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A REVIEW OF MEASUREMENTS OF PRESENT-DAY VERTICAL MOVEMENT IN ARCTIC CANADA

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Summary

Arctic Canada has experienced and continues to experience the largest postglacial uplift in the Northern Hemisphere. Measurements of this uplift have far-reaching implications for estimating ice-sheet thicknesses and deep-Earth structure. Present-day estimates of this uplift are derived from three sources: tide-gauge records, absolute gravity measurements, and Holocene relative sea-level data. At a time when the Global Sea-Level Observing System (GLOSS) is being implemented and the World Ocean Circulation Experiment (WOCE) and Canadian Absolute Gravity Program are underway, it is considered beneficial to review both tide-gauge records and absolute gravimetry data from the perspective of geodynamics and the measurement of postglacial uplift. In Arctic Canada, there are 12 tide-gauge records that have 3 or more years of data. Of these, only the gauge at Churchill, Manitoba, is still operating. As of December 1991, there have also been 38 absolute gravity measurements at 15 sites distributed in 8 Arctic settlements. At Churchill, there have been 8 measurements made by the Geological Survey of Canada and 1 by the U.S. National Geodetic Survey. A decreasing trend is beginning to develop, and this is thought to indicate uplifting land.

After analyzing the tide-gauge records and the absolute gravimetry data, recommendations are made into which sites should have priority. In order of priority, the tide-gauge sites are;

(1) Churchill, (2) Resolute, and (3) Tuktoyaktuk.

The absolute gravimetry sites are;

(1) Churchill, (2) Yellowknife and Shefferville, and (3) Resolute and Inuvik.

If necessary, other Arctic sites should be largely ignored in favour of these sites. These recommendations do not consider the large expenses involved in travelling to and operating in Arctic Canada. Hopefully these expenses will not become prohibitive.

Introduction

Both long-duration tide-gauge records and absolute gravimetry measurements have the potential to determine present-day vertical movements. Using tide-gauge records from northern Europe, Emery and Aubrey (1985) mapped the postglacial uplift caused by the Fennoscandian Ice Sheet. Tushingham (1992a) examined both the tide-gauge and absolute gravity records for Churchill, Manitoba, and found that they produce similar estimates of the rate of postglacial uplift.

In light of the recommendation by the Joint Oceanographic Institutions (1990) for the development and installation of sea-level measurement systems at polar sites and an upcoming report on the future of the Canadian tide-gauge network by the Department of Fisheries and Oceans, it was deemed desirable to review the measurements of vertical movement in Arctic Canada. Recent advances in the prediction of postglacial uplift (Tushingham and Peltier 1991) also imply the need for a review of these measurements.

Tide-gauge records

There are 12 Arctic tide-gauge records available from the Marine Environment Data Service (1992) that have record durations of 3 or more years. The locations of these tide gauges are shown in Figure 1. During the late 1970s and early 1980s, all the gauges except the one at Churchill were closed down. The tide-gauge records are displayed in Figure 2, with the record for the Churchill tide gauge presented separately in Figure 3. It is obvious that the records for Coppermine, Coral Harbour, and Frobisher Bay (now called Iqualuit) are useless for crustal motion studies. Most of the others are also of doubtful use.

The analysis of the tide-gauge records is undertaken using three calculations: (1) a straightforward trend is computed using every month with data available. This procedure ignores any potential effects from seasonal variations and gaps in the record, but does maximize the use of the limited data available. (2) To overcome the seasonal effects and the presence of gaps, an annual average is determined only for years with all 12 months of data available and a trend is computed from these annual averages. (3) In studies of the water levels of the Great Lakes, it is common practice to use only gauge data from the summer months (e.g., Tait and Bolduc 1985). For this report the "summer" months in the Arctic are taken to be July and August. An "annual" average is computed from the average of the gauge data for these two months only if both months had data. The use of only "summer" months reduces (or hopefully removes) the effects of storms, spring run-off, and ice build-up (Tait and Bolduc 1985).

Table 1 presents the results of these analyses, with the errors representing the standard error of the trend (e.g., Hicks 1978). The available data for Sachs Harbour in 1971, Frobisher Bay in 1977, and Coral Harbour in 1979 are not used as it appears different datums were employed. The very high and very low monthly values at Alert during the period October 1965 - January 1968, inclusive, are not used. Similar results from the three calculations are found for the records at Churchill, Resolute and, to a lesser extent, Cambridge Bay. For the remaining records, the rates from the three calculations vary widely or cannot be computed because of a lack of data. The summary estimates presented in Table 1 for Cambridge Bay, Churchill, and Resolute are approximately the range of values covered by the three calculations. The summary estimates for the other gauges are of doubtful quality.

It must be remembered that tide gauges measure the relative rate of change between the land and the sea. In the Arctic, not only is the land recovering from the weight of the Late Wisconsin ice sheets, but the sea is rising in response to the changing shape of the solid Earth and the change induced in the geoid by this recovery (Peltier and Tushingham 1989). This is in addition to any sea-level rise from climatological effects. At more ice-central sites (such as Churchill), the crustal response is much larger than any changes in sea level.

Absolute gravimetry

The Canadian Absolute Gravity Program (Lambert et al. 1989) made its first measurements in the Arctic at Alert during the period September 23-25, 1987 (Goodacre et al. 1991). Since 1987, 37 measurements of the acceleration due to gravity (g) have been made with the absolute gravimeter of the Geological Survey of Canada, denoted JILA-2, and 1 with the absolute gravimeter of the U.S. National Geodetic Survey (Table 2). These measurements have been made by the staff of the Gravity and Geodynamics Section of the Geophysics Division at 15 sites distributed in 8 Arctic settlements (Figure 1). Sites at Churchill, Shefferville, and Yellowknife are the only ones that have been visited for three or more years. Only the site at Churchill has enough data to make a meaningful estimate of the rate of change of g (Lambert et al. 1992; Tushingham 1992a). Figure 4 shows the measurements recorded at Churchill, including one by the U.S. National Geodetic Survey. The anomalously-high value for g measured in late 1990 is most likely due to the proof-mass problem discussed by Lambert et al. (1992), so it was not included in the calculation of the trend. A value at Yellowknife in 1990 is also anomalously high. The trend at Churchill of -1.6 ± 0.5 μGal/a (1 Gal$=$0.01 m/s^2) can be converted to a rate of uplift using a deformation gravity gradient of -0.18 μGal/mm (Tushingham et al. 1991). This value for the deformation gravity gradient is probably valid for ice-central sites, but not necessarily valid for ice-marginal sites. In the future, differences between trends from tide-gauge records and those from absolute gravimetry may be able to better constrain this important physical parameter.

Relative sea-level data

Relative sea-level data from the Holocene can be used to estimate the present-day rates of uplift. This data usually consists of radiocarbon-dated organic samples found in close proximity to ancient shoreline features (e.g., Tushingham 1992b). With a sufficient number of dated samples, a relative sea-level curve can be constructed. Nearby relative sea-level curves are available for 7 of the 12 Arctic tide-gauge sites and 5 of the 8 absolute gravimetry sites.

