Papers

Importance of the Radiocarbon Standard Deviation in Determining Relative Sea Levels and Glacial Chronology from East Baffin Island

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ABSTRACT. Examples of the importance of the radiocarbon standard deviation in the evaluation of relative sea levels and a local glacial chronology are presented. Techniques for evaluating the data are described. In the early stage of *postglacial emergence,* uncertainties in the radiocarbon age of a sample, presumed to date the marine limit, can lead to a twenty per cent error in the estimated elevation of lower sea levels. As recently as about 4,300 radiocarbon years ago, glaciers from the inland ice sheet over Baffin Island were reaching to sea level in at least this one area.

RÉSUMÉ. *Importance de la déviation standard du radiocarbone dans la détermination des niveaux marins relatifs et dans les chronologies glaciaires : un exemple pour l'est de l'île de Baffin.* L'auteur donne des exemples de l'importance de la déviation standard du radiocarbone dans l'évaluation des niveaux marins relatifs, de même qu'une chronologie glaciaire locale. Il décrit les techniques d'évaluation des données. Dans la première étape de l'émergence postglaciaire, des incertitudes sur l'âge radiocarbone d'un échantillon, qu'on présume dater la limite marine, peuvent conduire à une erreur de vingt pour cent dans l'altitude estimée des niveaux marins inférieurs. Aussi récemment que 4,300 années-radiocarbone avant aujourd'hui, des langues glaciaires alimentées par la calotte intérieure de l'île de Baffin atteignaient le niveau de la mer, tout au moins dans la région étudiée ici.

РЕЗЮМЕ. *Роль стандартного отклонения в радиоуглеродном методе датировки при определении относительных морских уровней и хронологии ледникового времени на примере восточной части Баффиновой Земли.* Приводятся примеры роли стандартного отклонения в радиоуглеродном методе датировки при определении относительных морских уровней и дается хронология ледникового времени в восточной части Баффиновой Земли. Описывается методика оценки полученных данных. В ранней стадии *послеледникового поднятия,* неопределенности в радиоуглеродном возрасте пробы, предположительно датирующей морскую границу, могут привести к оценке высоты нижних морских уровней с ошибкой до 20%. Ледники материкового ледяного покрова на Баффиновой Земле доходили до уровня моря еще около 4300 радиоуглеродных лет тому назад, во всяком случае в описываемом районе.

INTRODUCTION

In recent years this journal and others have published papers on postglacial emergence and/or uplift of the Canadian Arctic (e.g. Muller and Barr 1966; Matthews 1967; Hattersley-Smith and Long 1967; and Farrand 1962; Lee 1962; Ives 1964; Henoch 1964; Løken 1965; Andrews 1966). Recently, Andrews (1968a) considered the form of postglacial uplift curves from that part of arctic Canada formerly covered by the Laurentide Ice Sheet and showed that they are mathematically similar. The above study indicated that about 33 per cent of

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postglacial uplift occurs in the first thousand years of recovery (for a discussion of the definitions of the various phases of glacio-isostatic recovery, see Andrews, 1968b). Because of this initial rapid uplift in postglacial time, the precision of the estimate for date of deglaciation and commencement of postglacial uplift becomes critical.

The aim of this paper is to illustrate: 1) the importance of the radiocarbon standard deviation in estimating former relative sea levels; 2) graphical methods for presenting postglacial uplift data and 3) techniques for establishing a local glacial chronology in an area where the radiocarbon ages of two distinct moraine systems overlap. The area that serves as an example is the head of Ekalugad Fiord, east Baffin Island, Northwest Territories, Canada (Fig. 1).

