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## Thinning of the ice sheet in northwest Greenland over the past forty years

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Thermal expansion of the oceans, as well as melting of glaciers, ice sheets and ice caps have been the main contributors to global sea level rise over the past century. The greatest uncertainty in predicting future sea level changes lies with our estimates of the mass balance of the ice sheets in Greenland and Antarctica<sup>1</sup>. Satellite measurements have been used to determine changes in these ice sheets on short timescales, demonstrating that surface-

elevation changes on timescales of decades or less result mainly from variations in snow accumulation<sup>2</sup>. Here we present direct measurements of the changes in surface elevation between 1954 and 1995 on a traverse across the north Greenland ice sheet. Measurements over a time interval of this length should reflect changes in ice flow—the important quantity for predicting changes in sea level—relatively unperturbed by short-term fluctuations in snow accumulation. We find only small changes in the eastern part of the transect, except for some thickening of the north ice stream. On the west side, however, the thinning rates of the ice sheet are significantly higher and thinning extends to higher elevations than had been anticipated from previous studies<sup>3</sup>.

Because the Greenland ice sheet is still responding to climatic changes that occurred thousands of years ago<sup>4</sup>, a complicated pattern of thickening and thinning is expected. The earliest data of sufficient precision appear to be those of the British North Greenland Expedition (BNGE)<sup>5</sup>; we compare these with the latest digital elevation model<sup>6</sup>. The BNGE used trigonometric levelling to measure elevation at about 300 stations on a 1,200-km traverse in 1953–54 (Fig. 1)<sup>7</sup>. The survey started at Krebs Bjerg in Dronning Louise Land and ended at sea level on the west coast. The route crossed the north ice stream<sup>8</sup>. The work was spread over two summers; a tripod was left standing at the midpoint, station B73, throughout the winter.

The closure error, found by calculating the elevation of B73 from each coast, was 13.8 m, elevations calculated from the east being the higher. It was subsequently reduced to 11.8 m when the elevation of Krebs Bjerg was redetermined. It was distributed as follows. East of B73, each height difference between adjacent stations was reduced by 5.9 m times the distance between them, expressed as a fraction of the total distance between Krebs Bjerg and B73. Height differences west of B73 were increased in a similar way. To set error limits, for stations east of B73 the elevation calculated from the east coast was taken as the upper limit and the lower limit was taken as that value minus twice the adjustment in elevation. Similarly, for stations west of B73, the elevation calculated from the west coast set a lower limit and twice the adjustment was added to obtain the upper limit. A second scheme, with the adjustment proportional to the elevation difference, rather than the distance, between adjacent stations was also used. Elevations calculated by the two schemes differed by up to 3 m. Their mean was taken as the true elevation; the maximum error is the root mean square of the adjustments calculated for the separate schemes. The latitude and longitude of each station were found

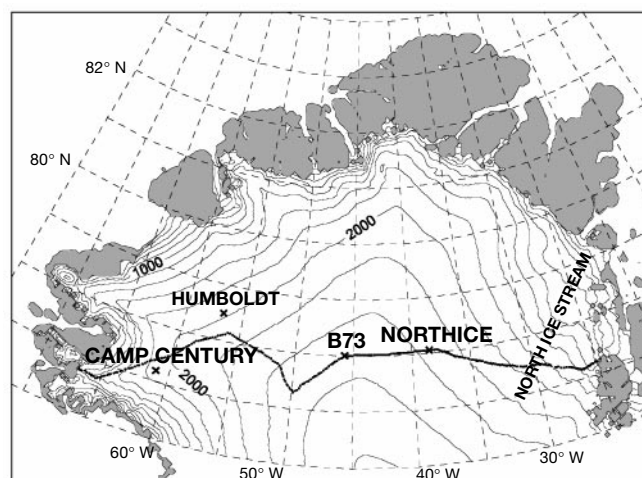
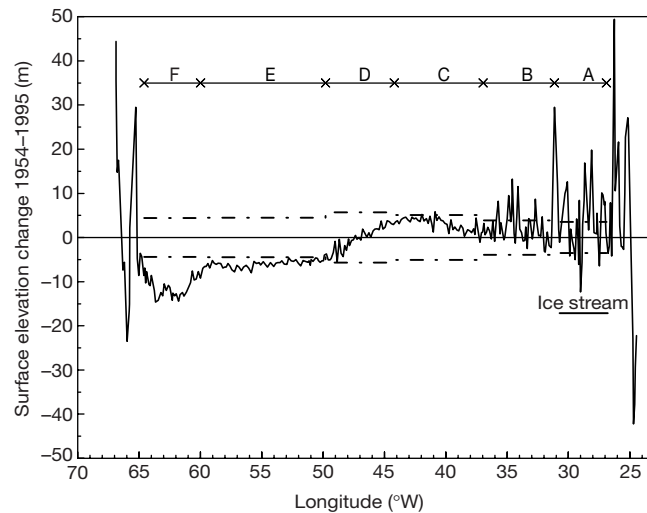