Four sites have a tide-gauge record, absolute gravimetry data, and a nearby Holocene relative sea-level curve; i.e., Alert, Churchill, Resolute, and Tuktoyaktuk/Inuvik. Dredge and Nixon (1992) constructed a curve for Churchill from the elevations and radiocarbon ages of marine shells (Figure 5), which implies a present-day rate of uplift of 9.0 mm/a. It must be noted that all radiocarbon ages are converted to sidereal, or calendar, ages using the conversion curves of Pearson et al. (1986)., Stuiver et al. (1986), Bard et al. (1990), and Becker et al. (1991) (Figure 6). This curve is also discussed by Tushingham and Peltier (1992a). The conversion is necessary because of variations in the flux of cosmic rays that cause the formation of ^{14}C in the atmosphere. Near Resolute on the southern Cornwallis Island, Washburn and Stuiver (1985) collected a large number of samples that were subsequently dated by radiocarbon techniques. Their tentative emergence-curve envelope is shown in Figure 7, and the present trend of this envelope ranges from 2.2 mm/a to 4.5 mm/a. England (1983) revised his earlier curve (England 1976a) for the Alert-Wood River area. Although the new curve shows unrealistic behaviour circa 9000 cal years BP (Tushingham 1991), there is no difference in the two curves for the last few thousand years (Figure 8). The present trends of both curves are estimated to be 2.5 mm/a. In the Beaufort Sea near Tuktoyaktuk, Hill et al. (1985) dated submerged peat from geotechnical boreholes. Their data and preferred curve are shown in Figure 9. Data from the Yukon coast (Forbes 1980) show less subsidence than the data from the coast near Tuktoyaktuk.

Present-day uplift rates computed from radiocarbon-controlled relative sea-level curves are available for over half the sites (Table 3).

Discussion

Table 3 summarizes the rates of uplift for the three methods. For comparison, theoretical rates from the glacial isostatic adjustment model ICE-3G (Tushingham and Peltier 1991) have also been included. This model was constructed by fitting relative sea-level data from 191 ice-covered or ice-peripheral sites, and its predictions compared favourably to data from 201 sites located far from the former ice sheets (Tushingham and Peltier 1992b). For approximately half the sites considered here, no estimate of uplift rate could be made from either absolute gravimetry or the tide-gauge records. For the remaining sites, given the shortness of the tide-gauge records and the sparseness of the absolute gravimetry data, the best that can be said is that at least the various estimates are generally not inconsistent. The most consistent estimates are from the site at Churchill, which has all four between 7 mm/a and 9 mm/a. The absolute gravimetry and tide-gauge records at Churchill are each the longest available in Arctic Canada. At Resolute, the three available estimates all produce rates between 2 mm/a and 5 mm/a. This consistency is only possible because of the quality of the tide-gauge record. There are few gaps and no large fluctuations, both of which are common in other records. Unfortunately, the record only spanned 19 years. It is interesting to note that the very short absolute gravimetry records at Yellowknife and the Shefferville seismic vault produce rates (6.1 mm/a and 7.9 mm/a, respectively) which are similar, probably fortuitously, to the rates predicted by ICE-3G (5.2 mm/a and 9.3 mm/a, respectively).

Recommendations

The recommendations listed below are guided by one overriding principle: for geodynamic applications, one or two long-duration records are preferred over a dozen or more short-duration records. These recommendations ignore the considerable financial restrictions facing both the Department of Fisheries and Oceans and the Department of Energy, Mines and Resources. The expense of travelling to and working in the Arctic has forced the Canadian Absolute Gravity Program to stop visiting High Arctic sites, such as Resolute and Alert, and may result in a change of emphasis in the program to sites around the Great Lakes (A. Lambert, personal communication, 1992).

The recommendations for tide-gauge and absolute gravimetry sites are listed separately. The sites are listed in order of their priority and, if necessary, other Arctic sites should be largely ignored in favour of these sites.

Tide-gauge sites

(1) Churchill

This gauge is the only one of the twelve gauges still operating, and it has over a 50-year history. No other record has a duration half this long. The gauge does have a problem resulting from the diversion of the Churchill River and consequent reduction of river outflow (Tushingham 1992a). The diversion may ultimately allow an estimate of the effect of river flow on tide-gauge measurements, such as discussed by Meade and Emery (1971).

(2) Resolute

The lack of large fluctuations in the record suggest that the tide gauge was placed in a stable location. If the gauge is reactivated it may play a role in the World Ocean Circulation Experiment (WOCE) (Woods 1985). The Joint Oceanographic Institutions (1990) have called for the installation of gauges on islands and in straits for the use in WOCE. The Parry Channel, south of Resolute, is likely to be involved in the exchange of water between the Arctic and Atlantic oceans. The Greenhouse effect is likely to cause large changes in the cryosphere (Ad Hoc Committee 1985), and this may potentially affect this exchange.

(3) Tuktoyaktuk

This gauge has the second longest record in the Arctic (22 years), although the fluctuations in the observed sea level are nearly twice those observed at Resolute. This site will be useful in the study of the peripheral bulge collapse (e.g., Peltier et al. 1986). It may also have a use in the Global Sea-Level Observing System (GLOSS) (Intergovernmental Oceanographic Commission 1989), particularly as the Joint Oceanographic Institutions (1990) recommended that sea-level measuring systems be developed and installed at polar sites. Pugh (1987, p. 413) proposed three tide-gauge sites in the Canadian Arctic for use in GLOSS; namely Alert, Resolute, and Sachs Harbour. However, because of its longer record, Tuktoyaktuk should be favoured over Sachs Harbour. With the site at Tuktoyaktuk, there is also the possibility of comparing the long-term sea-level trends to the absolute gravimetry record at nearby Inuvik.

All the above recommendations are made under the assumption that any new gauge can be geodetically-tied to the old gauge, and so the new record becomes an extension of the old record.

Absolute gravimetry sites

(1) Churchill

There have been more measurements at Churchill than at any other site in Arctic Canada. A trend in the data is already developing and hopefully will be established in just a few more years (Tushingham et al. 1991). Churchill should be visited by the absolute gravimeter once per year. The large number of measurements at this site allow for quick identification of anomalous data, which may imply the existence of a problem with the absolute gravimeter. At Churchill there are also available tide-gauge observations (Tushingham 1992a) and GPS measurements (Bock 1988). Results from a 5-year GPS campaign at Churchill have not yet been published.

(2) Yellowknife and Shefferville

At these two inland sites, no other method (except possibly, in the future, GPS) has the potential to record postglacial uplift. The results to date appear promising. Shefferville is located near the centre of the last major remnants of the Laurentide Ice Sheet, and the rate of uplift may be useful in constraining models of the final phase of deglaciation. As the Laurentide Ice Sheet was thought to start its growth over northern Quebec (Andrews and Mahaffy 1976) the absolute gravimetry measurements may be used in the study of potential initial disequilibrium of the ice load (e.g., Peltier et al. 1986). The sites at Yellowknife and Shefferville are on the relatively stable Canadian Shield and are ideal for measuring postglacial uplift, as other motions are likely to be much smaller. These sites should be re-occupied every 2-3 years. For the near-future, all three sites at Shefferville should be continued, as any difference in the three trends may in itself be physically interesting. The site at Yellowknife can be tied to a nearby mobile VLBI antenna, which was in operation in 1984, 1985, and 1991. (Note: between 1984 and 1989, a mobile VLBI antenna was located at Whitehorse as part of a VLBI campaign to measure horizontal motions in Alaska (Ma et al. 1990), however, Yellowknife has a longer absolute gravimetry record than Whitehorse.)