DESCRIPTION OF THE FIELD AREA

Two kilometres from the head of Ekalugad Fiord, east Baffin Island, a large end moraine extends across the fiord (Fig. 2). A narrow channel, cut through

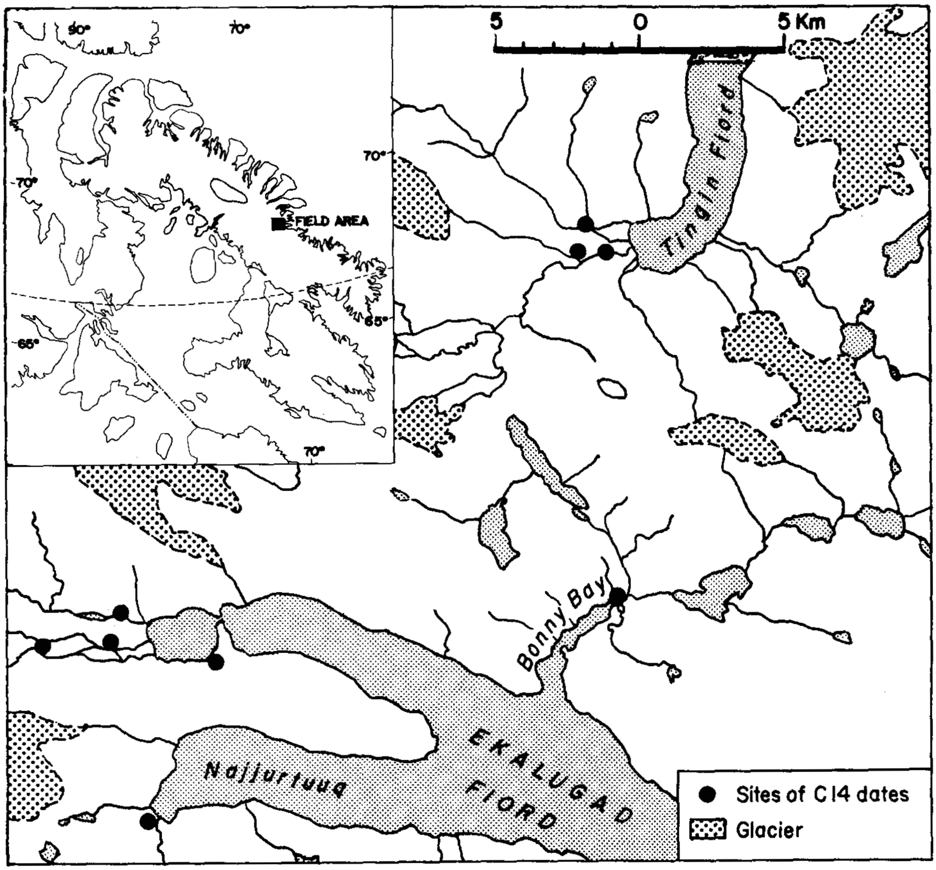

FIG. 1. The head of Ekalugad Fiord and the surrounding fiords, east Baffin Island, showing location of sites from which C^{14} dates have been obtained and the extent of present glacierization.

the northern part of the moraine, allows sea water to penetrate *Venturi Bay* (name not approved by Board on Geographical Names). A delta lies along part of the southern shore of *Venturi Bay;* it was formed by meltwater moving laterally along the former glacier margin and debouching into a higher sea level. Field relationships of the delta to the *Venturi Bay* moraine indicate that both were formed at about the same time. At the head of the fiord, streams are actively eroding an old sandur (outwash) that rises toward the southwest from 18 to 40 m. above sea level (a.s.l.). Three valleys converge at the head of the old sandur, and low terminal moraine loops occur near the point of convergence (Fig. 2) and testify to a period of marginal stability that followed the deposition of the *Venturi Bay* moraine and delta. Outwash from the glaciers standing at the 3 moraines grades imperceptibly downvalley and constitutes the sandur surface described above. The old sandur surface is called the T2 surface by Church (1966), and this nomenclature is used here.

There is no visible trace of any significant glacial episode between the *Venturi Bay* moraine and the moraines associated with the T2 surface, and I believe that retreat over the 6.8 km. was moderately rapid.

