SIR,

Reply to the comments of H. Slupetzky on "Mass balance of glaciers other than the ice sheets" by Cogley and Adams

We agree with nearly all the points made by Slupetzky. However, he writes that his indirect method of estimation of the mass balance of Stubacher Sonnblickkees, based on measurements of accumulation-area ratio (AAR), is "certainly as accurate as 'direct' mass-balance measurements". From information given by Slupetzky (1991) in connection with his equations 5 and 7, the standard error of his regression of mass balance B on AAR, measured concurrently from 1964 to 1980, is ±118 mm a^{-1}. The total error in his indirect estimate of B is the geometric sum (Cogley and others, 1996) of the standard error of the regression and the standard error of B. The latter is not given by Slupetzky (1991), but if we choose Cogley and Adams' (1998) nominal figure of ±200 mm a^{-1} the total error in Slupetzky's indirect estimate is about ±230 mm a^{-1} (that is, $\sqrt{200^2 + 118^2}$). Here we assume no correlation between errors in B and in AAR. If these measurement errors are correlated, the error in the indirect estimate will be greater (up to ±318 mm a^{-1}, the arithmetic sum of the errors).

In short, an indirect estimate of mass balance must in practice be less accurate than the direct measurements against which it is calibrated. Methods such as Slupetzky's serve vital functions, for example in regional extrapolation, and we did not mean to discount such work. But the uncertainty of the direct measurements is itself a serious problem. Cogley and others (1996) note that, quite apart from the systematic errors which they discuss, a tenfold reduction in random errors will be needed if climatically expectable trends are to be identified in mass-balance time series. Reducing the measurement errors, for example through better control of the biases and better calibration by periodic geodetic surveys, should be a more urgent priority than enlarging the global network of balance estimates in ways which risk blurring the distinction between measurement and inference.

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29 March 1999

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SIR,

Formation of supraglacial sediment accumulations on Kötlujökull, Iceland

In this journal, Näslund and Hassinen (1996) discussed the formation of supraglacial sediment accumulations on the snout of Kötlujökull, an 8 km wide, 15 km long southeasterly outlet glacier of the ice cap Mýrdalsjökull in south Iceland. As participants in the Nordic Course in Dynamic Geomorphology and Sedimentology at Mýrdalsjökull in August 1994, Näslund and Hassinen studied ice-cored sediment accumulations on the surface of the northeastern part of Kötlujökull. They found that the supraglacial sediments consist primarily of non-striated rounded boulders, gravel and sand; the roundness of the material and the absence of finer components were suggestive of esker sediments. Furthermore, they found remnants of water conduits at high elevations. The largest conduit observed was 12–15 m in diameter, and was exposed along a length of 40 m; higher up, the tunnel had collapsed due to ablation. Näslund and Hassinen combined these observations, and concluded that the large sediment accumulations were transported to the glacier surface by water flow within high-level conduits. This could have resulted from a jökulhlaup-like event, with much more meltwater present than usual; such an event could explain the large size of the conduits and the transportation of large amounts of coarse sediments.

During the past two decades, however, detailed studies (cf. Krüger, 1985, 1994, 1997; Aber and others, unpublished information, http://edcwww.cr.usgs.gov/pecora/aber/aberja.html) have shown that the sediment accumulations on the surface of Kötlujökull are more differentiated in texture and origin than reported by Näslund and Hassinen, and that the water-worked sediments were not transported to the ice surface by water flow, but currently emerge from debris bands and debris-laden thrust-planes. In the following, we will comment on the arguments of Näslund and Hassinen and present our alternative evidence.

Kötlujökull transports huge quantities of debris which melt out on the glacier surface from numerous debris bands and thrust-planes (Fig. 1a). Aerial photographs and Landsat multispectral scanner images demonstrate that the upper limit of dirt cover has migrated down-glacier. Analysis of satellite imagery (Aber and others, unpublished information) indicates movement of the 1918 tephra bed clearly in the outlet glacier; it migrated about 800–1200 m down-glacier during the period 1973–86 (60–90 m a^{-1}). This compares with the 80 m a^{-1} average velocity determined by Krüger (1994) from aerial photographs for the period 1960–80. The northern part of the glacier, where the large sediment accumulations are situated, appears to have moved farther than the southern part. The dynamic behavior of this glacier is thought to reflect variations in volcanic heating and meltwater production in the caldera. The longitudinal compressive flow, being generated when the outlet glacier expands widely beyond its confining valley walls onto the extensive Mýrdalssandur plain, is responsible for intense deformation of the ice, which tends to fracture by shear in its terminal 1–1.5 km. Because the glacier is subject to longitudinal compressive flow, the snout area also displays radial crevasses reflecting transversal tensile stresses. The intense upward-directed thrusting of the ice mass has resulted in production