(3) Resolute and Inuvik

Both absolute gravimetry sites are near sites that once had tide gauges, and both are located in interesting areas for the study of postglacial uplift. Resolute is located in the Queen Elizabeth Islands, and there is considerable controversy as to the amount of ice that once covered these islands (Blake 1970; England 1976b, 1983; Tushingham 1991). The simple knowledge of the sign of the gravity changes will aid in the understanding of the glacial history of this area (Tushingham et al. 1991). Inuvik is located in the peripheral bulge region of the Laurentide Ice Sheet. The collapse of the bulge on the U.S. east coast is well documented (e.g., Newman et al. 1980), but only a few observations are available in the Beaufort region. The comparison of absolute gravimetry measurements at Inuvik and the tide-gauge record at Tuktoyaktuk (hopefully reactivated) may help in determining the deformation gravity gradient at non-ice-central sites. The expected rates of gravity change at Resolute and Inuvik are small enough that occupations of these sites by the absolute gravimeter need only occur on a 3-4 year cycle.

All recommendations in this report are from the point-of-view of geodynamic applications, and in particular, the measurement of the postglacial uplift phenomenum. This report does not explicitly consider the large expenses incurred in transporting and operating equipment in the Arctic. It is hoped that these expenses do not become prohibitive.

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Table 1: Analysis of tide-gauge records

Site	Lat. (N)	Long. (W)	Epoch	Rates (mm/a)			
				Monthly	Annual	Summer[a]	Summary estimate
Alert	82°30'	62°19'	1961-1977	2.2±2.4	11.1±12.9	3.2±10.9	>0
Cambridge Bay	69°07'	105°04'	1961-1982	4.5±1.6	6.2±2.7	2.7±2.8	2-6
Cape Parry	70°09'	124°40'	1966-1982	2.6±2.7	18.5±19.1	2.8±8.6	>0
Churchill	58°47'	94°12'	1940-1991	8.8±0.3	8.0±1.0	7.9±0.8	8-9
Coppermine	67°53'	115°13'	1974-1982	8.1±4.4	-	-	-
Coral Harbour	64°05'	83°06'	1971-1978	16.6±14.8	-	-	-
Frobisher Bay	63°44'	68°32'	1963-1974	34.6±16.7	-	-	-
Inukjuak	58°27'	78°06'	1970-1980	6.0±5.1	-	20.2±8.7	>0
Resolute	74°41'	94°53'	1959-1977	3.2±1.2	2.6±1.9	3.0±2.3	2-4
Sachs Harbour	71°58'	125°15'	1972-1982	11.0±6.6	-	1.3±23.8	-
Spence Bay	69°32'	93°31'	1971-1982	10.3±4.8	-	18.0±8.4	>0
Tuktoyaktuk	69°25'	132°58'	1961-1982	-4.1±2.1	-27.5±9.6	-9.2±3.8	<0

[a] Data from July and August

Table 2: Absolute gravimetry measurements

Site	Latitude (North)	Longitude (West)	Epoch	No. of measure-ments	Rate of gravity change (μGal/a)
Alert	82°30'	62°20'	1987	5	-
Churchill:					
seismic vault	58°46'	94°05'	1987-1991	9[a]	-1.6±0.5[b]
airport	58°45'	94°04'	1989	1	-
hill	58°46'	94°08'	1989	1	-
Inuvik	68°18'	133°30'	1987	2	-
Kuujjuarapik:					
geomagnetic vault	55°18'	77°45'	1988-1989	2	-13.6?
airfield	55°17'	77°45'	1988-1989	2	-2.5?
Telesat	55°17'	77°45'	1989	1	-
Resolute	74°43'	94°58'	1987	1	-
Shefferville:					
McGill	54°48'	66°49'	1988-1991	3	+0.5±1.4?
seismic vault	54°49'	66°47'	1988-1991	3	-1.4±0.8?
VOR	54°49'	66°46'	1988-1989	2	-9.9?
Whitehorse:					
air station	60°43'	135°05'	1990	1	-
McIntyre	60°44'	135°09'	1990	1	-
Yellowknife	62°28'	114°26'	1987-1991	4	-1.1±0.1[b]?

Note: question mark indicates that the record is too short to make a reliable estimate.

[a] Including one measurement made by the U.S. National Geodetic Survey.
[b] One data point was thought to be affected by a proof-mass problem in 1990, and so it was not used in the calculation of the trend.

Table 3: A comparison of uplift rates (mm/a)

Site	ICE-3G rate	Tide-gauge range	Ab. grav. rate [a]	RSL data	
				Rate	Reference
Alert	4.6	>0	-	2.5	England 1983
Cambridge Bay	4.0	2-6			
Cape Parry	-2.2	>0			
Churchill	7.3	8-9	8.9±2.8[b]	9.0	Dredge and Nixon 1992
Coppermine	3.3	-			
Coral Harbour	4.8	-		2.6-6.0	Walcott 1972
Frobisher Bay	0.1	-		<3.2	Squires 1984
Inukjuak	5.9	>0			
Inuvik	-1.6		-	-1.0--1.8	Forbes 1980
Kuujjuarapik	9.2		13.9[c]?	11.0	Hillaire-Marcel 1980
Resolute	2.3	2-4	-	2.2-4.5	Washburn and Stuiver 1985
Sachs Harbour	-3.8	-			
Shefferville	9.3		7.9±4.3[b]?		
Spence Bay	1.5	>0		4.0-5.0	Walcott 1972
Tuktoyaktuk	-3.1	<0		-4.8	Hill et al. 1985
Whitehorse	3.1		-		
Yellowknife	5.2		6.1±0.4?		

Note: question mark indicates that the record is too short to make a reliable estimate.

[a] Converted using a deformation gravity gradient of -0.18 μGal/mm (Tushingham et al. 1991)
[b] Seismic vault value
[c] Airfield value