Figure 1 Traverse route. Northice was the Expedition's ice-sheet station. Long-term snow accumulation data are available for Humboldt Station and Camp Century.



**Figure 2** Measured changes in surface elevation between 1954 and 1995. Dashed-dotted lines indicate maximum errors. Letters denote longitude bands used in the data analysis.

from the measured distances and azimuths and checked by Sun sights at some stations. The precision is 0.1 minute of latitude and 0.5 minute of longitude, or about 200 m in each direction.

The digital elevation model (DEM) of the ice sheet, which has a grid spacing of 1 km, is based, in north Greenland, on radar altimetry from the ERS-1 satellite collected in 1994–95. The data were corrected for a slope-dependent bias that arises because the radar oversamples the crests of surface undulations relative to the troughs. The corrected radar data were compared with measurements of surface elevation made by laser altimeters in an aircraft. Because these have a precision of about 10 cm, the standard deviation of the difference between DEM and laser elevations, which is a function of surface slope, measures the precision of the DEM<sup>6</sup>. Although the laser elevations are more precise than the DEM, the data points are more scattered and some are several kilometres from the nearest BNGE station. We have therefore used the DEM.

DEM elevations are relative to the World Geodetic Systems 1984 (WGS 84) ellipsoid whereas BNGE elevations are relative to sea level. The conversion, made using the latest geoid model (Ohio State University 1991A; OSU 91A) improved with local gravity, introduces a maximum error of  $\pm 1$  m.

Figure 2 shows the measured changes in surface elevation. They can be interpreted as ice-thickness changes because bedrock beneath the ice is unlikely to be rising more than a few millimetres per year. To test the significance of the changes, we grouped the stations into longitude bands and calculated average values for each. We excluded the marginal regions, where the radar was probably measuring the elevations of nunataks off the traverse route. (A nunatak is an isolated peak of rock projecting above the surface of land ice.) The maximum error has four components: uncertainties in the BNGE elevations and in the DEM, both calculated as described above, the geoid–ellipsoid conversion, and the scatter of elevation changes within each band. The standard deviation of the DEM elevations and the standard error of the mean elevation change in each band were multiplied by two to make them comparable with the other errors, which are maximum errors. The components were combined by taking the square root of the sum of their squares.

We conclude that, between 1954 and 1995: (1) The ice stream (band A in Fig. 2) has thickened at a rate of  $9.7 \pm 8.4$  cm yr<sup>-1</sup>; (2) ice thickness has not changed significantly in bands B–D; (3) the

average thinning rate is  $16.5 \pm 11.0$  cm yr<sup>-1</sup> in band E and  $31.0 \pm 10.7$  cm yr<sup>-1</sup> in band F. These bands span elevations from 2,500 to 1,500 m. All limits quoted are maximum, not standard, errors.

We believe that the 41-year interval is long enough to ensure that we are measuring the dynamic response of the ice sheet rather than fluctuations in snow accumulation. Furthermore, annual accumulation data from a station on Humboldt Glacier<sup>9</sup> and from near Camp Century (Fig. 1; E. Mosley-Thompson, personal communication) show no trend over this period.

