# Evidence for Neoglacial Solifluction at Okstindan, North Norway[1]

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ABSTRACT. A section excavated through two adjacent turf-banked solifluction lobes has revealed buried soils beneath each solifluction sheet. Five radiocarbon dates are reported from the buried soils and these reveal evidence of soil movement which probably extends over nearly 3,000 years until the present. The initiation of the movement appears to be linked to the late Sub-Boreal climatic deterioration and Neoglacial glacier expansion which induced the development of a late-lying snow patch at the study site. The first period of movement appears to have been faster than that during the later phase. It is suggested that this reduced rate is associated with a decrease in slope angle and to increased distance from the late-lying snow bank at the head of the slope, rather than to a less severe climatic environment.

RÉSUMÉ. *Indices de solifluxion néoglaciaire à Okstindan, dans le nord de la Norvège.* Une section creusée à travers deux lobes de solifluxion adjacents et bordés de gazon a révélé la présence de sols enfouis sous chaque nappe de solifluxion. Les auteurs présentent cinq radiodatations de ces sols enfouis, qui donnent la preuve d'un mouvement du sol qui s'étend probablement sur 3,000 ans jusqu'au Présent. Le début de ce mouvement semble lié à la détérioration du climat à la fin du Subboréal et à l'expansion des glaciers au Néoglaciaire, qui ont provoqué le développement d'une flaque de neige tardive sur le site étudié. La première période de mouvement semble plus rapide que la seconde. Les auteurs suggèrent que ce ralentissement est lié à une réduction de la pente et à l'éloignement progressif du banc de neige tardif au sommet de la pente, plutôt qu'à un milieu climatique moins sévère.

РЕЗЮМЕ. *Исследование неоледниковой солифлюкции в районе Окстиндан* (*Северная Норвегия*). В результате радиоуглеродного анализа почв, погребенных под солифлюкционными пластами, получено пять дат, указывающих, что на исследуемом участке грунты перемещаются вероятно в течение последних 3000 лет. Начало движения видимо относится к ухудшению климата в позднем суб-бореальном времени и новоледниковому наступлению, что привело к развитию позднолежащего гнезда снега на изучаемой местности. В первоначальный период передвижение происходило с большей скоростью, чем в последующий период. Предполагается, что замедление скорости связано с уменьшением крутизны склона и увеличением расстояния от снежного пласта на вершине склона, и не является результатом изменения климата.

## INTRODUCTION

The measurement of current rates of solifluction has been practised at various locations throughout the widespread periglacial environments of the world. Consequently it is now possible to undertake comparative studies of the contemporary variation in the established rates of movement and relate these to the range of factors which influence them, especially precise climatic factors. A fundamental problem associated with data derived from such investigations relates to an

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assessment of its long-term validity. Few sites have been monitored for more than 25 years and, even if the results of measurements taken over an entire life span were available, the true geomorphological significance would remain somewhat difficult to evaluate. A further problem concerns the duration of solifluction conditions during the period since the end of the last major glaciation. Clearly, therefore, alternative methods are required if attempts are to be made to make meaningful generalizations concerning the dating, total amount and possible significance of this particular kind of periglacial mass movement during the postglacial period.

One approach to this problem which has been adopted is to select a site containing a well-marked linear morphological feature related to an event of known age, and then to measure the total amount of modification which has occurred since its formation. An example of this latter type of situation is afforded by Lindell's (1966) study of the postglacial deformation of ice-dammed, lake shorelines in the Grövelsjö area of west central Sweden. In this instance between 2 and 9 metres of downslope solifluctional displacement of former wave washing features cut in till could be demonstrated as having developed since around 8,000 years BP, as dated on the varve time scale. However, such sites are uncommon, and this particular example occurred where the surface slope was in the range of 25-33 degrees, a value much higher than that which is often encountered in areas exhibiting extensive solifluction. Thus it can be readily appreciated that this type of approach must necessarily be restricted to only a few areas.

In the absence of a synchronous morphological feature, the alternative is to have recourse to stratigraphic techniques which, fortunately, happen to be especially appropriate in areas of extensive solifluction because of the nature of the process itself. The latter invariably involves the overriding and burial of land surfaces immediately in front of the risers of solifluction lobes. Consequently, at the base of such landforms there often occur buried phenomena which display characteristics inherited from the land surface overridden by forward movement of the lobe front. These usually consist of fossil soils incorporating humic horizons, representing the organic accumulations on the former surface. This organic material is amenable to radiocarbon dating and consequently it is possible, theoretically at least, to obtain numerical information on the timing, amount and estimates of the long-term average rates of movement expressed in radiocarbon years. The occurrence of buried humic rich layers beneath solifluction lobes and terraces is much noted in the literature (for example, Williams 1957), although only two localities are known to the present writers where radiocarbon dating has been systematically applied: namely, the Colorado Front Range (Benedict 1966, 1970) and Mt. Kosciusko, Snowy Mountains, Australia (Costin *et al.* 1967).

Turf-banked solifluction lobes have been subjected to detailed investigations since 1968 as an integral part of the University of Reading's Okstindan Research Programme. Progress reports concerning current frost creep and solifluction process studies have already been published by Harris (1972, 1973). These pertain to the study site to be considered further in this paper, the objective of which is to report evidence bearing on the basic evaluation problem which has been outlined above, and to consider how this fits into the current picture of climatic history during the postglacial period in Scandinavia. It is considered by the writers that solifluction has probably operated in the Okstindan area since at least 2,500 years BP — that is, within the time span of Neoglaciation.