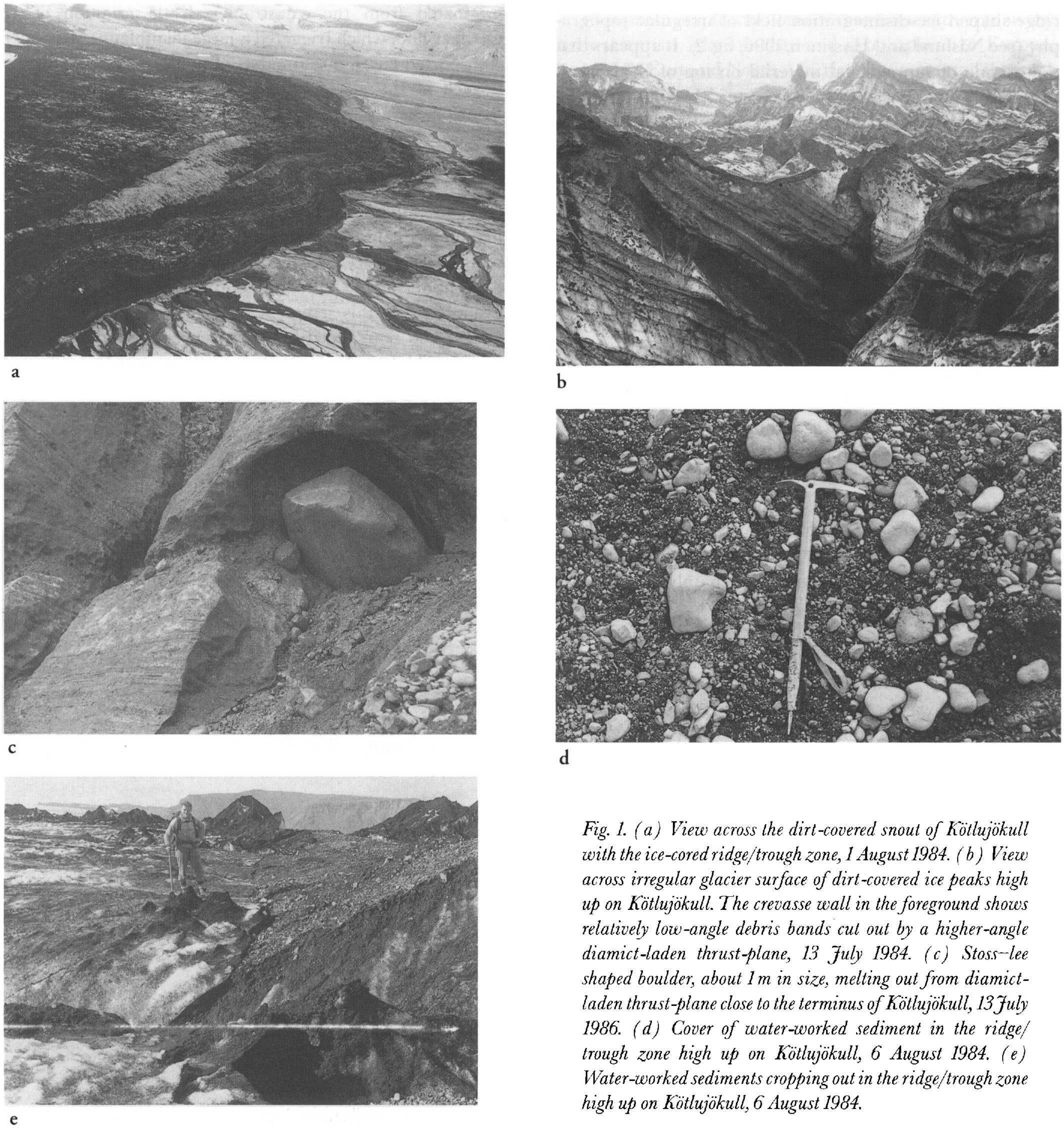

Fig. 1. (a) View across the dirt-covered snout of Kötlujökull with the ice-cored ridge/trough zone, 1 August 1984. (b) View across irregular glacier surface of dirt-covered ice peaks high up on Kötlujökull. The crevasse wall in the foreground shows relatively low-angle debris bands cut out by a higher-angle diamict-laden thrust-plane, 13 July 1984. (c) Stoss–lee shaped boulder, about 1 m in size, melting out from diamict-laden thrust-plane close to the terminus of Kötlujökull, 13 July 1986. (d) Cover of water-worked sediment in the ridge/trough zone high up on Kötlujökull, 6 August 1984. (e) Water-worked sediments cropping out in the ridge/trough zone high up on Kötlujökull, 6 August 1984.

of many thrust-planes and repetition of the debris-band sequences (Fig. 1b).

