Stratigraphic Studies of the Winter Snow Layer Mount Logan, St. Elias Range

DONALD ALFORD[1] AND CHARLES KEELER[2]

ABSTRACT. Results of a traverse study of near-surface snow properties in the King Trench area of Mount Logan, St. Elias Range, are presented. Based upon the assumption that these snow properties are related to thermodynamic processes operating during the depositional period, a climatological model of the King Trench is presented which relates the observed variations in snow properties along the traverse line to localized topographic obstruction or enhancement of katabatic air drainage. It is suggested that the near-surface climate of snow-covered slopes generally may be inferred partially from the interaction between local topography and katabatic wind flow.

RÉSUMÉ. *Études stratigraphiques de la couche de neige hivernale, Mont Logan, chaîne de Saint-Élie.* Les auteurs présentent les résultats d'une étude par cheminement des propriétés de la neige infra-superficielle, dans la zone de la *King Trench,* sur le mont Logan, chaîne de Saint-Élie. En supposant que ces propriétés de la neige sont liées aux processus thermodynamiques agissant pendant la période de déposition, les auteurs proposent un modèle climatologique de la *King Trench* qui relie les variations observées dans les propriétés de la neige le long du cheminement à une augmentation ou une rétention topographique localisée de l'écoulement catabatique de l'air. Les auteurs supposent qu'au voisinage de la surface des pentes couvertes de neige, le climat peut généralement être partiellement déduit de l'interaction entre la topographie locale et l'écoulement catabatique de l'air.

РЕЗЮМЕ. *Стратиграфические исследования зимнего снежного покрова на г. Логан в горах Св. Ильи.* Обсуждаются результаты маршрутного изучения свойств приповерхностного слоя снежного покрова в районе Кинг Тренч на г. Логан в горах Св. Ильи. Исходя из предположения, что эти свойства обусловлены термодинамическими процессами, происходившими в период отложения снега, дается климатологическая модель Кинг Тренч, сопоставляющая данные по изменениям свойств снега вдоль маршрута с положительным или отрицательным влиянием местного рельефа на скорость катабатического течения воздуха. Высказано предположение, что приповерхностный климат снежных склонов в общем случае может быть частично объяснен на основе взаимодействия местного рельефа с катабатическими ветровыми потоками.

INTRODUCTION

Stratigraphic studies of snow and firn on the Greenland Ice Sheet are a useful approach to understanding the climate there (Benson 1959, 1962). These studies were made by correlating stratigraphic units from the edge of the ice sheet to

[1]Montana State University, Bozeman, Montana.
[2]U.S. Army Terrestrial Sciences Center, Hanover, N.H.

the high interior by digging a series of pits. Variations in the layering of the snow produced by annual, seasonal and individual storm cycles may be correlated with variations in wind speed, air temperature and rate of accumulation. Thus the annual snow layer is equivalent to an infinite set of automatically-recording climatological stations. The primary difficulty lies in learning to read the records correctly.

In order to apply these techniques to other areas, it is necessary to assume that extensive melting did not occur and that weather, snow sedimentation and post-depositional changes are sufficiently inter-related so that stratigraphy provides a climatic record. If this assumption is valid, it should be possible to study the regional climate of any geographical area which possesses a significant snow cover during all or most of the year. One such environment, of which at present we have only the most limited knowledge, is that found in the earth's major mountain ranges. Similarities between ice caps and mountain ranges indicate that techniques devised for use in one could be applied to studies in the other. The primary differences between the two are the greater significance of topography and local relief in mountain ranges and the relatively small surface area of mountain ranges when compared to that of the Greenland ice sheet.

The greatest difficulty in applying traverse snow study techniques to the study of the climate of a large mountain range is that of movement from place to place. At present, the only generally practical means of conducting a traverse study in the mountains is on foot. This is much less efficient than mechanized transport and reduces the time available for the study and the amount of scientific and support equipment which can be used.

To ascertain if the techniques of stratigraphic analysis could be successfully applied to studies of the alpine climate, the U.S. Army Cold Regions Research and Engineering Laboratory of Hanover, New Hampshire, in June 1965, sent a reconnaissance expedition to the west flank of Mount Logan (6,050 m.) in the St. Elias Range on the Alaska-Yukon border. The objectives of this expedition were:

- To determine if systematic variations in snow properties could be detected using the simple tools and techniques which back-packing necessitates;
- To attempt to establish the relative influence of topography and elevation on any variations which were observed.

