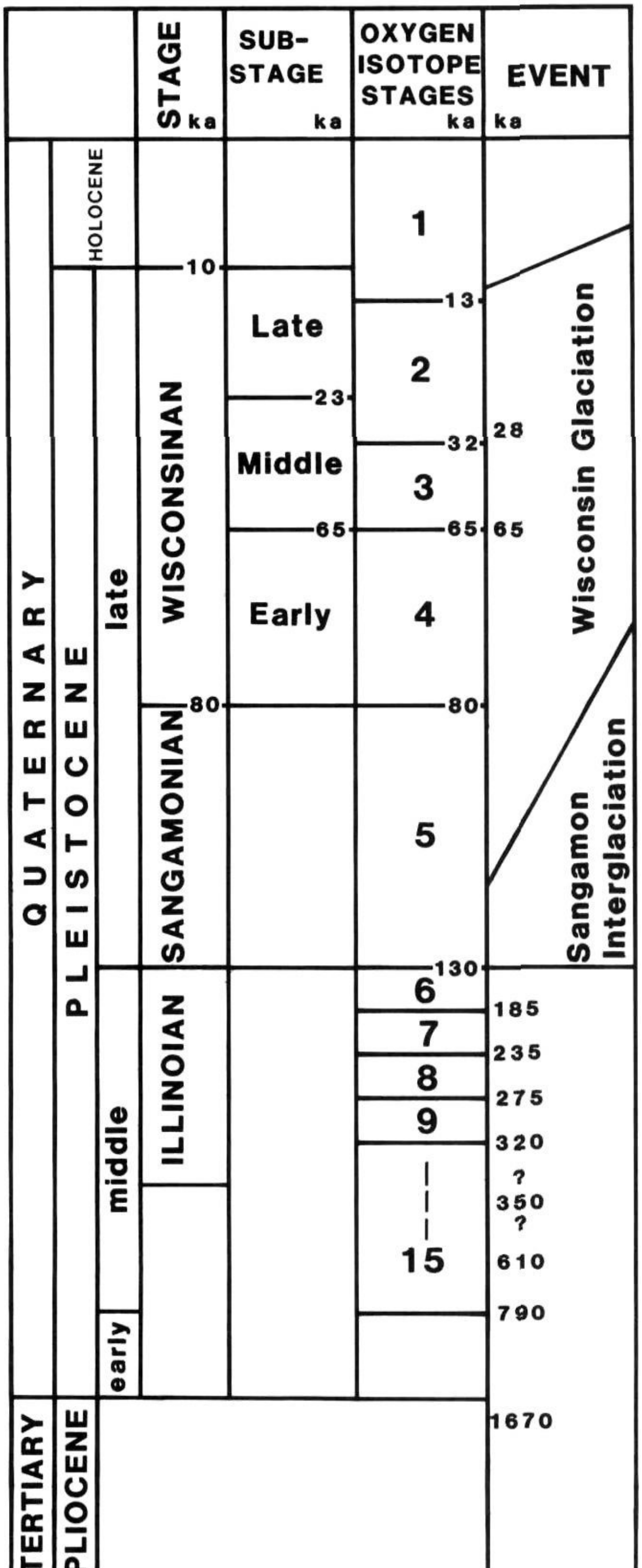

FIGURE 2. Quaternary nomenclature which has been used in Canada and that is used in papers dealing with temporal aspects of the Laurentide Ice Sheet.

Nomenclature du Quaternaire qui a été utilisée au Canada et qui est utilisée dans les études qui traitent des aspects temporels de la calotte glaciaire laurentidienne.