The chronological term Neoglacial is here used in the way defined by Flint (1971); that is, it concerns the birth and/or growth of glaciers following the Hypsithermal interval (climatic optimum). The other potentially ambiguous term "postglacial" is here used in an informal sense and is restricted to the period of time from the dissipation of the last inland ice cover in the Scandinavian context.

## LOCAL SITE ENVIRONMENT

The site to be described is located at the eastern exit of an east-west trending valley unofficially called Austre Okstindbredal, and lies at an altitude of 710 m. Immediately to the southwest lies the Okstindan ice cap which is situated across latitude 66°N in Nordland County, north Norway. An outlet glacier, Austre Okstindbreen, descends from the ice cap to block the western end of Austre Okstindbredal. This glacier has been in essentially continuous retreat in recent years, and is now approximately 2.0 km. distant from the study site (see Fig. 1).

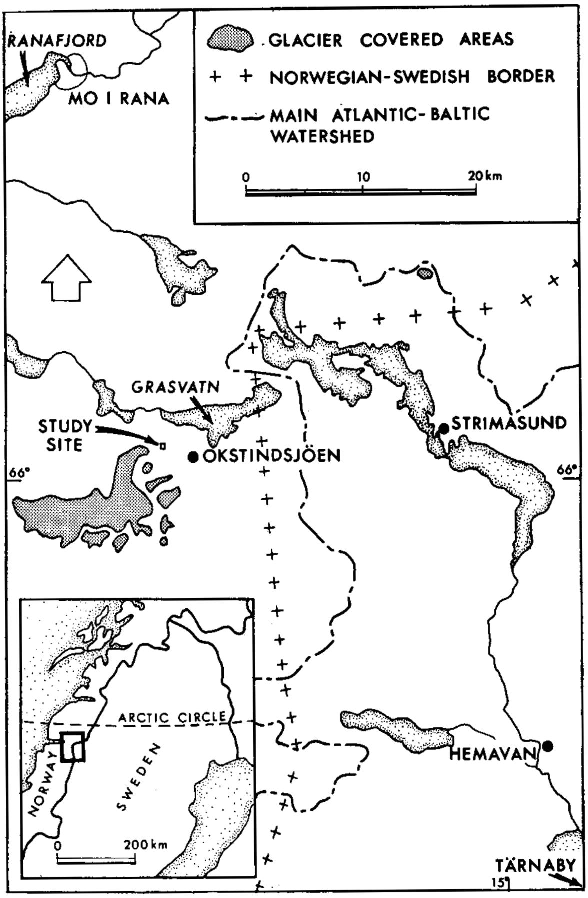

FIG. 1. Location of the Okstindan ice cap and the study site.

Precise climatological data for the area are not available but, on the basis of extrapolation from the nearest Norwegian inland meteorological station at Hattfjelldal and from incomplete observation from the site and the nearby Okstindsjøen Field Station, the mean annual temperature is estimated as −3° C.

The solifluction lobes are developed on an east-facing slope with a gradient ranging between 5° and 17°. Apart from the surficial mass-movement layer of about 1 metre in thickness, the slope is underlain by till which is banked against a heavily striated and glacially smoothed bedrock knoll protruding into the valley from the northern side (see Fig. 2). The lobes are formed from a remanié silty sandy till and lie downslope from a snow patch which persists well into the summer during most years. In terms of the altitudinal sequence of vegetation belts recognized in Scandinavia (Sjörs 1967) the site lies in the low alpine belt. However the upper limit of the sub-alpine birchwood belt reaches an elevation of only 40 m. below that of the study locality at a distance of 400 m. to the east. At the surface the vegetation consists mainly of Bearberry *(Arctostaphylos alpina),* Crowberry (*Empetrum nigrum*), Least Willow (*Salix herbacea*), Dwarf Birch (*Betula nana*), Billberry *(Vaccinium myrtillus),* and *Carex* spp. Below the vegetation mat a thin soil is present, probably best described as a skeletal brown earth. A full soil profile description together with analytical data is given in the appendix.

## STRATIGRAPHY

To obtain an insight into the general site stratigraphy a trench 10 m. long and 1.5 m. deep was excavated. This lay along a transect parallel with the slope in an area where disturbance of the ground during excavation would not adversely affect the instrumentation installed for the process investigations — that is, between sites B and C of Harris (1972). The section in the trench revealed the stratigraphy through two turf-banked lobes.

Where the two lobe fronts (risers) made contact with the adjacent treads, it was apparent that an organic-rich horizon could be traced along the upslope projection of the tread surface which lay downslope from each lobe (see Fig. 2).

FIG. 2. The study site viewed from the south prior to the excavation. Immediately below the snow patch to the right is an instrument housing 1 m. in height.