The supraglacial sediment accumulations originate from different debris sources (Krüger, 1994, p. 119–122). (1) *Sorted sediments*, chiefly of sand size, emerge from numerous debris bands all over the terminal part of the ice tongue. This material originates from volcanic eruptions and dust-storm events, but many of the thin debris bands may also represent old ablation surfaces containing visible debris. Snow diagenesis and ice flow have incorporated the individual accumulation layers and moved them from the catchment area to the ablation area. (2) *Diamict sediments* emerge from debris-laden thrust-planes positioned chiefly close to the glacier terminus. They are gravel-silt-sand or silty sand (according to the classification of Lawson, 1979) with subangular to subrounded stones and boulders, many of which are well striated, suggesting that this material represents outcrops of basal traction-zone debris which has been thrust up into the ice (Fig. 1c). (3) *Sediments comprising poorly sorted gravelly sand with non-striated subangular to rounded clasts* emerge higher up on the glacier (Fig. 1d). This type of sediment was classified as diamict by Krüger (1994) because it melted out directly from ice; we agree with Näslund and Hassinen that these sediments have been water-worked. A large accumulation of this type of sediment was seen in the 1980s in a restricted zone 600–800 m up-glacier from the ice margin, *not as a ridge* as described by Näslund and Hassinen (p. 190), but as a slightly curved girdle, 1.2 km long and 200–300 m wide, comprising two to four parallel, sharp-crested, ice-cored ridges, 2–15 m high, with intervening troughs that are chiefly ice-floored (Fig. 1a). The geometry of the ridges is expressed as cropping-out debris bands or debris-laden thrust-planes (Fig. 1e). In 1994, when Näslund and Hassinen visited Kötlujökull, this large sediment accumulation had reached the terminus region because of ice flow, and developed into a ridge-shaped ice-disintegration field of irregular topography (see Näslund and Hassinen, 1996, fig. 2). It appears that the mantle of supraglacial material on top of Kötlujökull originates from at least three different debris sources, and that the water-worked sediments in question had been elevated to the glacier surface chiefly along debris bands and thrust-planes, and *not* by water flow within high-level conduits as suggested by Näslund and Hassinen.

Näslund and Hassinen also suggested (p. 191) that the large conduits with a diameter of 12–15 m were of great size also when they actively drained meltwater, and that they therefore resulted from a jökulhlaup-like event with much more meltwater than usual. In the terminal part of Kötlujökull, high-level conduits are relatively common. They drain meltwater from snowmelt in spring and summer surface ablation. Additionally, sudden drainage of supraglacial lake basins can account for production of conduits, an example being given by Krüger (1994, p. 140). Näslund and Hassinen's argument (p. 192) is probably correct, that normal meltwater production cannot account for the large amounts of water needed for the production of *large* water conduits. There is documentation, however, to demonstrate that the great size of the observed conduits is mainly a product of ice-wall backwasting which amounts to 40–90 mm d^{-1} during the ablation season (Krüger, 1994, p. 125). It means that the diameter of a medium-sized open tunnel may increase at least 2 m month^{-1} due to summer-season ablation. This opening was actually observed in the 1997 and 1998 field seasons (July–September), and is also evident from the up-glacier view of the largest meltwater conduit observed on Kötlujökull by Näslund and Hassinen (1996, fig. 3). This tunnel is floored by a narrow esker-shaped accumulation of stony sediment, but the coarse-grained esker sediments are clearly fringed by sand which has melted out from the backwasting debris-laden tunnel walls. This firmly implies that the tunnel was smaller when it actively drained meltwater and the esker sediments were accumulated. The observed esker sediments within the conduit could simply represent supraglacial material reworked by supraglacial stream flow and deposited on the tunnel floor.

Näslund and Hassinen (p. 192) refer to studies made by Kirkbride and Spedding (1996) in New Zealand and Iceland, to find support for their alternative explanation, that the supraglacial sediment load was transported to the glacier surface by water flow within high-level conduits. However, Kirkbride and Spedding concluded that "[p]ronounced upward motion within strongly compressive flow will elevate any debris within the ice. The same will not be true of active conduits, which tend to find successively lower levels within the ice, so that only the abandoned *conduit fills* reach the surface, and not the flowing water" (p. 162, our emphasis). We therefore suggest that the observed high-level water conduits exposed by roof collapse result either from drainage of snow and glacier meltwater, or from drainage of supraglacial or englacial bodies of meltwater dammed up in crevasses or behind ice-cored ridges and mounds; ice-wall backwasting has subsequently increased the size of the exposed conduits.

It is a problem for Näslund and Hassinen (p. 192) to find the process by which sediment is entrained into the englacial system. As noted by Krüger (1994, p. 120) with reference to Jonsson (1983), much of the englacial debris load may have originated from the catastrophic Katla eruption of 12 October 1918, which triggered a large jökulhlaup. Meltwater transported enormous amounts of material both across the surface of the glacier, and englacially through conduits, shear-planes and crevasses. According to Tómasson (1996), some of the water flow under the glacier may have issued from channels in that part of the terminus region we have studied. Given the high rates of ice migration and ablation, it seems unlikely that any morphologic forms of the 1918 jökulhlaup could survive intact today. The water-worked sediment of the ice-cored ridges may have formed as "esker" deposits during the 1918 jökulhlaup, as Näslund and Hassinen proposed, but this sediment has subsequently been transported and rearranged by ice movement, deformation and surficial ablation. No connection exists between this sediment and modern ice tunnels of the ablation zone. Such a process could also explain the cropping-out of circular accumulations of water-worked debris found by Näslund and Hassinen (p. 192) higher up on the glacier. The shape of the cropping-out sediment accumulations simply reflects the geometry caused by the intersection of the ice surface and abandoned conduit fills.

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