The Canadian Shield was the site of early centres of ice sheet growth. The shield consists mainly of low uplands or rolling plains underlain by Precambrian age rocks that in general can be characterized as consisting of igneous and crystalline metamorphic lithologies but which also include a great variety of lower grade metamorphic, volcanic and sedimentary rocks (DOUGLAS, 1969). In addition to the areas of generally low relief, the shield includes several mountainous regions (largely at its north eastern margin), and broad, high uplands on Baffin Island and the Ungava Peninsula. From the early centres of growth, the ice expanded into two major basins, Hudson and Foxe that lie within the shield. These basins, which now are mainly below sea level, are underlain by Phanerozoic sedimentary rocks (Fig. 3). When the ice sheet complex expanded outward from the shield it overrode adjacent areas of Phanerozoic rocks. These are mostly low relief plains underlain by shales, some carbonates and sandstones. At a number of sites the Laurentide Ice Sheet carved basins or troughs at the margin of the shield. These include the basins of Great Bear Lake, Great Slave Lake, and Lake Winnipeg, and the marginal trough off the coast of Labrador. In the west and the south, the Laurentide Ice Sheet pushed up the regional gradient. This means that not only was the ice flowing over a relatively deformable bed after it left the Shield but it also was in places advancing into glacial lakes. In the north and east where it left the shield, the Laurentide Ice Sheet pushed into topographically diverse areas which to a large extent were, and remain, below sea level. Because of the nature of the topography in these areas, the ice sheet was channelled into troughs such as the Laurentian Channel and the inter-island channels at the northern margin of the shield, which led the ice into the sea. It is presumed that ice shelves developed off the mouths of these channels, but because these areas are submerged, areal information on the nature and extent of former ice shelves is not readily available.

DEVELOPMENT OF THE CONCEPT OF THE LAURENTIDE ICE SHEET

The work of inland glaciers was first studied in 1845 in the Lake Temiskaming basin, along what is now the Ontario-Québec border (LOGAN, 1847). In the following decades several geologists reported on the glaciation of large areas in eastern and central North America. During the 1880s geologists were reporting consistent patterns of ice flow features and transport of erratics, and from this the concept of glaciers flowing outward from the Laurentian Shield Highlands was developed. DAWSON (1890) proposed the name Laurentide glacier although at that time he still believed much of the drift was of marine origin. J. B. TYRRELL (1898), who conducted geological studies in several parts of the shield and made use of observations from other parts of the shield, proposed the name Keewatin glacier, for ice that had been centred in the District of Keewatin (west of Hudson Bay), and the name Labradorean glacier for ice that had been centred in Québec-Labrador (east of Hudson Bay). Later he proposed a centre of outflow in what is now northern Ontario (south of Hudson Bay) which he named the Patrician glacier (TYRRELL, 1914).