It should be noted that the present mountain ice caps and associated glaciers (Fig. 1) bear no relationship to the late-glacial ice tongues that deposited the moraines at the head of Ekalugad Fiord. (*Late-glacial* is used throughout this paper in a literal sense. It thus has only a local time connotation and refers to

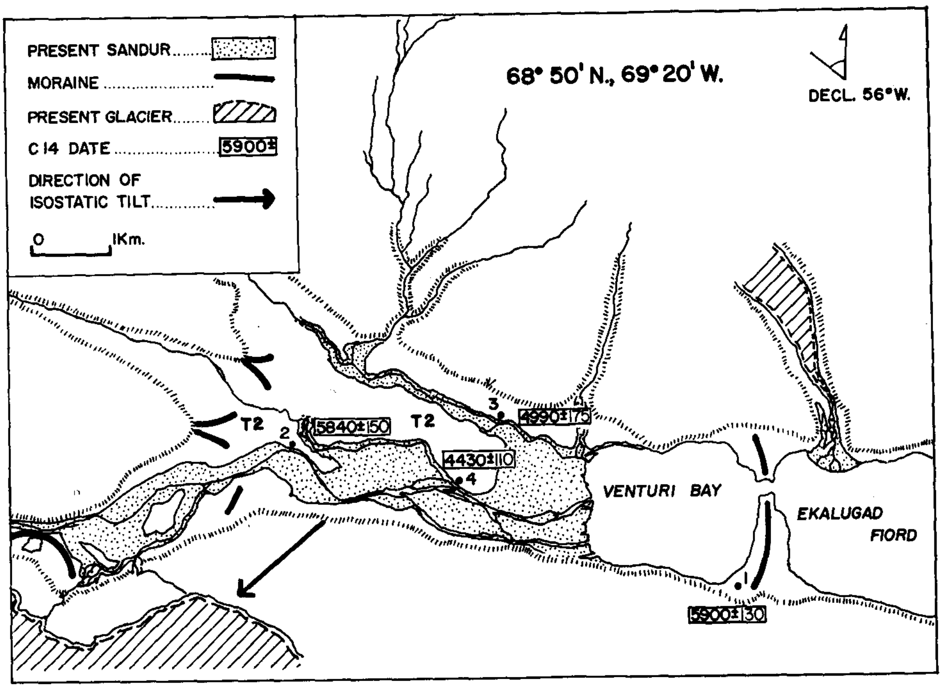

FIG. 2. Detailed map of the head of Ekalugad Fiord showing moraines, location of C^{14} dates and direction of isostatic deformation (note: arrow is pointing toward 230 degree bearing).

the period — whatever the radiocarbon date — when the fiord glaciers were in the process of retreating from the area). The mountain ice caps did not develop in this area until some time after the retreat, and possible disappearance, of the interior Baffin ice cap (Ives and Andrews 1963).

SITES AND RADIOCARBON DATES

Four radiocarbon dates have been obtained from samples of marine shells (Fig. 2 and Table 1). The samples were dated in order to obtain information on the late-glacial history of Ekalugad Fiord and to provide an estimate of sedimentation rates and sandur progradation during the construction of the T2 surface (Church 1966).

TABLE 1. Radiocarbon dates from deposits at the head of Ekalugad Fiord, Baffin Island, N.W.T.

Date B.P.	*Lab. No.*	*Two Standard Deviations* (±)	*Range*	*Marine Limit*	*Collector*	*Site and Date No.*
5,900 ± 130*	1-2412	260	5,640 to 6,160	54	J. T. Buckley	1
5,840 ± 150	1-3062	300	5,540 to 6,140	43 ±	M. Church	2
4,990 ± 175*	1-2442	350	4,640 to 5,340		M. Church	3
4,430 ± 110*	1-2584	220	4,210 to 4,650	23 ±	M. Church	4

*For further details on these dates see: Andrews 1967.