This paper presents the preliminary results and conclusions of this expedition.

GEOGRAPHICAL DESCRIPTION OF THE STUDY AREA

Mount Logan is approximately 20 miles north of the Alaska-Yukon border near the centre of the extensively glacierized St. Elias Range. On the north, south and east, near-vertical walls with a relief approaching 3,000 m. separate the summit snowfields from the surrounding glaciers. It is only on the western flank that a breach exists. This is the King Trench, which rises from Upper Ogilvie Glacier at an elevation of 2,300 m. to King Col at 4,500 m. From King Col, access to the summit plateau of the mountain is relatively straightforward. Fig. 1 is a sketch map of the King Trench showing the route, location and elevation (in
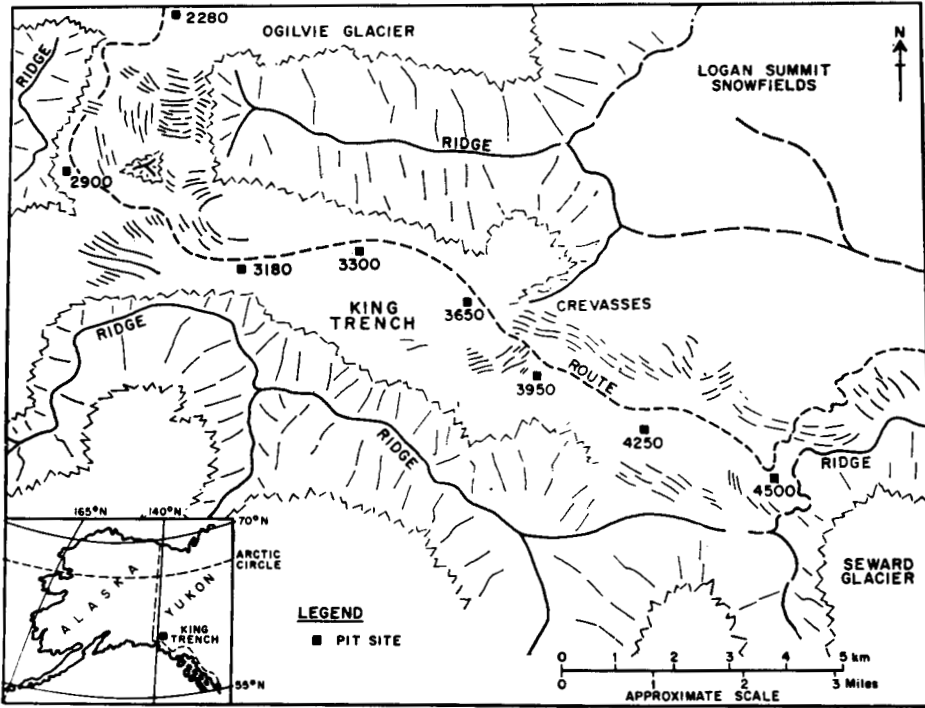
FIG. 1.   The King Trench on the west flank of Mount Logan, St. Elias Range, showing the traverse line and pit locations. Numerical value adjacent to pit sites indicates approximate elevation in metres.

metres a.s.l.) of the pit sites. Fig. 2 is a cross-section of the traverse route. It can be seen that the central portion of the Trench is relatively flat-lying with fairly steep ice falls above and below. The slopes above the upper icefall, while still quite gentle, are somewhat steeper than those found in the central portion of the Trench. The total elevation range covered by the traverse was approximately 2,200 m. in a horizontal distance of 16 km. (Fig. 2).

STUDY TECHNIQUES

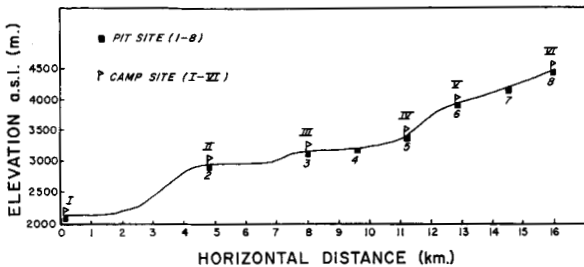Only a brief summary of the techniques of snow stratigraphy is given here. Details are given by Benson (1962).