It was clear that the creep and/or flow of the lobes had progressively buried the tread surfaces lying in the path of the movement. The organic horizon of the lower lobe could be traced back from the lobe front for a distance of 5.5 m. and that of the upper lobe for a minimum distance of 3.5 m., since it had not failed at the head of the trench section. In the former case, as it was traced upslope away from the lobe front, the organic horizon became thinner and less distinct, but in no instance was it seen to be broken before it finally became indistinguishable. The two organic beds are considered to be buried soils. Associated with the frontal parts of both lobes were other subsurface organic beds, but these were of rather restricted extent. It is suggested that these minor organic horizons represent former poorly developed soils which had formed on the lobe surfaces during former periods of relative stability. This proposal is consistent with the general concept which emerged from the contemporary process study, that an important element of the present-day movement might be associated with the rare event when a certain combination of environmental factors is in phase. Thus a period of rates of movement well above average may occur from time to time to produce an untypically large amount of movement in a particular year. This unusual happening could well take the form of accelerated movement of near-surface material in the frontal zone by saturated flow, and thereby cause the type of complex pattern of organic horizons observed in the frontal part of the lobes.

Nine samples from representative parts of the section were tested for moisture content, Atterberg limits and loss on ignition, and the results are presented in Table 1. From this it may be seen that the high organic content of the buried soil is demonstrated by the result for sample no. 1. The organic material is thought to have an origin in the former A horizon of the relict soil. Evidence to substantiate this view comes from the observed occurrence of large, rounded cobble- and boulder-sized material concentrated at, or immediately below, the buried organic bed, for similar concentrations are encountered within 0.25 m. of the present-day surfaces. Other concentrations of boulders were located at the lobe fronts beneath the vegetation cover, with the long axes imbricated upslope. Most of these large clasts were rounded, often striated, and were probably derived from re-cycled material from the till. The low values for the plastic limit and liquid limit

TABLE 1. Soil properties within the section.

| Sample | Moisture content % | Plastic limit % | Liquid limit % | Ignition loss % |
|---|---|---|---|---|
| 1 | 24.1 | 55.3 | 56.5 | 36.1 |
| 2 | 9.5 | 24.3 | 28.5 | 5.4 |
| 3 | 9.9 | 17.25 | 23.5 | 3.5 |
| 4 | 19.0 | 27.4 | 31.8 | 6.3 |
| 5 | 13.1 | 18.5 | 27.0 | 3.2 |
| 6 | 14.1 | 25.7 | 28.0 | 5.9 |
| 7 | 9.3 | 21.2 | 21.5 | 5.0 |
| 8 | 8.4 | 18.6 | 23.5 | 2.4 |
| 9 | 8.5 | 17.9 | 29.5 | 3.2 |

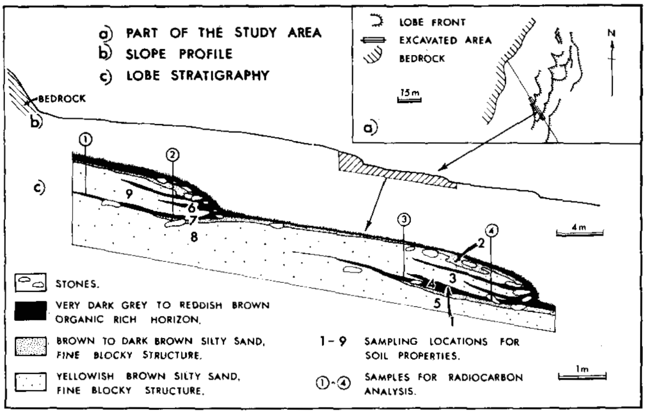

FIG. 3. Map, profile and stratigraphy of the study site.

obtained from the samples other than the main organic bed strongly suggest that failures leading to movement on the slope probably occur under saturated conditions by viscous flow rather than by slip failure. Naturally, in view of the sandy nature of the till underlying the slope, an impermeable substratum is necessary for this type of movement. Such a layer will occur at the site so long as a continuous subsurface frozen layer is maintained into the summer. The incidence and persistence of this frozen layer may be the crucial factor in determining those occasions when significant viscous flow is operative.

## RADIOCARBON DATING

The locations within the trench of the samples collected for radiocarbon age determination are shown in Fig. 3. The dry weight of each sample was approximately 200 gm., and care was taken to collect only that part of the humic material which was closest to the upper surface of the buried horizon. In the laboratory the samples were dry-sieved through a coarse screen and any rootlets which may have intruded into the deposit after burial were removed. The absence of any reaction to a test with hydrochloric acid was taken to indicate that no carbonates were present in the sample, and so one potential source of contamination leading to a spurious age determination could be disregarded. This result was consistent with three pH measurements on samples from a pit adjacent to the section which all gave a reading of 5.4. Estimated ages for the samples were requested by the Trondheim Radiological Laboratory at the time of their submission and, since these were somewhat younger than the resultant radiocarbon ages, a further age determination was made on part of the material constituting sample no. 4. This enabled an independent check to be made on the reliability of the first four results, as only the alkali-soluble fraction was used in this latter instance, and thus any non-soluble contaminants which may possibly have been present in the sample were avoided. (See, for example, the difficulties encountered by Østrem (1965) when graphite was disseminated throughout the surficial sediments). As may be seen from a comparison of the dating results of sub-samples 4a and 4b in Table 2, the possibility of non-soluble contaminants can be discounted in this instance.

