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CORRESPONDENCE

The Editor,

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SIR,

Ice motion on deformable sediments

The phenomenon of the deformation of subglacial sediments under high pore-water pressure has recently entered the discussion about the dynamics of different ice masses. Lliboutry (1977) assumed deformation of unfrozen subglacial sediments to occur in the case of Glaciar Hatunraju in the Cordillera Blanca, Peru. Fisch and others (1978) and Haeberli and others (1979) suggested that the deformation of sub-permafrost sediments under high pore-water pressure may account for the seasonal velocity variations of active rock glaciers in the Alps (Barsch and Hell, [1976]). Based on direct observations at the margin of Breiðamerkurjökull in Iceland, Boulton and Jones (1979) proposed that the behaviour of Pleistocene ice sheets may have been largely influenced by the deformation of unfrozen subglacial sediments. The present author feels uneasy about this direct comparison between a local observation at the margin of an actual glacier in a maritime climate and large-scale processes at the base of Pleistocene ice sheets under very different climatic conditions.

In their discussion about geologic evidence for former subglacial deformation of unfrozen sediments Boulton and Jones (1979) make reference to tectonically disturbed Pleistocene morainic deposits described, e.g. by Kupsch (1962) and Woldstedt (1954, 1965), stating that the bed of Quaternary ice sheets in Europe and North America may have been unstable in parts. In the context of the current discussion this argumentation could be misleading. A long time ago it was already recognized that folding and overthrusting of layers of unconsolidated sediments up to tens of metres thick is only possible if the sediments are frozen and the rock matrix is cemented by ice (see Kälin, 1971, for references). In a recent contribution Schindler and others (1978) discussed the problem of stress transmission from the glacier to the sediments and concluded that shear stresses increase along the base of the glacier in the marginal zone, where the ice is frozen to the sediments. Some subglacial deformation of frozen sediments may take place, but the highest stresses and, thus, strong strains occur at the glacier front. In the strict sense of Embleton and King (1968)—corresponding to the meaning of the German expression *Stauchmoränen*—the "push moraines" described by Kupsch and Woldstedt are undoubtedly proglacial features in a permafrost condition and actually occur in Arctic and alpine permafrost regions only (Kälin, 1971; Haeberli, 1979). They cannot serve as examples for subglacial deformation of unfrozen sediments.

This point needs further consideration, because some of the phenomena involved may set important boundary conditions for a theory of deforming glacier beds. Pleistocene glaciers and ice sheets in Europe had their ablation zones in an environment of a very cold continental climate and continuous permafrost. The maximum depression of the mean annual air temperature during the last glaciation was at least 10 to 12 deg (Washburn, [1979]). The mean annual air temperature at the equilibrium line of Alpine glaciers during this time was on the order of $-10°C$. This does not necessarily imply that the glaciers were cold-based everywhere, but it certainly means that they were frozen to their (sediment) beds in a marginal zone of unknown extent. Such a marginal zone of cold ice and subglacial permafrost represents a barrier to all three parts of the dynamic and interacting ice–water–sediment system. The cold marginal zone especially acts as a barrier to the sediment flux at the base of the ice. The question of whether the flux of sediments through upward transportation from the bed to the surface at the boundary between cold- and warm-based ice (Weertman, 1961, 1966; Souchez, 1967; Hooke, 1968) is of the same order as the flux of sediments along the base of the glacier due to deformation of unfrozen subglacial sediments at a rate which is comparable to the sliding velocity of the glacier, needs quantitative consideration. It may also be useful to remember that even today wide parts of the beds of alpine glaciers do not consist of hard bedrock but of till as has been revealed by seismic reflection in earlier studies (see Süsstrunk, 1951, for references). This seems to contradict the assumption of an extremely effective erosional process at glacier beds consisting of unconsolidated sediments such as the process of fast large-scale deformation of unfrozen subglacial sediments proposed by Boulton and Jones (1979).

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