Date No. 1 was obtained on marine shells from an oxidized sand bed within the *Venturi Bay* delta (Fig. 2). Further details on this and another 2 dates are provided by Andrews (1967). Beach notches on the north side of the fiord at 54 m. a.s.l. and a terrace at the distal side of the moraine 53 m. a.s.l. that leads toward the delta's apex indicate that the delta was built into a relative sea level about 54 m. a.s.l. and confirms that the moraine and delta were deposited synchronously. A discussion on the accuracy and precision of radiocarbon dates comes later in this paper, but suffice to note that all dates in column No. 1, Table 1, are listed with a $\pm$ 1σ error. Using a 2σ criterion, date No. 1 indicates that the *Venturi Bay* delta (and moraine) was deposited between 5,640 and 6,160 years ago. (It should be understood that all dates in this paper refer to *radiocarbon years ago.*)

Date No. 2 was obtained on *in situ* marine shells collected from the steeply dipping foreset beds of the T2 sandur. The site is located close to the junction between the younger moraines and their related outwash surface. The foreset beds are truncated and are capped by coarse outwash gravels. Relative sea level at the time these shells lived was at least 40 m. a.s.l. Modern analogues on the present sandur and foreset beds indicate that possibly between 1 to 3 m. have to be added to the above elevation to obtain a relative sea level estimate for the interval 5,540 to 6,140 years ago.

The samples for which dates No. 3 and No. 4 were obtained were collected from sites approximately half way between No. 1 and No. 2 (Fig. 2). The older date was from marine shells collected from silt overlain by the prograding foreset beds of the T2 surface, whereas the younger date was from shells, with siphons still attached, from within the foreset beds themselves. A relative sea level of 23 m. a.s.l. is used for this site (Table 1).

Preliminary statements on the glacial geomorphology of the area are given by Andrews (1966b), Buckley (1966) and Church (1966).

THE PROBLEM

The problem is to assign age estimates to: 1) the *Venturi Bay* moraine, 2) the inner moraines, and 3) the length of sedimentation involved in the construction of the T2 surface. The radiocarbon dates from sites No. 1 and No. 2 that should date both moraine phases overlap and only suggest that both were probably formed sometime between 5,540 and 6,160 years ago. Furthermore, the evidence suggests that the T2 surface developed over a maximum of 1,930 years and a minimum of 890 radiocarbon years (dates No. 2 and No. 4, Table 1). Either estimate indicates a prolonged period of continuous sedimentation and little glacial retreat.

PRECISION AND ACCURACY OF THE RADIOCARBON DATES

It is necessary to consider both the accuracy and precision of radiocarbon dates in defining a detailed glacial chronology. Accuracy defines the relationship between the radiocarbon years and calendar years, whereas precision is concerned more with variations in individual measurements and thus affects the standard deviation. McIntyre (1963) has discussed these two terms and their significance in geochronometry.

We possess only meagre information on the accuracy of radiocarbon dates derived from marine shells within arctic Canada. Few, if any, dates have been reported on pre-bomb, modern shell samples, although such a sample from East Greenland was dated 500 radiocarbon years B.P. (Washburn and Stuiver 1962). Even if such dates were available, it is uncertain if they could be applied as a standard correction because of local conditions. Thus the application of a 500-year correction to radiocarbon dates from the Canadian Arctic (Muller and Barr 1966; Hattersley-Smith and Long, 1967) is not considered appropriate at this time. Work on tree ring dates (e.g. Stuiver and Suess 1966; Dyck 1966) shows that the C^{14} concentration has varied with time (the deVries effect). However, similar studies have not been made on marine organisms within our area of interest. There is indirect evidence that implies that major changes in the oceanic C^{14} concentration have *not* occurred in Canadian Arctic waters. The reason for this guarded statement is found in the close similarity between predicted and observed postglacial uplift curves based on dates from marine shells over a time span 12,500 to 5,000 radiocarbon years ago (Andrews 1968a). Such correspondence would be unlikely if large geographical and temporal variations had occurred in the C^{14} concentration.