TABLE 2. Radiocarbon ages from the buried soils.

| Sample (for location see Fig. 1) | Uncorrected radiocarbon age in years BP | Trondheim sample: reference no. |
|---|---|---|
| 1 | 2480 ± 90 | T-1115 |
| 2 | 1420 ± 150 | T-1116 |
| 3 | 2550 ± 80 | T-1117 |
| 4a | 2070 ± 100 | T-1118/1 |
| 4b | 2200 ± 150 | T-1118/2 |

As is generally known, one of the basic assumptions made in the calculation of a radiocarbon age is that the level of radiocarbon activity in the biosphere has remained constant throughout time. Once the technique was applied to samples of known age, *i.e.* historically dated material, it became apparent that the discrepancies which emerged from the results were related to something more fundamental than simply errors related to the mechanics of preparation and counting. During the last decade careful radiocarbon age determinations made on samples derived from precisely-dated sequences, mainly dendrochronologically dated wood specimens, have permitted the production of a graph showing the actual radiocarbon activity level in the sample with respect to true time. Suess (1970, plate 1) published a 'calibration curve' for conventional radiocarbon ages for the last 3950 years BP derived from 273 measurements of "bristlecone-pine, wood from Europe and from the American *Sequoia gigantea*". This curve shows that sometimes the usual statistical uncertainty associated with individual radiocarbon dates is actually increased when the date is converted into a 'true' calendar date. For instance, at certain periods in calendar time identical radiocarbon dates may result from age determinations made on materials with a known range of true ages.

The discussion at the symposium which featured the presentation of the Suess curve showed that it was not accepted unanimously by those radiophysicists present. There is no doubt that radiocarbon ages diverge from true calendar ages by a significant amount after about 2,000 years BP in such a way that they are consistently underestimated. At the time of writing the debate continues as to the precise course of the calibration curve, and this is well illustrated by the discussions held at the latest radiocarbon dating conference held in New Zealand late in 1972. The basic trend of the curve is agreed, but the details of the smaller oscillations are not. Until such time as a majority of workers can agree on a means of converting radiocarbon ages into calendar time, the Quaternary geologist is faced with the dilemma of which means of correction to choose. On this occasion the Suess (1970) curve will be adopted since it is available in a readily-usable form, although it must be recognized that close inspection reveals the somewhat subjective nature of its derivation from the various age determinations plotted. The alternative approach is to simply "sit on the fence" and attempt no interpretation until some future date. Since this particular case illustrates a problem which will no doubt be encountered by other workers in the near future it seems profitable to attempt a conversion into calendar ages so that the problems involved may be clarified. Thus in Table 3, the radiocarbon ages reported by the Trondheim Laboratory are

TABLE 3. Calendar age calculated from the Suess (1970) curve.

| Sample | Radiocarbon age in years BP | Converted calendar age in years BP |
|---|---|---|
| 1 | 2480 ± 90 | 2640 ± 170, (2810 - 2470) |
| 2 | 1420 ± 150 | 1380 ± 120, (1500 - 1260) |
| 3 | 2550 ± 80 | 2645 ± 175, (2820 - 2470) |
| 4a | 2070 ± 100 | 2110 ± 210, (2320 - 1900) |
| 4b | 2200 ± 150 | 2165 ± 255, (2420 - 1910) |

converted with the aid of the Suess (1970) curve. The present writers cannot overstress how fully aware they are of the potential dangers associated with this exercise, and would emphasize the tentative nature of the conclusions derived from it. Such are the uncertainties involved that the calendar dates obtained will be quoted as the $1\sigma$ range. It can be seen that the $\pm\ 1\sigma$ uncertainty factor has actually increased in four of the results and only decreased in one (sample no. 2).

## APPLICATION OF RADIOCARBON RESULTS

Two issues arise related to the application of the radiocarbon dates to the buried soils. This general topic has been previously discussed by Benedict (1966) and only a brief outline need be given here.

(1) A modern soil, especially the A horizon, will consist essentially of a mixture of the modern vegetation and the decaying remains of past vegetation, and consequently such an horizon will have an age, in terms of its radiocarbon content, which will be determined by the average period of residence of the organic material at a given level. In time, oxidation and/or leaching will promote the breakdown of the organic matter which will then gradually move down the profile to lower horizons. As this process progresses the radiocarbon content will decrease with depth and the age will also, therefore, increase with depth. However, concurrently with this process, new material will continually be contributed from the vegetation mat above. This concept of a dynamic equilibrium in the soil profile was first coherently expressed by Nikiforoff (1942), and it follows that in a fully-developed soil the radiocarbon age will, theoretically, remain constant provided that the general environment does not change.

(2) The second issue requiring consideration concerns the spatial characteristics of a buried soil with respect to time. Can it be assumed that the whole buried soil had an "average period of residence age" similar to that of a modern soil? That is, was the soil fully developed at the time of burial, since if it were not, then possibly its "age" may have been less than that held by the modern soil. It is assumed in this case that the soil, once buried, becomes truly inert with respect to modern soil forming processes, and in particular no organic material of any age is subsequently added to it. In view of the thickness of the overlying sheet of solifluction material in the case under discussion, this seems to the writers to be a reasonable assumption to make.