The only other direct measurements of elevation changes in this area come from a study covering the whole ice sheet for the period 1994–99 (ref. 10). It shows slight thickening in bands E and F where we measured significant thinning. The thickening probably resulted from variations in snow accumulation.

An indirect method avoids the difficulties in interpreting short-term thickness changes<sup>3</sup>: the total snow accumulation over a drainage basin is compared with the ice flux out of it. This certainly measures the dynamic response of the ice sheet, but only a rough average over a large area<sup>11</sup>. The Greenland study was restricted to elevations above 2,000 m by measuring fluxes at that contour. In north Greenland east of longitude 40° W an average thickening of 2 cm yr<sup>-1</sup> was obtained. This is consistent with our results except in the ice stream, a feature this method cannot resolve. Thinning was observed to the west but, even if the upper limits are used, at rates substantially less than those we measured. □

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**Late Cretaceous relatives of rabbits, rodents, and other extant eutherian mammals**

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Extant eutherian mammals and their most recent common ancestor constitute the crown group Placentalia. This taxon, plus all extinct taxa that share a more recent common ancestor with placentals than they do with Metatheria (including marsupials), constitute Eutheria<sup>1</sup>. The oldest well documented eutherian-dominated fauna in the world is Dzharakuduk, Uzbekistan<sup>2</sup>. Among eutherians that it yields is *Kulbeckia*, an 85–90-Myr-old member of Zalambdalestidae (a family of Late Cretaceous Asian eutherians)<sup>3</sup>. This extends Zalambdalestidae back by some 10 million years from sites in the Gobi Desert, Mongolia<sup>4</sup>. A phylogenetic analysis of well described Late Cretaceous eutherians strongly supports Zalambdalestidae, less strongly supports ‘Zhelestidae’ (a Late Cretaceous clade related to Tertiary ungulates), but does not support Asioryctitheria (a group of Late Cretaceous Asian eutherians). A second analysis incorporating placentals from clades that include rodents (*Tribosphenomys*), lagomorphs (*Mimotona*) and archaic ungulates (*Protungulatum* and *Oxyprimus*) strongly supports Zalambdalestidae in a clade with Glires (rabbits, rodents and extinct relatives) and less strongly ‘Zhelestidae’ within a clade that includes archaic ungulates (‘condylarths’). This argues that some Late Cretaceous eutherians belong within the crown group Placentalia. The ages of these taxa are in line with molecularly based estimates of 64–104 Myr ago (median 84 Myr ago) for the superordinal diversification of some placentals<sup>5</sup>, but provide no support for a Late Cretaceous diversification of extant placental orders.

Timing of the origin of major clades of extant placental mammals remains controversial. Some molecular studies place the origin of such clades (orders) far back into the Cretaceous<sup>6</sup>. Most palaeobiologists argue that such clades originated in the Palaeocene or later<sup>7,8</sup>. Others argue that more inclusive extant placental clades (superordinal groupings) may not be discernible even in the Late Cretaceous<sup>9</sup>. Some proposed exceptions are Late Cretaceous representatives of Ungulatomorpha (‘Zhelestidae’<sup>10</sup>), lipotyphlans (*Paranactoides* and *Batodon*<sup>11</sup>) and Glires (Zalambdalestidae<sup>11</sup>). The timing of the origin and relationships of Glires are among the most controversial subjects in studies of mammal evolution.

Glires includes extinct early Tertiary taxa, as well as extant Rodentia (rodents) and Lagomorpha (rabbits and pikas). The monophyly of Glires has been repeatedly upheld<sup>5</sup> but the timing of the origin of Glires is contested; on the basis of molecular studies

one of its members, Rodentia, has been argued to appear over 100 Myr ago<sup>6,12</sup>. This is almost as old as the oldest eutherian fossils<sup>13–15</sup>. The relationships of Glires to other eutherian taxa are also disputed; it has been argued that Glires may share a common ancestry with the Late Cretaceous Zalambdalestidae<sup>11</sup>.