The accuracy of a radiocarbon determination also depends on the estimate for the half-life of C^{14}. Radiocarbon laboratories use a value of 5,568 $\pm$ 30 years whereas a closer approximation is 5,730 ± 40 years. There is, therefore, a 3 per cent error in the age estimates of Table 1. Dates in this paper are 126 to 185 years too young. A final cause of inaccuracies in radiocarbon dates is through contamination of the sample. The preservation of the shells in all 4 samples is such that this aspect can be discounted.

The marine shell samples from the head of Ekalugad Fiord are considered to have the same relative accuracy because 1) they have similar radiocarbon ages, 2) they are from geographically close sites and 3) they are from relatively shallow (4 to 32 m.) water deposits (Polach and Golson, 1966).

The precision of a radiocarbon date partly depends on the age of the sample, the size of the sample, counting time, etc. The error ranges reported in this paper (Table 1) are independent of uncertainties due to fractionation and the deVries effect and they are essentially computed from variations in counting rates (information from Isotopes, Inc.). They were reported with a $\pm 1\sigma$ error. In this paper the practice advocated by Polach and Golson (1966) is followed, that is, 1) the quoted error is doubled so that there is a 95.45 per cent chance of the radiocarbon age being included within the limits, and 2) the age range is set out. Thus a sample 5,000 ± 100 years B. P. is quoted as between 4,800 and 5,200 years old. This practice, particularly the second point, avoids problems connected with paying lip service to the error term while still thinking in terms of the quoted age. During the reconnaissance phase of glacial investigations in arctic Canada, there was little need for the field investigator to consider this problem. Collecting sites were tens or even hundreds of kilometres apart, thus reducing the probability that deposits, distinct in terms of distance and thus time, had similar radiocarbon ages. Here I am referring, for instance, to the retreat of a glacier up a fiord or bay. Consider, for example, a glacier retreat of 10 m. yr.$^{-1}$ and 200 m. yr.$^{-1}$; assume a 95 per cent error range of 400 years. In the first case, deposits only 4 km. apart and related to the marine limit could have different radiocarbon ages, whereas in the latter case sites closer than 80 km. to each other could produce statistically similar dates. There is, therefore, still a considerable need for the relative dating of glacial deposits and the establishment of glacial sequences by geological and geomorphological techniques.

RELATIVE SEA LEVELS AND A CHRONOLOGY FOR THE HEAD OF EKALUGAD FIORD

The problem has been defined above. In order to develop techniques for the analysis of these dates, the following statements are made:

- The *Venturi Bay* moraine is older than the inland moraines.
- Investigations on the direction of isostatic deformation in the Home Bay area indicate that strandlines (i.e. former synchronous water planes) dip toward 050° (Fig. 2).

In another paper (Andrews 1968a) I examined 21 postglacial uplift curves from arctic Canada, exclusive of the Queen Elizabeth Islands, and showed that they could all be closely approximated by:

$$Up_t = \frac{A(1-i^t)}{1-i}, \; i \neq 1.0, \; t \geq 1.0, \; Up_{1.0} = A \qquad [1]$$

where Up is the amount of postglacial uplift in time t, $t = 0.0$ is the moment of deglaciation and hence the beginning of *postglacial* uplift (Andrews 1968a, 1968b) and further t is expressed as x 10^3 years. A is constant for each equation, although it varies with both time and amount of postglacial uplift. Tables for A per cent have already been published (see Andrews 1968a). Finally, i is a constant for the data examined equal to 0.677. Note that this equation predicts postglacial uplift, *not* emergence. Total postglacial uplift is defined as the algebraic sum of the elevation of the marine limit and the appropriate eustatic sea level correction. Despite disagreement of the precise form of eustatic sea level variations (Jelgersma 1966), the use of Shepard's (1963) curve produced close agreement between predicted and observed postglacial uplift and emergence curves. Given the elevation and age of the marine limit, equation [1] can be used successfully to predict the age and elevation of relative sea levels.