With respect to the Okstindan situation it is unfortunate that the modern soil was not radiocarbon dated, but financial resources did not permit more than four

TABLE 4. Jotunheimen soil radiocarbon dates (Østrem 1965).

| Locality | Height (m.) | Depth (cm.) | Date | Reference No. |
|---|---|---|---|---|
| Gråsubreen | 1900 | surface | modern | T-405 |
| Smådalen | 1200 | 3-5 | 250 | St-1364 |
| Veodalen | 1350 | 3-5 | 385 ± 70 | St-1366 |

datings from this locality to be commissioned. In the absence of such information, evidence for modern soil age from the arctic-alpine zone of Scandinavia is required. As part of a comprehensive study of ice-cored moraine ridges, Østrem (1965) investigated the radiocarbon age of modern soils adjacent to some glaciers in the Jotunheimen of south Norway and Kebnekaise in Swedish Lapland. Many of his results proved to be anomalous owing to contamination of the soils by infinitely old graphite derived from the local bedrock. However, three of his results obtained from soil material which chemical analysis subsequently showed to be uncontaminated by graphite may be useful in the present context. These dates are shown in Table 4.

As is predictable from theory, the surface sample from Gråsubreen was undatable, being composed of present-day organic material plus some which must have died in the very recent past, and so it was impossible to measure a radiocarbon decay rate below the standard in the sample. The other two results suggest that the soil A horizon has an age ranging from 0-455 years at ± 1$\sigma$. Apart from these dates, no other published information from comparable environments is known to the writers, except Benedict's result from the modern soil in Colorado of 355 ± 115 years BP (I-1510). The depth of this latter sample was not given in the text, but is estimated as approximately 0.10 m. from Fig. 4 of Benedict (1966).

On the basis of this it can be suggested that the radiocarbon age of the modern soil at the study site is likely to be of the order of a few hundred years at the most. Unpublished data from the Sarek Mountains, which lie between Okstindan and Kebnekaise, are consistent with this conclusion (George Denton, personal communication, 1973). Accepting this, it seems to the writers that when the application of a correction factor based on the age of the modern soil is considered in relation to the buried soils in this instance, the procedure becomes absurd. This is because of the paucity of data on the ages of modern sub-arctic type soils and, more important, the vagaries of the Suess calibration curve between 2,000-3,000 and 0-450 years BP. Thus any attempt to calculate an average figure from the information available would be both meaningless and dishonest in that it would give a false sense of accuracy to the result. Accordingly this particular correction factor has been ignored.

## TIMING AND RATES OF SOLIFLUCTION

It is clear from the discussion above that evaluations of timing and rates of solifluction based upon radiocarbon dating evidence must necessarily be very tentative. When considering the ± 1$\sigma$ ranges of the two oldest samples, the degree of coincidence is obvious. The stratigraphic relationships in conjunction with the dates indicate that this part of the soil, then lying at the surface, became buried sometime after about 2,800 years BP. The field data are considered insufficient to permit a positive conclusion being drawn concerning the thinning of the outcrop in the section when traced upslope. This might signify either progressive immaturity or differential post-formational erosion. The site characteristics suggest that, perhaps a few centuries previous to the date of the oldest buried soil which has been preserved, higher up the slope, a snow patch had started to persist into the summer, thereby promoting solifluction processes on the slope. In the absence of other data suggesting the contrary, the simplest interpretation would be to propose that the pre-existing soil which had developed during the period before the climatic deterioration was initially destroyed in the newly-established periglacial environment. We can only speculate as to whether this was the first major solifluction episode to occur at the study site since the wastage of the inland ice which probably took place about 9,000 years BP. If it were, then a partial explanation would exist as to why solifluction associated with the last 3-4 centuries has not apparently caused any widespread destruction of the soil cover in the area. It could be that the slope had been reduced in the early first millennium BC by periglacial conditions to such an extent that the subsequent solifluction periods have been less effective. Certainly the measurements of current movements are consistent with a relatively low level of activity in the present climatic environment.

More dates will be required from the buried soil before an attempt can be made to obtain a detailed picture of past variations in the manner achieved by J. B. Benedict (1966) who, it should perhaps be noted, did not have the possibility of correcting his dates in the light of modern knowledge concerning past levels of radiocarbon in the atmosphere. From the dates available from Okstindan an attempt can be made to obtain an idea of the likely approximate rates of solifluction movement. This can be done in terms of the average along the whole section or in two stages of 2 m. and 1 m. in length respectively. In each case the rates will be calculated with respect to AD 1970, and to facilitate discussion the two stages will be termed (a) and (b) for the newer and older stages. As we have seen, all the sample ages include a "mean residence time factor" which makes them slightly older than the burial event. The modern reference year in this case is AD 1970 (strictly - 20 years BP) which does not include such a factor, and hence in the calculation of the average rates of movement the resultant will be a little underestimated.

TABLE 5. Approximate past rates of lobe front movement.
(assuming that the corrected radiocarbon dates are accurate)

| Lobe | Distance upslope from present front | Date of burial | Average rate in stage (a) | Average rate in stage (b) |
|---|---|---|---|---|
| Upper | 3 m. | 2640 | | |
| | 1 m. | 1380 | 1.59 mm/yr. | 0.71 mm./yr. |
| Lower | 3 m. | 2645 | | |
| | 1 m. | 2137* | 3.94 mm/yr. | 0.46 mm./yr. |

*mean of samples 4a and 4b. (See table 3)

From the data given in Table 5 it can readily be seen that the average rate of movement along the whole of each lobe section must inevitably be very similar, since the two starting dates are almost identical and the total distance involved is the same. When the breakdown into the two stages (a) and (b) is examined, it appears that there was a significantly greater movement rate in the past than in more recent times. As has been commented upon earlier in this paper, this apparent reduction in the movement rates of the lobe fronts does not necessarily indicate that the periglacial environment has become any less severe climatically as the present is approached. This is because the rate of soil movement under present-day conditions decreases downslope, seemingly as the effects of the late-lying snow patch at the head of the slope decreases and the slope angle is reduced. Thus it might be expected that the rate of migration would have decreased with time as the lobes became more distant from the snow bank at the head of the slope.