We present new data for the oldest known zalambdalestid, *Kulbeckia kulbecke*, from the 85–90-Myr-old Dzharakuduk fauna, Bissekty Formation, Uzbekistan<sup>2</sup>. Until recently, zalambdalestids were known almost exclusively from 75-Myr-old fossils from the Gobi Desert (J. R. Wible, M. J. Novacek & G. W. Rougier, manuscript in preparation; and ref. 16). *Kulbeckia* was named in 1993, on the basis of a few teeth<sup>17</sup>. Possible affinities with zalambdalestids were not recognized until 1997 (ref. 3). During field seasons at Dzharakuduk (1997–2000), over 40 additional specimens were recovered including teeth, dentaries, petrosals, a partial skull, and postcrania (Figs 1, 2). Similarities of zalambdalestids and Glires warrant further consideration.

The hallmark of Glires is its enlarged, medially placed pair of incisors, which are procumbent, have enamel restricted to the more ventro- or dorsolabial margin of the tooth, are open-rooted, ever-growing, and have Hunter–Schreger bands<sup>18</sup>. Other mammals possess incisors that have some of these traits, but only Glires has all six character states. In the lower incisors, the zalambdalestid *Kulbeckia* possesses the first four of these states, although the enamel encompasses a greater circumference of the crown, which is a slightly more ancestral condition (Fig. 2c). We cannot demonstrate that the open-rooted lower incisor was ever-growing and scanning electron micrographs (SEMs) of the surface of the lower incisor did not reveal Hunter–Schreger bands. Although suggestive, these character states alone are not strong evidence for a phylogenetic relationship, because other eutherians possess some of these traits. Under a suite of other comparisons is added, the zalambdalestid–Glires link becomes more plausible.

The two larger, anterior upper incisors and much smaller third upper incisor known for *Kulbeckia* are preserved only as roots; thus, the disposition of enamel is unknown. One (or two) smaller, more medial incisor(s) may have been present (Fig. 2a, b). Rodents possess one upper incisor on each side while lagomorphs possess two, and thus the condition in *Kulbeckia* could have been ancestral to both of these orders. *Kulbeckia* and other zalambdalestids (*Zalambdalestes* and *Barunlestes*) warrant further comparison with Glires, especially with more basal members. All have narrow, elongate snouts (Figs 1a and 2b). *Zalambdalestes* and *Barunlestes* fall between the ancestral condition in which most of the elongation is within the maxilla and the derived condition in Glires in which half or more of the elongation is in the premaxilla. Although it shows some premaxillary elongation, *Kulbeckia* is close to the ancestral condition. In the morphocline *Kulbeckia* to *Zalambdalestes* to *Barunlestes* to Glires, we see a reduction of incisors from 3, 4, or 5/4 (5 in the upper jaw, 4 in the lower jaw) to 2/3 or 3/3 to 2/3 to 1/1 or 2/1. Homologies of the four lower incisors are open to interpretation. *Kulbeckia* may retain the ancestral therian condition of four incisor sites seen in some early eutherians. In these taxa, however, the incisors are of nearly equal size, while in *Kulbeckia* the most medial incisor is six times longer and perhaps as much wider than the three following teeth. In Glires embryological evidence suggests that the medial, enlarged lower tooth is the second, lower, deciduous incisor<sup>19</sup>. Unfortunately, embryological evidence does not help in determining homologies in available fossils, and thus without ontogenetic information we use the overall anatomy of the dentitions to support the view that the medial pair of lower incisors in zalambdalestids and Glires are homologous.

In the same taxa, canines are never large, ranging from two roots above (in the upper jaw) and below (in the lower jaw) to one above and below to no canines. In *Kulbeckia* there are 4/4 premolars while later zalambdalestids have 3/4 or 4/4, and among some Glires, 3/3 are retained. Upper molars of both *Kulbeckia* and early Glires such as