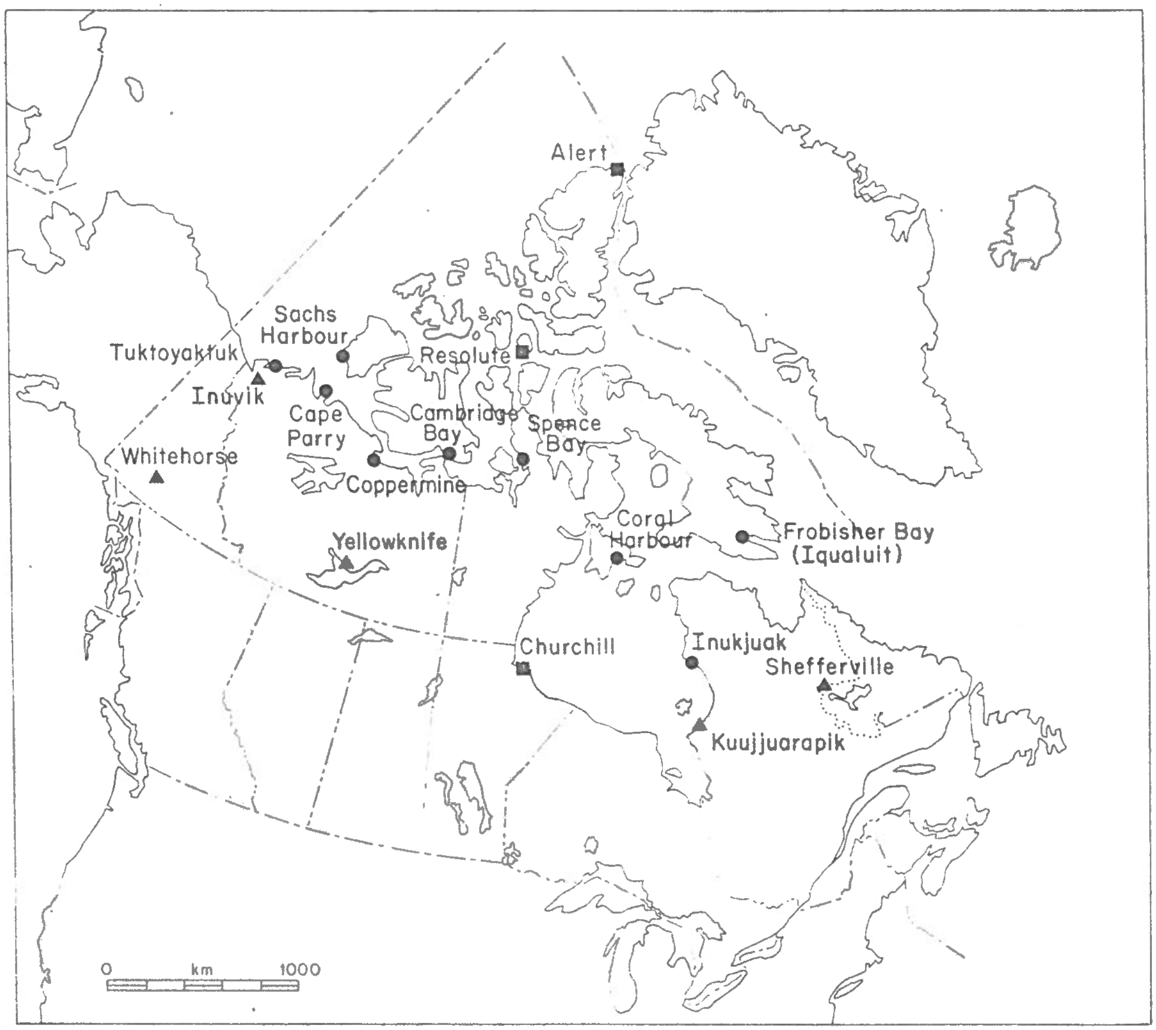

Figure 1. Location map for tide-gauge and absolute gravimetry sites in Arctic Canada. Dots, tide-gauge sites; triangles, absolute gravimetry sites; squares, both.

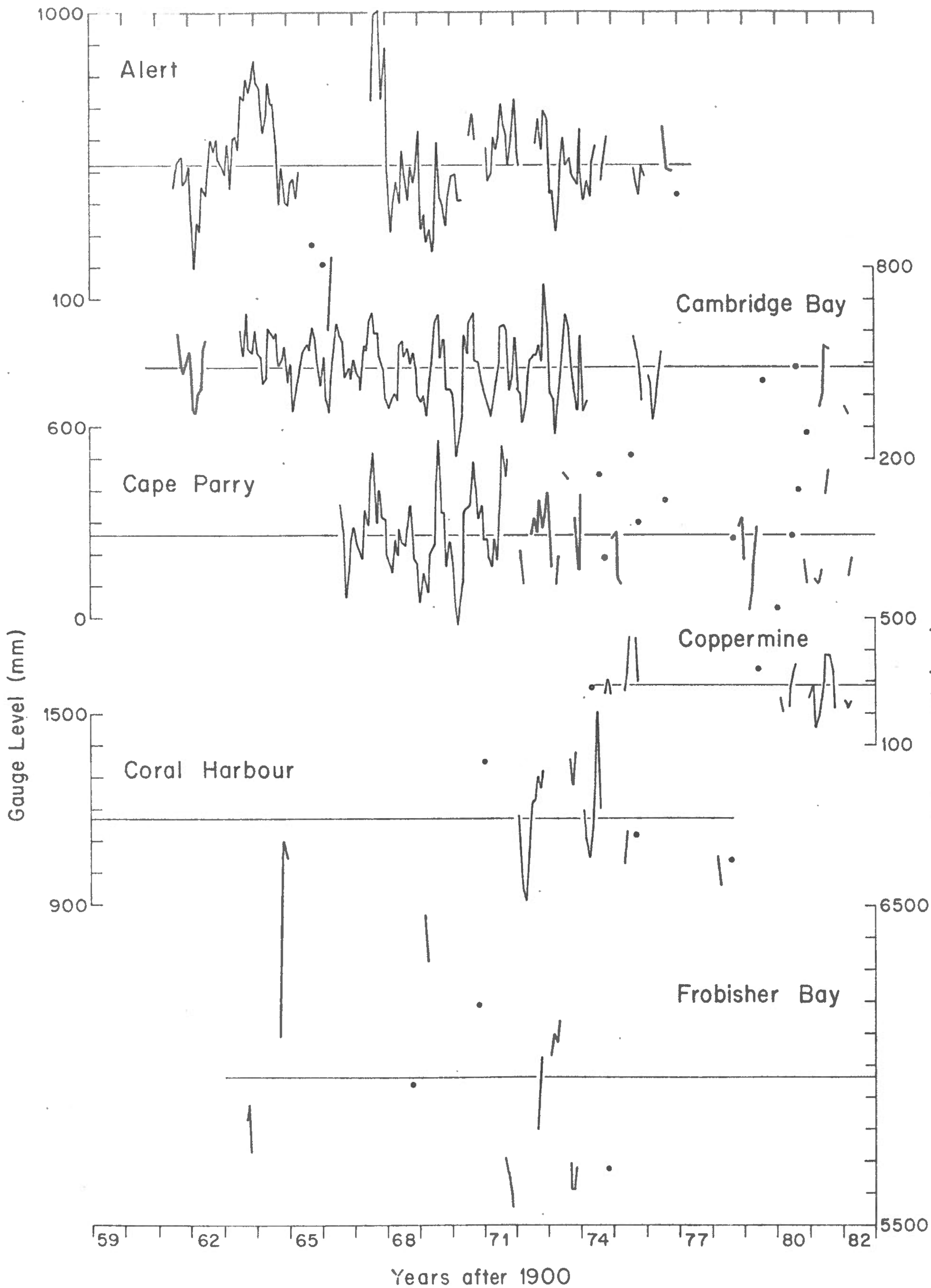

Figure 2. Arctic tide-gauge records with durations of 3 or more years (Marine Environmental Data Service 1992). The mean gauge levels are shown for each record. Dots show isolated monthly values.