The calculated average movement rates associated with each stage obviously show no correlation between the respective values from the upper and lower lobes. This apparent anomaly can be considered from two standpoints:—

(i) on the assumption that the dates are accurate. Here the dates can be interpreted as indicating that during the (a) stage of movement the upper lobe was moving less rapidly than the lower. Normally the reverse might be expected, since the effects of the snow patch should have been greater upslope, as just noted. Since the two lobes exhibit insignificant differences in slope angle, this factor is unlikely to have influenced this issue. Thus from a geomorphological point of view it appears that one of the lower dates is inconsistent with theory.

(ii) assume that the dates are incorrect. Since the two upslope dates are in each instance so similar, it is impossible to evaluate these independently on the basis of the present data. However it should be observed that both of these samples occur at the same distance from the lobe fronts (3 m.). Making the simplest assumption that the total forward movement of each lobe over time has been the same, then the predicted ages should be alike, as is the case in this instance. Attention must, therefore, be focused on the downslope dates, and in this instance we fortunately have a check on the accuracy of sample no. 4, since two age determinations were made on this, one on the bulk sample and the other on the alkaline soluble fraction. Since the $\pm\ 1\sigma$ uncertainties from these two determinations clearly overlap there is good reason to believe that these are more likely to be correct than is the single determination. Thus it can be suggested that the date from sample no. 2 may be erroneous, and possibly it may be too young due to contamination by some younger material. Should this be so, then the higher rate of movement of stage (a) — that is, the rate obtained from the lower lobe — may be more reliable. It may just be possible that the discrepancy is linked to the vagaries of the fluctuations in biospheric radiocarbon level.

We may conclude that on the whole it is more likely that the concept of an initially more rapid period of movement followed by a much longer period of lower movement rates is the more realistic interpretation of the evidence. A movement rate in the first or (a) stage seems to have approached an average of 4.0 mm./year, and in the later (b) stage an average rate below 0.5 mm./year obtained. However it is again stressed that these figures should not be taken as precise values. It has been seen that the lobe stratigraphy may be interpreted in terms of occasional relatively rapid movements rather than of a steady progressive creep rate. Thus upon a probable overall reduction in the movement rate there were likely to have been superimposed short term fluctuations related to rare events promoting more rapid slope failure.

## C14 DATINGS AND POSTGLACIAL CHRONOLOGY

The relation of the C14 datings to the known Scandinavian postglacial chronology is perhaps best achieved by discussion under three headings:—

### (a) *Evidence from the Okstindan area*

The till and glacially eroded bedrock surface at the solifluction site are thought to be the products of the last major Scandinavian glaciation (Weichselian), a period during which ice derived from Sweden moved westwards across the Okstindan area towards the Atlantic Ocean. This event terminated in the area under discussion during the early part of the Holocene and thus there is an older age limit to the site. The glacier Austre Okstindbreen has during the last 2-3 centuries advanced to within 300-400 m. of the site, and there is morphological evidence that on a previous occasion locally derived Okstindan ice had penetrated a similar distance. At present there is no positive evidence from the area to date this glacial phase other than the relative geomorphological relationships, which clearly show a moraine ridge system postdating the Swedish inland ice sediments, yet predating the moraine ridges defining the recent (18th century) advance.

Some 150 m. below the site at an elevation of 587 m. lies a large lake, Grasvatn, around which several archaeological sites are known (Gaustad 1969; Worsley 1970). At one of these sites, site VI, on the southeast shore of the lake, 2 km. west of the international boundary and 6 km. from the study site, an occupational sequence has been excavated, lying upon the ice moulded bedrock associated with the inland ice erosion. This excavation has yielded evidence that the occupation occurred between 7,000 and 3,000 radiocarbon years BP. Charcoal included in the basal occupation debris has given a radiocarbon age of 6,990 ± 115 years BP (Birm-117), and similar material from the uppermost archaeological horizon gave 3,090 ± 180 years BP (Birm-116). The whole sequence was sealed by a peat bed (Worsley 1970). Gaustad (personal communication) has obtained a further five radiocarbon dates from charcoal samples derived from the site VI sequence, plus another two from a house site excavation 0.5 km. to the east, all of which fall within the time span defined by the two ages given above. This series of archaeological dates lends support to a concept of fairly continuous human presence in the Grasvatn area for 4,000 years or so. The termination of this episode of occupation is an unsolved problem, but Worsley (1970) was tempted to suggest that it was linked to the well-documented climatic deterioration which set in towards the end of the Sub-Boreal period (see below). This view is still maintained. Clearly, there is here a suggestion of a climatic link between the cessation of human activity in the Grasvatn region and the onset of active solifluction, as indicated by the radiocarbon dates from the buried soils.