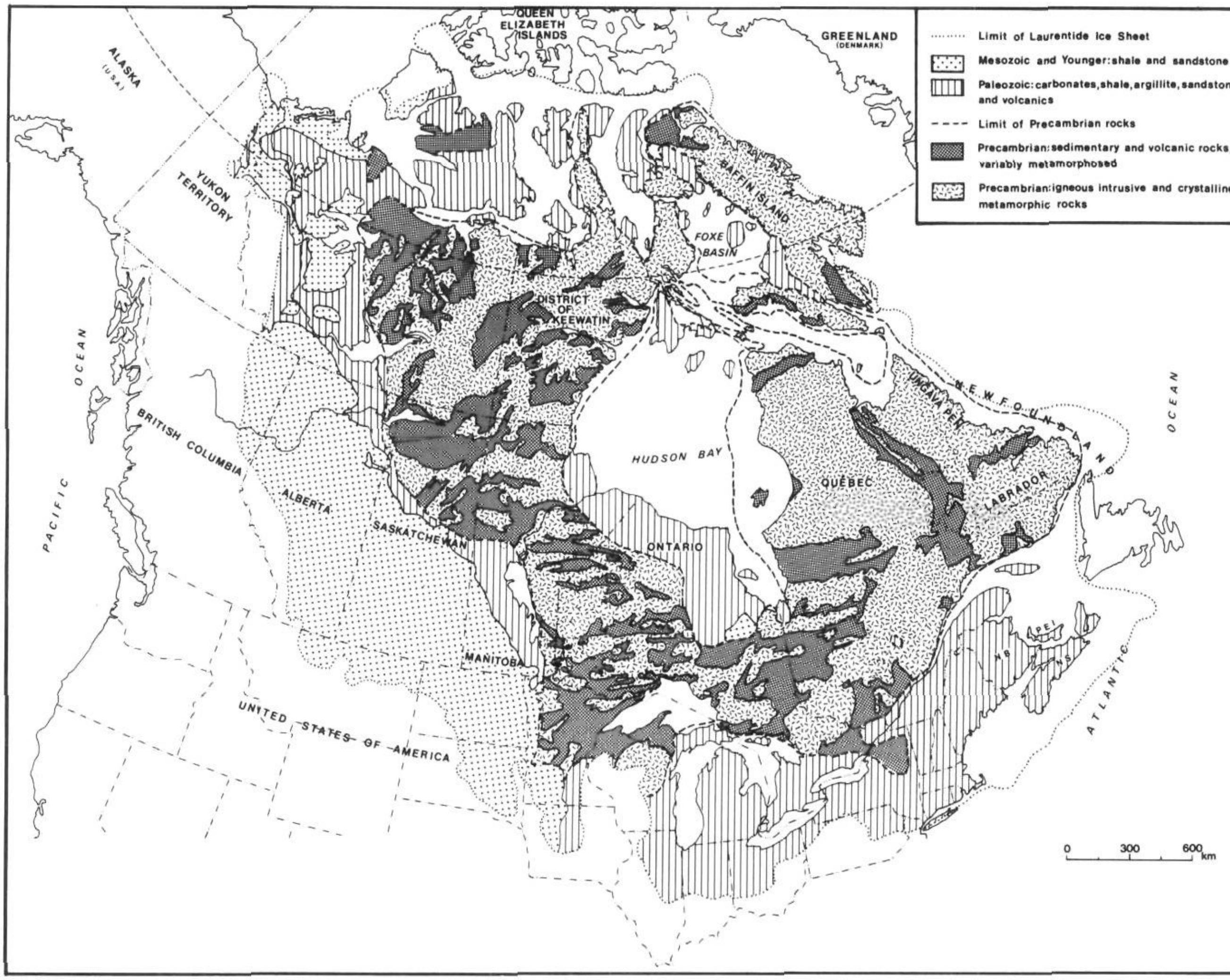

FIGURE 3. General geology of the area overridden by the Laurentide Ice Sheet.

Géologie de la région recouverte par la calotte glaciaire laurentidienne.

The multi-centre or multi-glacier view was accepted for several decades. But FLINT (1943) proposed the term Laurentide Ice Sheet for the monolithic ice sheet that he envisaged was centred on Hudson Bay throughout much of the Wisconsin Glaciation. He viewed the areas occupied by Tyrrell's "glaciers" as too low, dry and warm to have acted as significant accumulation centres. According to his theories, ice sheet inception could only have occurred in the highlands at the northeastern margin of the Shield where a combination of high elevation and abundant moisture supply would have generated alpine glaciers. These would have developed into piedmont lobes and the area of accumulation would have migrated westward until eventually an ice sheet, centred on Hudson Bay, had formed. Flint recognized that there was abundant evidence for radial flow from Keewatin and Labrador centres but attributed this to late flow. IVES (1957) could not accept Flint's theories on inception and growth of the Laurentide Ice Sheet and proposed the idea of "instantaneous glacierization" (further refined in IVES *et al.*, 1975) as a mechanism for growing the Laurentide Ice Sheet on the plateaus of Baffin, Keewatin and Québec-Labrador. The general idea behind this theory is that snow remaining on the plateaus would cause a permanent upper atmospheric trough to form above these areas and that this would modify atmospheric circulation, increasing precipitation, lowering snowline and rapidly bringing large expanses of plateau area under glacial ice. Computer modelling of this form of ice sheet growth indicated that this was a feasible means of quickly covering large areas with ice (ANDREWS and MAHAFFY, 1976). IVES *et al.* (1975), even though they disagreed with Flint's ideas on ice sheet inception, showed the Laurentide Ice Sheet as growing into a single dome centred on Hudson Bay and Foxe Basin. PREST (1957) however, showed the Laurentide Ice Sheet to have been made up of two main flow components one east and one west of Hudson Bay and PREST (1970) named the eastern component the Labrador Sector and the western component the Keewatin Sector. W. W. Shilts, studying dispersal of drift, on the west side of Hudson Bay found no evidence for ice flow westward out of the Bay (SHILTS *et al.*, 1979). These syntheses of flow pattern observations on drift dispersal started a swing back to some of the ideas Tyrrell put forward in 1898, *i.e.* that glaciation was accomplished by ice moving from several independent dispersal centres.