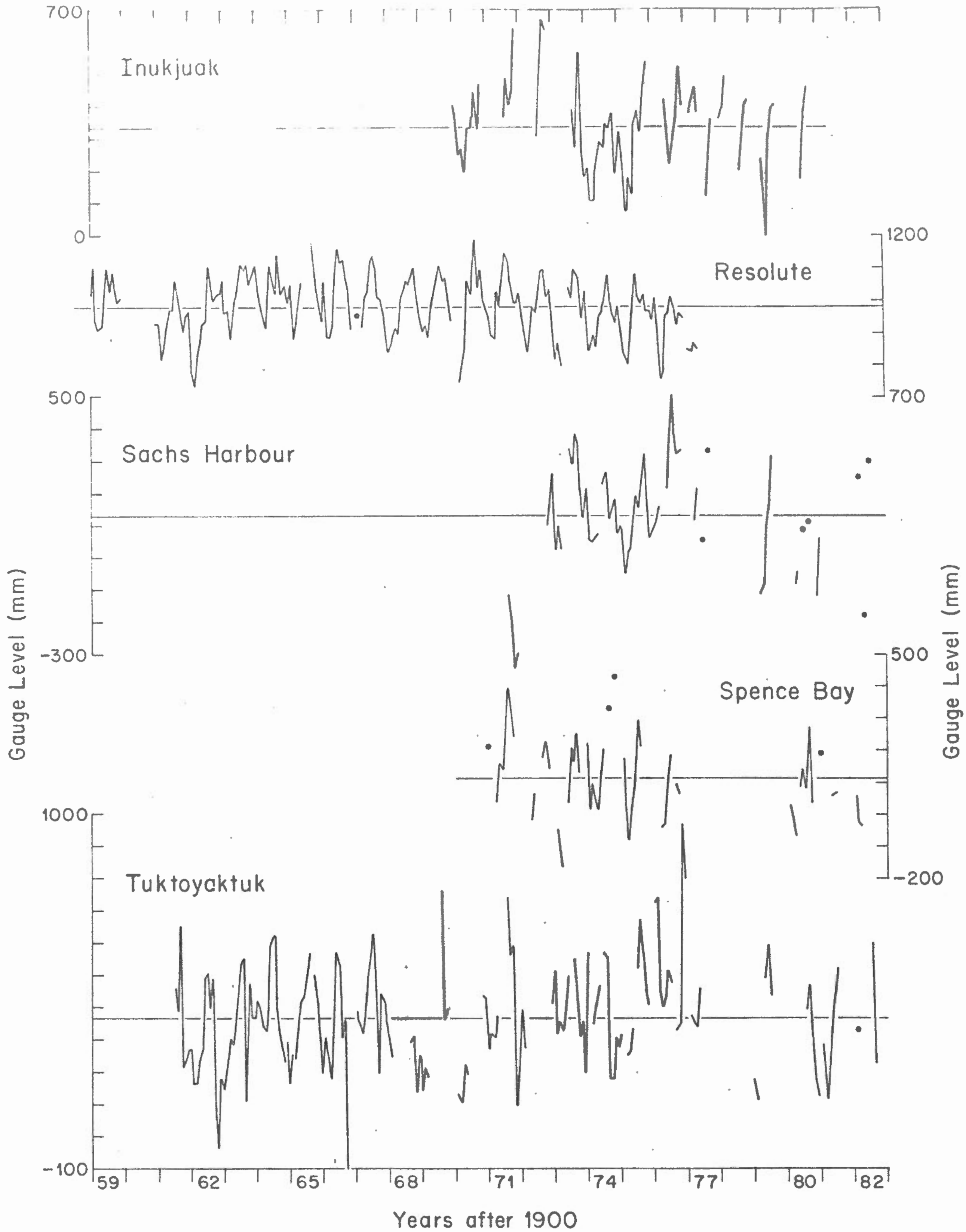

Figure 2. Continued.

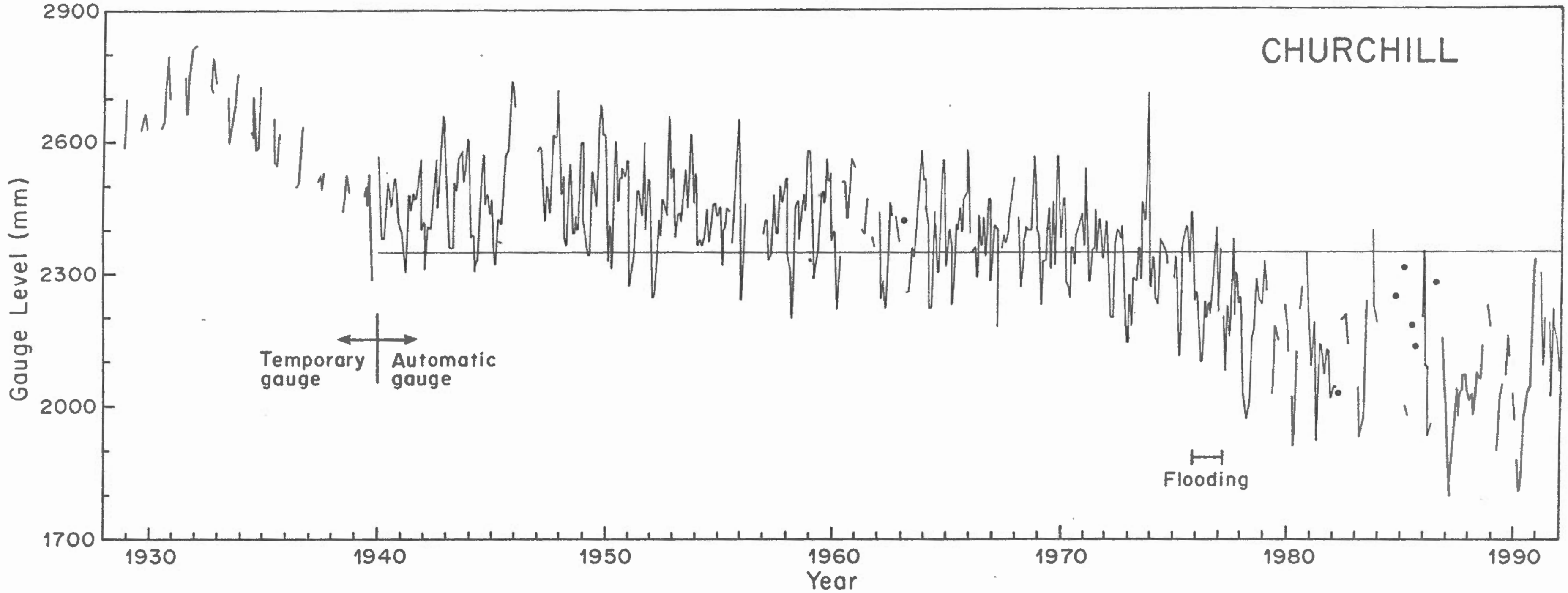

Figure 3. Tide-gauge record for Churchill, Manitoba (Marine Environmental Data Service 1992). The pre-1940 data are considered unreliable. The period of flooding caused by the Churchill River Diversion Project is indicated by the horizontal bar. Dots show isolated monthly values.