### (b) *Pattern of postglacial size variations in Scandinavian glaciers*

Ahlmann (1953) first published the valuable pioneer diagram constructed by Olav Liestøl which demonstrates how the approximate altitude of the firn line in western Norway may have changed during the last 12,000 years. This diagram, which has been reproduced by most writers on the subject, shows a high firn line from the period 7,000 to 3,000 years BP followed by a rapid lowering in the interval up to 2,500 years BP. Thereafter the firn line follows a relatively low elevation with a minimum altitude around 200 years BP (1750 AD), and a rise since then. This diagram was constructed from different kinds of evidence, including end moraines, pollen analysis, and other types of botanical evidence such as the study of recurrence horizons in peat bogs. These diverse approaches lead to conclusions which seem to be in general agreement with respect to the pattern of climatic change in the later part of the Holocene. This in turn is compatible with variations in the firn line and hence in the size of the glaciers. Subsequent work on Gråsubreen in Jotunheimen showed that this glacier must have existed during part at least of the postglacial warm period (Östrem 1970), and it could further be argued that some of the evidence derived from the ice-cored moraine ridges demonstrates a major glacial advance period around 2,500 years BP as extensive as the well known 18th century culmination. Support for the concept of a significant glacier presence around, or shortly after, 2,500 years BP is forthcoming from Sweden. Bergström (1955) was the first worker to suggest that older moraine ridges outside the recent advance limit may be tentatively assigned to a period around 2,500 years BP. Much stronger support for this idea comes from the Kebnekaise area where Karlén (1973), on the basis of geomorphological mapping and, particularly, lichenometrical studies, has been able to recognise terminal moraine ridges outside the limits of the recent major advance which he suggests are about 2,500 years BP in age. This conclusion is drawn largely on the basis of a lichenometrical growth curve with some radiocarbon dating control at about this period. Thus a growing body of opinion would seem to favour an interpretation invoking significant glacier growth and advance of similar dimensions to the 18th or 19th century event, starting shortly after 3,000 years BP.

### (c) *Record of vegetation change*

Finally, attention should be drawn to the record of vegetation change in Scandinavia, a region where this type of study was pioneered and which is also probably the best documented in the world. Although northern Scandinavia is less well known than its more southern parts, the north does present the advantage of relatively little anthropogenic activity by way of farming such as might obscure changes in natural vegetation response to climatic variation. The pollen diagrams record the climatic deterioration in the Sub-Boreal which is dated at around 2,500 years BP, a period when the archaeological evidence indicates a hunter-fisher type of economy (Fries 1965).

A corroborative piece of evidence relating to vegetation change emerges from the work of G. Lundqvist (1962). His studies involved an examination of the upper limits of *Pinus silvestris* along the entire Swedish side of the Caledonides. Associated with this project he undertook an extensive programme of radiocarbon dating samples obtained from the fossil pine stumps which had been located above the contemporary pine limit, and was able to show that the fossil trees had grown during a generally earlier time than had been previously accepted. In the northern sector, he found that the radiocarbon ages tended to fall within the range 7,000 - 4,000 years BP and, therefore, the stumps were the products of growth during the Boreal, Atlantic and Sub-Boreal climatic periods as defined by pollen analysis.

This project was continued and extended by J. Lundqvist (1969) who discovered a similar pattern.

Of particular interest in relation to the present discussion are the datings of samples obtained from Strimasund, a small settlement some 20 km. due east of the Okstindan study site. There G. Lundqvist (1962) collected from a fossil pine forest level in a small bog lying at a height of 550 m. two stumps which yielded radiocarbon ages of 4485 ± 80 years BP (St-541) and 2690 ± 80 years BP (St-621) respectively. On the basis of these results he concluded that a pine forest had existed at the locality for some 1,800 years. Rune (1965, p. 69) commented that the upper coniferous limit in southern Lapland was difficult to establish owing to edaphic conditions, but he gave figures from the Tärna area 40 km. south southeast of Strimasund. There the limit fell through 200 m. along a 40 km. east-west transect. The upper conifer limit at Hemavan was the nearest locality to Strimasund to be quoted by Rune. This lies some 30 km. distant to the south-southeast in a relatively sheltered location, and the limit was said to lie at 500 m. However, today in southern Lapland within the coniferous zone the dominant tree is the spruce (*Picea abies*), and pine seems to occur only in the lower part of this particular vegetation belt. Recognising the difficulties in comparing vegetation belts separated in time by 3,000 years, and especially the complications arising from the late immigration of spruce, it can only tentatively be suggested that the pine limit has been depressed by at least 50 m. and the possibility exists that it is a good deal more than this value over the period in question.

From Lundqvist's radiocarbon dates two points of relevance emerge:—

(1) A plotting of all the dates obtained so far shows pine growth to have been above its present limit in the north of Sweden over the period 8,000 to 3,000 years BP without significant interruption, and it follows that an extensive glacial advance during this period is unlikely to have occurred. It should perhaps be added that the land uplift factor has been taken into account in drawing this conclusion. The data do not support the hypothesis put forward by Page (1968) that the maximum postglacial extent of Norwegian glaciers was reached in the middle of the climatic optimum.