SIGNIFICANCE OF THE LAURENTIDE ICE SHEET

The Laurentide Ice Sheet occupied an area of between 10.2 and 11.3 x 10^6 km^2 and contained something like 20 x 10^6 km^3 of water. This immense body of ice had a profound influence on climate, life, the oceans, and the level of the land. The ice sheet provided a permanent source of Arctic air in the middle latitudes as it established itself as far south as 40° in the area south of the Great Lakes. BROCCOLI and MANABE (1987), in one of the papers that follows, explores the way in which this effected atmospheric circulation and the distribution of precipitation. Paleoecological studies have shown that the Laurentide Ice Sheet moved the tundra biozone at least 30° south, to the middle of United States, and the series of biological zones which once had spanned the North American Continent were telescoped into the area between the southern margin of the ice sheet and the Gulf of Mexico. The volume of water tied up in the Laurentide Ice Sheet was sufficient to lower global sea level by 40-55 m. In addition the climatic cooling, driven in part by the Laurentide Ice Sheet was sufficient for the pack-ice front in the Atlantic Ocean to push from its present position near the northern tip of Greenland (80°) south to about Iceland (65°). The total amount of depression of the crust caused by the weight of ice is not known but the east coast of Hudson Bay has been shown to have rebounded at least 300 m (HILLAIRE-MARCEL, 1976). The isostatic movement involved in depression of the crust, production of a forebulge, and recovery after the ice sheet disappeared resulted in drainage changes, incision of valleys and alluvial infilling of overdeepened valleys.

The Laurentide Ice Sheet rearranged the surface of the area it covered. It removed and destroyed the mantle of weathered rock and either deposited fresh sediment or left unweathered rock at the surface. As a consequence soils in the area are young and nutrient rich and fresh carbonate rich debris is now available to buffer acid precipitation in many areas where it otherwise would be absent. The ice sheet is also responsible for providing granular aggregate resources in many areas. Gradients throughout most of the area covered by the Laurentide Ice Sheet are low, significant quantities of coarse alluvial sediment are not produced under normal conditions and as a consequence coarse granular aggregate are generally not available in nonglacial sediments. The Laurentide Ice Sheet however, with its abundant meltwater and heavy load of debris, has endowed most of this region with rich resources of granular aggregate.

REASON FOR STUDIES OF THE LAURENTIDE ICE SHEET

Studies of the Laurentide Ice Sheet are important from the Canadian point of view because it covered 80 % of our country and consequently played a major role in producing and shaping the surface materials. Most of the soil that grows our food and supplies our forest, and most of the materials on which we construct our cities and engineering works are in someway a product of the Laurentide Ice Sheet. A knowledge of the former flow pattern of the ice makes it possible to locate the source of mineralized erratics. Also an understanding of glacier processes and knowledge of the history of the Laurentide Ice Sheet makes it possible to predict the distribution of granular resources and the distribution of materials which help buffer soils from acid precipitation.

From the point of view of geophysics, studies of the Laurentide Ice Sheet are important because the growth and decay of the ice sheet can be used as a geophysical experiment. Tilting of shorelines and changes in relative sea level provide a means of measuring the response of the crust to the application and removal of the ice load. Construction of a glacial history provides a time framework for loading and unloading the surface.

Major changes in the Laurentide Ice Sheet apparently resulted from relatively minor fluctuations of climate. An understanding of the history and dynamics of the ice sheet would allow us to comprehend the potential effect of small changes in climate. This will put us in a better position to predict the ecological impact of global climatic changes caused by man.

As a final point, study of the Laurentide Ice Sheet provides information that can aid in predicting dynamics of existing ice sheets. We can measure many properties of existing ice sheets and study the responses of these to short term changes. What we need to know however is the way these will respond to longer term changes such as variations in sea level or increases in temperature. Pertinent questions are: how much can sea level rise before it might cause the Antarctic Ice Sheet to surge. What volume of ice might be involved in such a surge. And by how much might the surge cause sea level to change. Studies of the history and dynamics of the Laurentide Ice Sheet provide information pertinent to these important questions.

In conclusion we can say that even though most of the ice sheet had disappeared 7000 years ago, study of the history and dynamics of the Laurentide Ice Sheet, provide valuable information pertinent to human developments and to the response of our environment to a variety of changes, and provide data that can aid in predicting the results of some of the changes we can see taking place around us today.

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