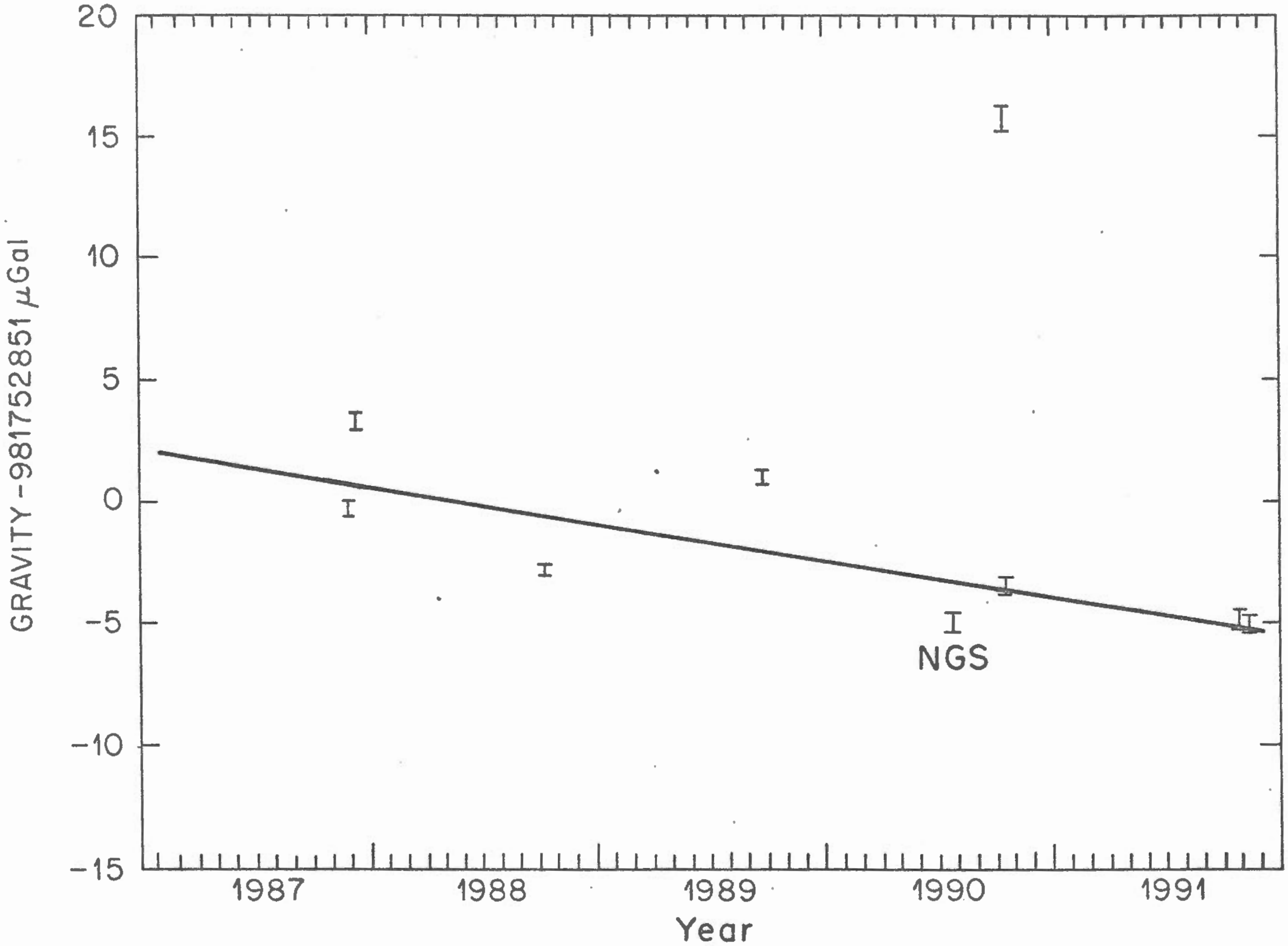

Figure 4. Absolute gravimetry measurements at Churchill with a linear trend of -1.6 μGal/a fitted to the data (Lambert et al. 1992). The letters "NGS" indicate the data point measured by the U.S. National Geodetic Survey. The outlying data point is thought to have been affected by a proof-mass problem as discussed by Lambert et al., so it was not included in the calculation of the trend.

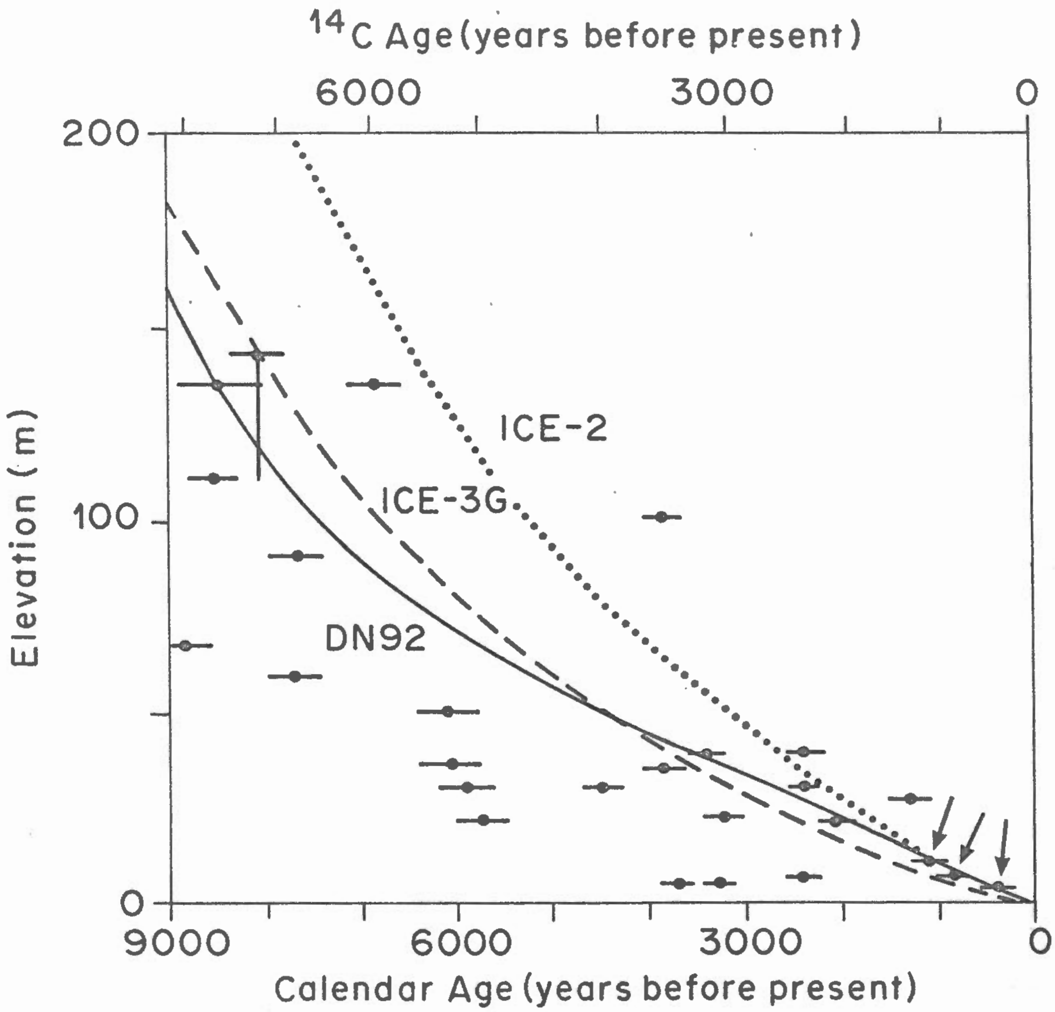

Figure 5. Relative sea-level data from the Churchill area (Dredge and Nixon 1992). Bars show position of data points, with arrows highlighting indistinct data points. Ages have been converted to sidereal, or calendar, years using the conversion curve presented in Figure 6. Predictions based on the ICE-3G model (Tushingham and Peltier 1991) and an older model (Wu and Peltier 1983) are shown. The preferred curve of Dredge and Nixon (1992) is denoted by "DN92".