(2) Pine growth near to Okstindan occurred as late as 2690 ± 80 radiocarbon years BP. It should be noted that this latter age on the Suess calibration curve is transformed to 2850 ± 25 calendar years BP. By coincidence this also happens to be the age of the youngest pine stump of the substantial number dated — that is, late Sub-Boreal in terms of the pollen assemblage zones. At first sight the date does not seem to be wholly compatible with the oldest corrected buried-soil date from the lower lobe at Okstindan, which has been interpreted as indicating solifluction at this time and, by inference, a climatic deterioration. The explanation

may lie in the unfortunate correspondence of the soil date with the previously discussed period of fluctuations in radiocarbon activity in the biosphere which is such that the median radiocarbon date in this instance could equally well be 2,820 or 2,470 calendar years BP. The calendar date given for this sample in Table 3 is the mean date of the ± $1\sigma$ on the calendar scale. Hence there could well be a real difference of at least 250 years, but even so the pine in question must have been a late survivor during the onset of a rapid climatic deterioration, if this reasoning is to have any cogency.

## CONCLUSION

It is considered that this study demonstrates the usefulness of applying the radiocarbon dating technique to the problem of elucidating the history of periglacial solifluction environments in the postglacial. In addition, it enables a better perspective to be gained of the problem of assessing the significance of measurements derived from studies of the rates of current geomorphological processes. Despite several fundamental difficulties in unravelling the true significance of the radiocarbon dates obtained in this study, it can reasonably be said that, with the onset of cooler conditions, an active periglacial climatic regime, as expressed by solifluction, was re-established in the Okstindan area. On the basis of the former minimum altitude of pine trees and archaeological inferences, there is an indication that the degree of cooling necessary to initiate the active solifluction occurred relatively rapidly. An undated moraine ridge produced by a former advance of Austre Okstindbreen immediately adjacent to the study site may be the product of glacial expansion as the result of this cooling. That glaciers became well established at this time — at least in some parts of Scandinavia — is best substantiated by Karlén's important discovery of a buried soil beneath the outermost terminal moraine ridge in front of Nipalsglaciären in Kebnekaise (Karlén 1973). He reports that this soil has yielded radiocarbon ages of 2320 ± 160 years BP (St-3811) and 2460 ± 90 years BP (I-6854) which, although affording a maximum age to the glacier advance, leaves little doubt that the glacial event was very closely associated with it. Certainly this period of cold conditions corresponds with the time when higher solifluction rates were operative at Okstindan. Since its initiation in late Sub-Boreal times it is likely that solifluction has been active almost continuously during some 3,000 years, but at varying rates of movement.

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## APPENDIX: Soil Profile Description.

Location: On solifluction lobe adjacent to the trench section.
Slope: 2° — 6°.
Elevation: circa 710 m.
Aspect: east facing.
Drainage: Waterlogged (immediately following snow melt), becoming freely — very freely drained after snow melt is completed (in certain years may remain waterlogged all summer).
Vegetation: *Empetrum nigrum,/Arctostaphylus alpina,* Carex sp., mosses and lichens.

| Horizon: | Depth (cm.) | |
|---|---|---|
| $O_L$ | 0 - 3 | Damp litter layer, comprising leaf and stem remains of *Carex* and *Empetrum nigrum*. Sharp, straight boundary. |
| $O_F$ | 3 - 4 | Dark reddish brown (5YR3/2)$^+$; damp, abundant fibrous roots and a few woody roots of *Empetrum nigrum* up to 2 mm. diameter; partly humified, becoming increasingly humified at depth, but no definite $O_H$ layer present. A few mineral grains become incorporated into the layer towards the base.<br>Sharp, irregular boundary. |
| $A_h$ | 4 - 6 | Dark yellowish brown (10YR4/4), but dark reddish brown (5YR3/3) where old roots had decomposed; silty fine sand with some coarse sand pockets of decomposing mica schist; weak angular blocky structure; few stones, usually well-rounded quartzite up to 1.5 cm. in diameter; few fibrous and woody roots, decreasing in frequency with depth. Indistinct — merging boundary. |
| (B) | 6 - 14 | Dark brown (7.5YR3/2), silty fine sand; weak angular blocky to single grain structure; few stones, mainly rounded quartzite up to 1.5 cm. diameter; very few roots in upper part of horizon, none present towards base. Sharp, straight boundary. |
| C | 14 - 32 | Olive brown (2.5YR4/4), silty fine sand, single grain structure; few rounded quartzite stones. |

$^+$ Munsell Soil Colour Notation (Munsell Color Company Inc. Baltimore)

Samples were taken for analysis from $A_h$, (B) and C horizons: —

| Sample | pH | Particle size analysis | | | Loss on ignition | Carbon % | Nitrogen % | C : N ratio |
|---|---|---|---|---|---|---|---|---|
| | | % sand | % silt | % clay | | | | |
| $A_h$ | 5.4 | 87 | 12 | 1.0 | 5.4 | 3.90 | 0.14 | 28 |
| (B) | 5.4 | 83 | 16 | 1.0 | N D | 2.26 | 0.09 | 25 |
| C | 5.4 | 81 | 18 | 1.0 | N D | 1.40 | 0.08 | 18 |

| Sample | Exchangeable bases me/100 grm. | | | | | % Base saturation | % Organic matter (%C x 1.724) | % $Fe_2O_3$ |
|---|---|---|---|---|---|---|---|---|
| | total | Ca | Mg | Na | K | | | |
| $A_h$ | 15.0 | 0.75 | 0.22 | 4.90 | 0.38 | 41.6 | 6.6 | 0.25 |
| (B) | 17.5 | 0.57 | 0.23 | 5.43 | 0.36 | 37.7 | 3.8 | 0.18 |
| C | 12.5 | 0.75 | 0.19 | 1.85 | 0.51 | 26.3 | 2.4 | 0.12 |