Construction of postglacial uplift and emergence curves

Postglacial uplift and emergence curves were constructed (equation 1) for sites Nos. 1, 2 and 4 using the oldest and youngest estimate for each site as determined by the 2σ error (Fig. 3). The x axes are time scales that read: 1) years of postglacial uplift, and 2) years B. P. (of postglacial emergence). Emergence is predicted by subtracting the amount of uplift in t years from the present elevation of the marine limit, by further subtracting the necessary eustatic sea level value and finally by converting time scale 1) into years B. P.

Fig. 3 shows that the oldest and youngest postglacial uplift curves for the three sites are similar. This is because the starting point $t = 0.0$ is the moment postglacial uplift commenced and it is thus independent of the length of the recovery period. However, Fig. 3A, B, and C shows that the predicted emergence curves are widely divergent for the first 1,000 years of emergence, although they converge toward the present day. Because of the 2σ error at site No. 1, there is a possible 8 m. error in the determination of the relative sea level for 5,000 years ago, whereas Fig. 3B indicates an uncertainty of 10 m. in assigning a relative sea level for 5,500 B. P. These are considerable errors. The main effect of the

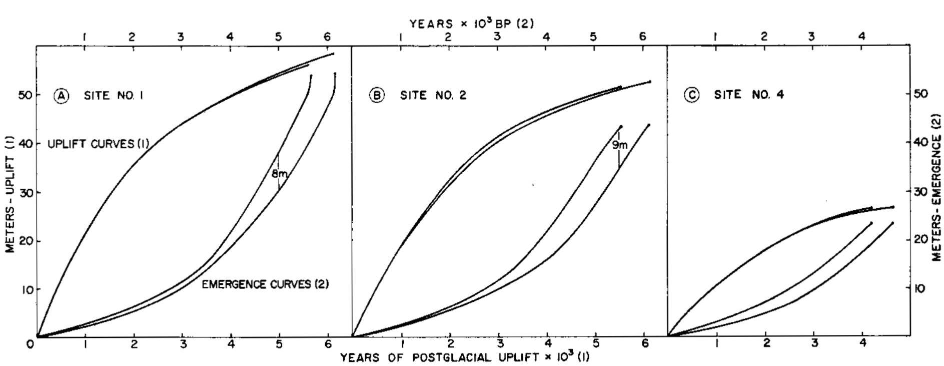

FIG. 3. Graphs of postglacial uplift and emergence drawn on the basis of equation [1] with the length of the postglacial recovery period varying by $\pm 2\sigma$ from the quoted age (Table 1). Note that the extreme left of time scale 2 is the *present day*.

imprecision in radiocarbon dating combined with the initial period of rapid postglacial recovery is to introduce the probability of significant error in studies of relative sea levels and marine strandlines. Fig. 3 illustrates that this error may amount to 20 per cent of total postglacial uplift. It is self-evident that the younger age limit will always predict a higher sea level for any date.

Construction of the equidistant diagram

Fig. 3 gives some indication of the errors involved in assigning ages to relative sea levels. The problem is to use these data, together with the statements on the relative ages of the 2 moraine systems and the direction of isostatic tilt, to obtain age estimates for use in a glacial chronology. How can this be done? The answer lies in using the equidistant diagram and recognizing that the second statement, page 18, indicates that strandlines decrease in elevation toward the northeast. Therefore, Fig. 4 was drawn with the sites projected onto a plane bearing 050 to 230°. Date No. 4 refers to a relative sea level at 23 m. a.s.l. and indicates this part of the T2 surface deposited between 4,210 and 4,650 radiocarbon years ago. The radiocarbon age (No. 3, Table 1) on shells from nearby,