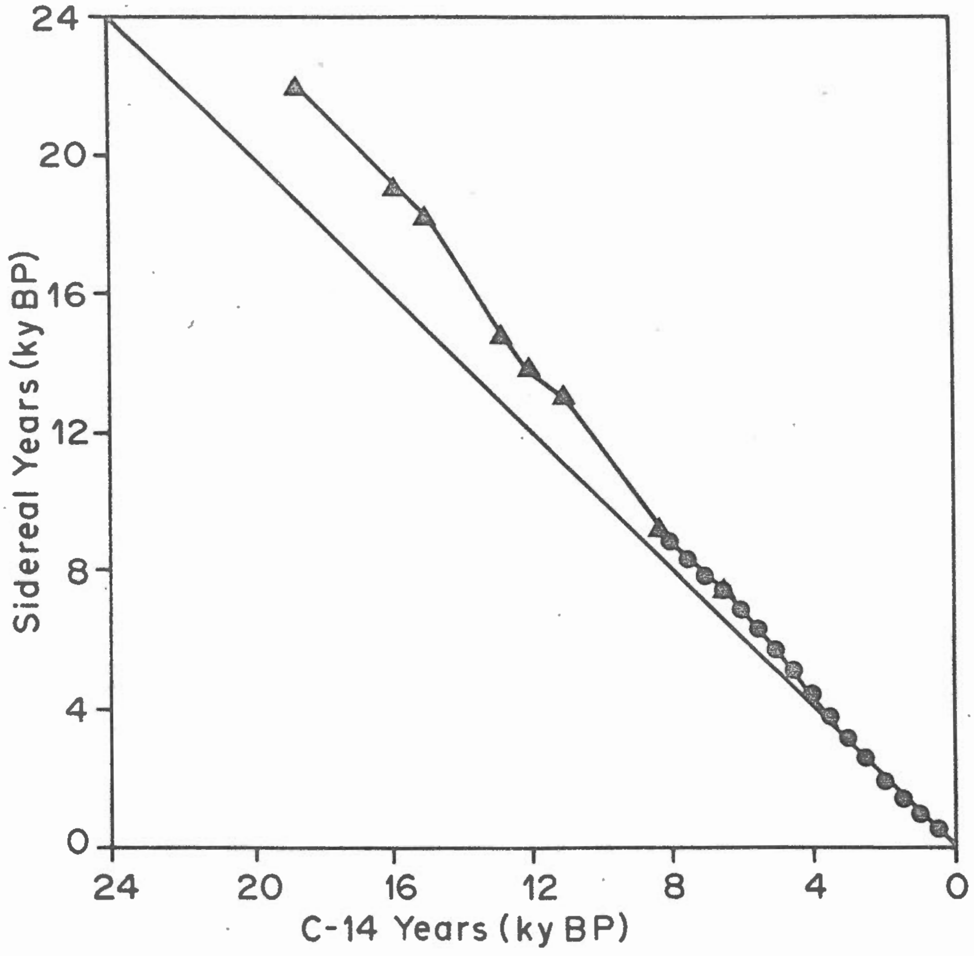

Figure 6. Radiocarbon conversion curve based on Pearson et al. (1986), Stuiver et al. (1986), and Becker et al. (1991) (dots), and Bard et al. (1990) (triangles). This curve was discussed by Tushingham and Peltier (1992a).

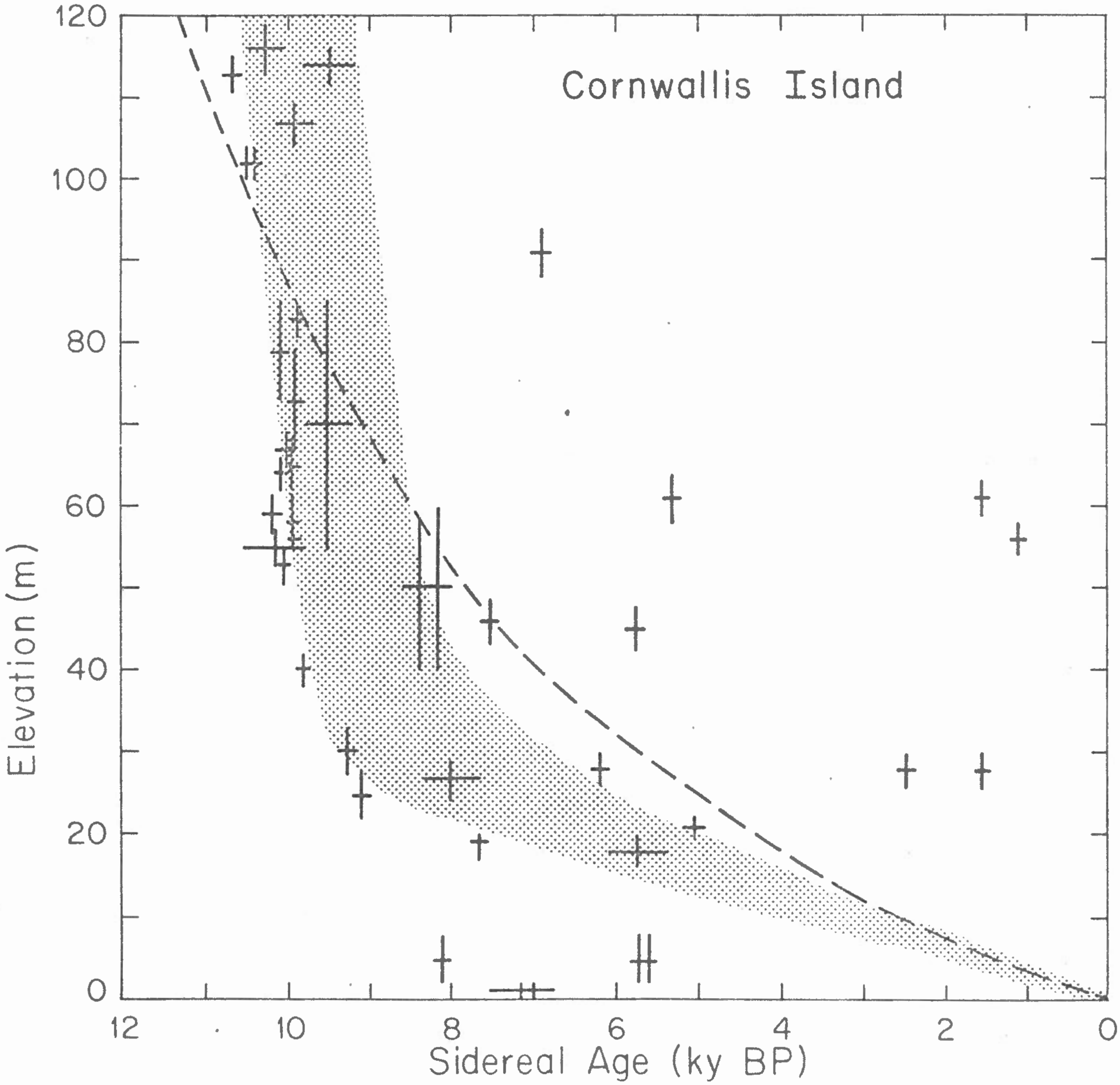

Figure 7. Relative sea-level data found on or near Cornwallis Island (Washburn and Stuiver 1985). A tentative emergence-curve envelope is shown by the shaded region. The predicted curve of ICE-3G is indicated by the dashed line.