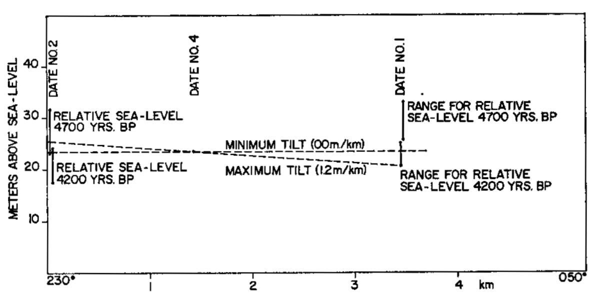

FIG. 4. Equidistant diagram for the head of Ekalugad Fiord drawn in the plane 050 to 230 degrees showing possible variation in relative sea level.

underlying marine silt is stratigraphically consistent. The difference in relative sea level elevations between each of the boundary curves (Fig. 3A and B) was noted for 4,200 and 4,700 years ago and for each site was plotted as two vertical lines on Fig. 4. Two limiting situations exist in deriving an answer from this figure. The first is a horizontal line passing through site No. 4, whereas the other is the steepest line dipping northeast that passes through Nos. 1, 2 and 3. This line (Fig. 4) tilts 1.2 m. km.$^{-1}$. The horizontal limit indicates that for site No. 1 relative sea levels 4,700 years ago are not applicable, whereas the line of maximum tilt eliminates relative sea levels at site No. 2 for 4,200 years ago. The age of the T2 surface at site No. 4 lies, therefore, between these two extremes. No unique solution can be proposed, but let us assume that the best estimate for the age of the marine shells at site No. 4 is 4,350 years B. P. Examination of the emergence curves (Fig. 3A and B) indicates that relative sea levels at sites Nos. 1 and 2 may vary from 22 to 27 m. and from 19 to 26 m. respectively. A maximum tilt of 0.5 m. km.$^{-1}$ is now possible. Such a gradient passes through the lowest point on the range of relative sea levels at site No. 1 and toward the top of the range at site No. 2. From Fig. 3A and B it can be seen that this suggests that 1) the best estimate for the *Venturi Bay* moraine is 6,100 years B. P., and 2) the age of the inner moraines and the initial deposition of the T2 surface is dated about 5,700 years B. P. The differential uplift at the three sites over this 4,350-year period is such that the rate of deformation is 0.011 cm. km.$^{-1}$ yr.$^{-1}$.

To test these suggestions, the analysis was extended to include nearby sites (Fig. 1). Postglacial uplift curves were drawn for Tingin Fiord, based on an estimated date of deglaciation of 9,000 B. P. (Andrews 1968a, p. 46) and a marine limit at 88 m. a.s.l. (incorrectly given at 95 m. in Andrews 1968a) and for *Najjurtuuq,* using a date of 5,090 to 4,610 years (I-3066) and a marine limit elevation of 37 m. Buckley (Andrews 1967) collected a sample of *Mytilus edulis* from 18 m. a.s.l. dated 4,650 to 4,200 years old (I-2413). The sample site was overlain by 2 m. of sand and gravel and the relative sea level at time of deposition was probably about 20 m. above present sea level.

Possible relative sea levels for 4,350 years ago were then projected onto an extended, equidistant diagram (Fig. 5). If the gradient of 0.5 m. km.$^{-1}$ is extended to Tingin Fiord, the relative sea level for this period should be 12 m. a.s.l. A sample relating to a sea level at 5.0 m. a.s.l. dates from between 3,820 and 3,340 years ago (Y-1831, Andrews 1967), and the emergence curve from the head of Tingin Fiord places the sea level 4,350 years ago 10 to 13 m. above present sea level. A gradient of 0.5 m. km.$^{-1}$ also *fits* the other points on Fig. 5 and adds support to the argument above.

CONCLUSIONS

Two types of conclusions emerge from this short paper: the first concerns the appraisal of techniques while the second concerns the establishment of a glacial chronology for the head of Ekalugad Fiord.