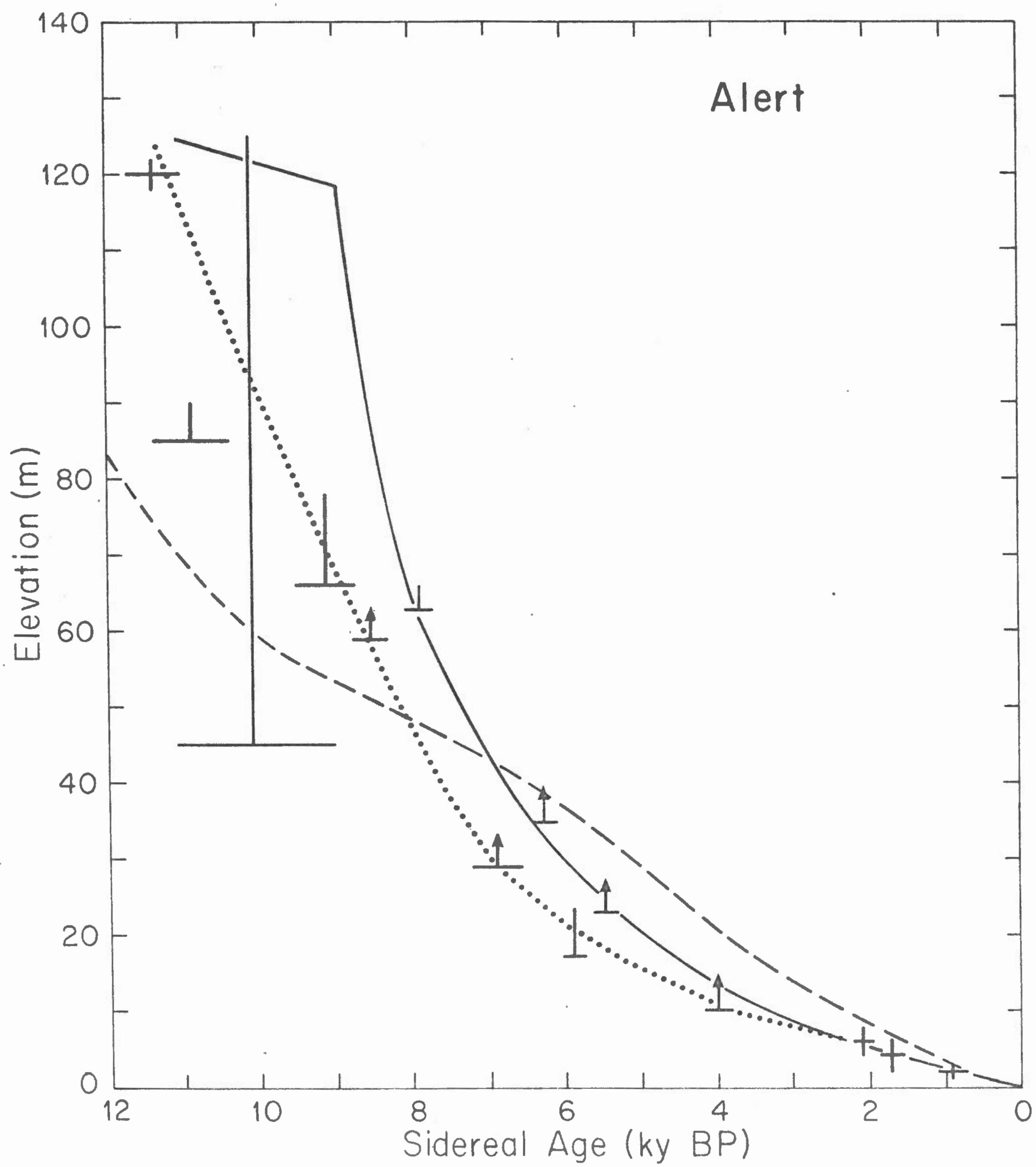

Figure 8. Relative sea-level data from the Alert-Wood River area of northern Ellesmere Island (England 1983). The preferred curves of England (1976a) and England (1983) are indicated by the dotted and solid curves, respectively. The dashed line indicates the predicted curve of ICE-3G.

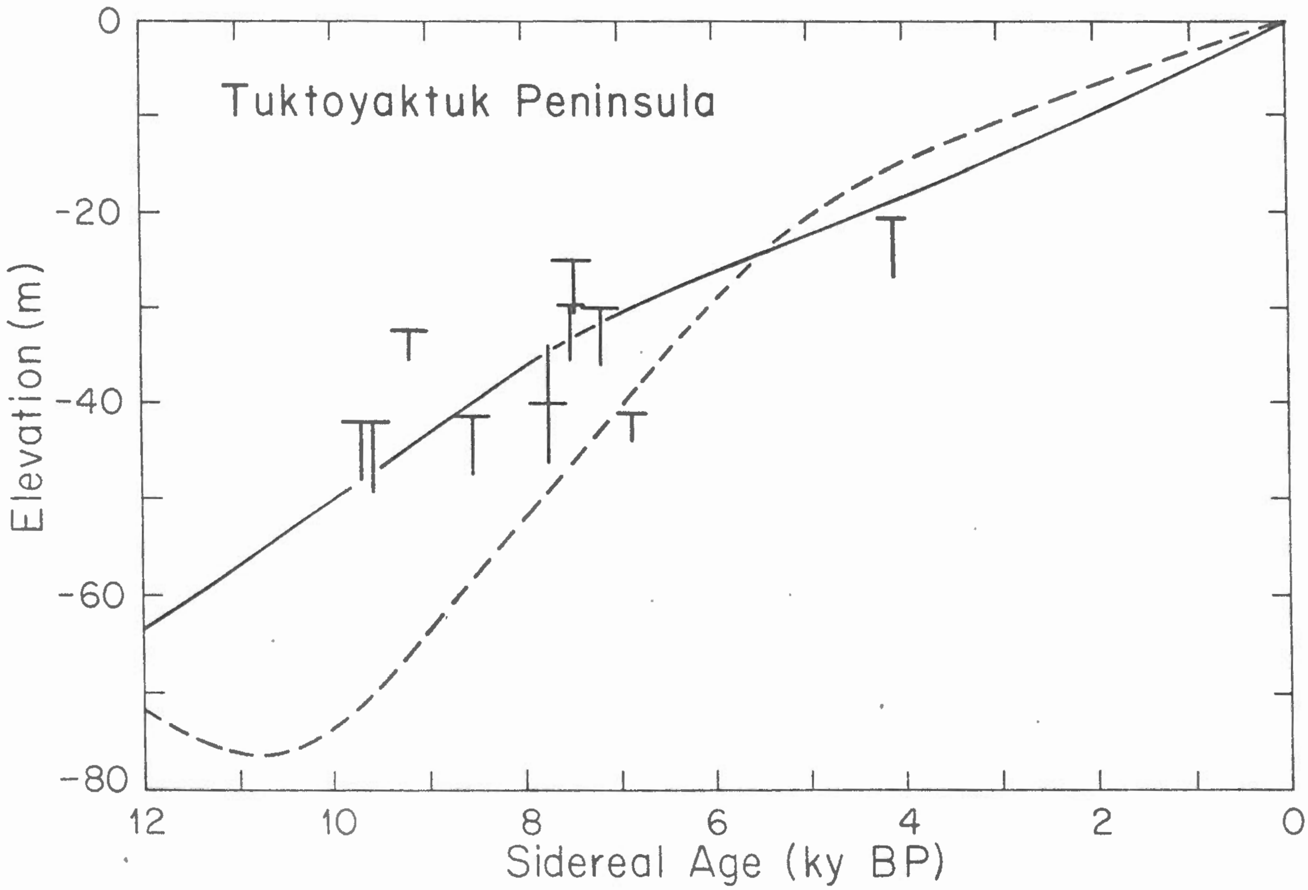

Figure 9. Relative sea-level data from geotechnical boreholes located off-shore of the Tuktoyaktuk Peninsula (Hill et al. 1985). The preferred curve is indicated by the solid line, and the predicted curve of ICE-3G is indicated by the dashed line.