The paper deals with the problem of error in estimating relative sea levels and a glacial chronology in a small area where radiocarbon dates provide some chronological control, but where the precision of the radiometric technique does not allow a clear-cut chronology to be developed on that basis alone. As mentioned earlier, the problem is related to a) the rate of glacier retreat, and b)

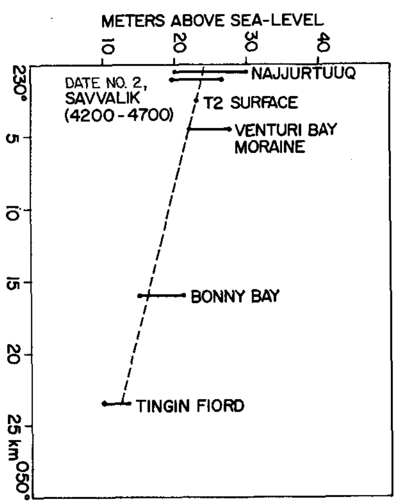

FIG. 5. Extended equidistant diagram drawn in the plane 050 to 230 degrees and including sites from Tingin Fiord, Bonny Bay and 'Najjurtuuq' (Fig. 1).

the linear distance parallel to ice flow over which the research is undertaken. During the exploratory phase of research into the late and postglacial history of Arctic Canada, which is still continuing, there was little need for the glacial geomorphologist or geologist to consider the error term of a radiocarbon date. As research becomes more specific, both to area and to problem, the precision of radiocarbon dating becomes critical. Witness, for example, the present discussion on the date of deglaciation of Hudson Bay (Falconer *et al.* 1965a and 1965b; Blake 1966).

If the detailed field work involves an area where glacial moraines can be correlated with specific sea levels, then the techniques presented in this paper can be used to derive an internally consistent sequence of dates. The construction of postglacial uplift and emergence curves provides the first step in the analysis. In this paper radiocarbon dates fortunately refer to reasonably well-defined sea levels and this enables the use of the prediction equation [1]. Elsewhere, I have presented a graphical development of this equation which enables the age of the marine limit to be estimated given the age and elevation of *any* relative sea level (Andrews 1969). In constructing postglacial and emergence curves, it is recommended that the 95 per cent *envelope* be plotted, based on either end of the range for the age of the marine limit. If then the direction of isostatic deformation is known, data can be plotted as Fig. 4 and Fig. 5, thus enabling the researcher to delimit more precisely the age of various glacial events.

These techniques have been applied to the glacial sequence at the head of Ekalugad Fiord, east Baffin Island, N.W.T.; they suggest that the *Venturi Bay* moraine is about 6,100 radiocarbon years old, that the ice retreated and stood at the inland moraine system about 5,700 years ago, at which time the initial deposition of the T2 surface began. Retreat between the two moraine units was about 17 m. $yr.^{-1}$. Between the initial formation of the T2 surface 5,700 years ago and about 4,350 years ago, sea level fell by about 20 m. In this interval the T2 surface actively prograded downvalley by 3.5 km. through the deposition of successive foreset beds, which were in turn overlapped by a veneer of outwash gravels. The average rate of progradation is considered to be about 2.6 m. $yr.^{-1}$. The coherence of this surface (the T2) is remarkable, and it required for its formation a continual supply of sediment. This has an important bearing on the overall glacial chronology of east and central Baffin Island as the sediment could only be glacially derived. The implications are that glaciers lingered in the valleys from 5,700 to *at least* 4,350 years ago (an unknown amount of the T2 surface has been removed by subsequent stream meandering). As the glaciers were fed from the inland ice cap over Baffin Island, this indicates that deglaciation of the interior plateau west of Ekalugad Fiord was not accomplished until sometime after 4,350 years ago. With the final retreat of the glaciers and the resulting deficiency of materials, the rivers began to downcut and meander (Church, *personal communication*). The glacial history of the head of Ekalugad Fiord is thus very different from that recorded at the head of Inugsuin Fiord about 100 km. further north where evidence indicates that the fiord head became ice-free between 8,650 and 7,290 radiocarbon years ago (I-1673 and I-1602; Løken 1965; Barnett in Andrews 1967).

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