FIG. 2.   Longitudinal profile of King Trench showing camp and pit sites.

Table 1. Elevations and locations

Camp	Location	Pit	Approx. Elev.	Dist. from Base Camp	Date
Base	Ogilvie Glacier	1	2280 m.	—	6/2/65
I	Lower King Trench	2	2900 m.	5.0 km.	6/6/65
II	Lower King Trench	3	3180 m.	8.0 km.	6/9/65
	Middle King Trench	4	3300 m.	9.5 km.	6/12/65
III	Middle King Trench	5	3650 m.	11.5 km.	6/19/65
IV	Upper King Trench	6	3950 m.	12.5 km.	6/15/65
	Upper King Trench	7	4250 m.	14.5 km.	6/18/65
V	King Col	8	4500 m.	16.0 km.	6/17/65
VI	Summit Plateau	—	5150 m.	18.5 km.	
				21.5 km. to summit	

Note: Vertical and horizontal distances between camps have been taken from the St. Elias 1:250,000 sheet, Canada Department of Mines and Technical Surveys. Conversion to metres and kilometres is approximate. While the absolute values may be greatly in error, it is felt that relative elevations are accurate to within ± 50 m.

Eight pits were excavated through the annual layer at approximately 300 m. vertical intervals between the upper Ogilvie Glacier and King Col. Table 1 summarizes the elevations and locations of the individual camps and pit sites.

Following excavation of each pit, one wall was smoothed and brushed with a whisk broom to bring out discontinuities in snow cohesion. A steel tape, graduated in centimetres, was suspended from a board lying on the surface of the snow pack and was used as a reference for all measurements. Weston dial thermometers, graduated in degrees C. were inserted into the pack at 10 cm. intervals to measure the existing temperature gradient between the surface and the bottom of the pit. Stainless steel tubes with an internal volume of 500 cm.³ were placed in the pit wall at 5 to 10 cm. intervals, then cut out, trimmed, capped and weighed to measure vertical variations. The individual density measurements were also averaged over the depth interval of the pit to obtain the average density for the snow at that point. Density measurements were considered accurate to within 0.005 gm./cm.³, temperature measurements to within 1.0°C.

OBSERVATIONS AND DISCUSSION

1) The 1964-65 winter accumulation layer varied from 23 cm. water-equivalent at base camp on the Ogilvie Glacier to over 1 m. at King Col (Fig. 3). On the Ogilvie Glacier, this snow layer was underlain by glacier ice, indicating that at that elevation, none of the winter accumulation of 1963 had persisted through
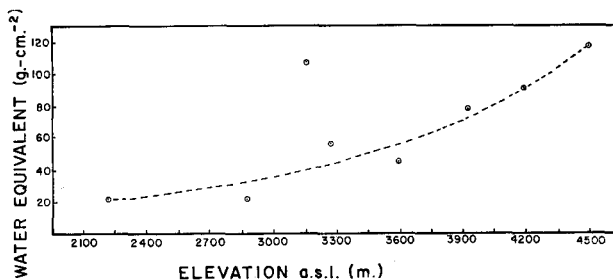

FIG. 3.   The water-equivalent of the 1964-65 winter snow layer in the King Trench as a function of elevation.

the summer melt season of 1964. At Camp I (Pit 2), the depth of this layer had increased only 4 cm., to 60 cm., but at this elevation it was underlain by very coarse, well-cemented firn rather than solid ice. At Camp II (Pit 3), there was no clear break between the 1964-65 accumulation and that of the preceding year. At this elevation, a series of interbedded ice layers and coarse-grained, poorly-bonded snow was interpreted as the transition between 1963-64 and the 1964-65 accumulation. At King Col, it is not believed that the pit penetrated the entire thickness of the 1964-65 winter accumulation. However, measurements of the thickness of individual ice bands (assumed to represent the mean annual accumulation) in crevasse walls in the upper icefall indicate that 1 m. of water-equivalent may closely approximate the annual accumulation in the vicinity of King Col.

These observations indicate that the firn line was below 3,000 m. during the summer of 1964. Since most of the surface area of the King Trench lies above this elevation, it seems reasonable to infer that the Trench is an area of net annual accumulation. On the other hand, the Ogilvie Glacier, lying mainly below this elevation, would appear to have a negative annual budget in terms of seasonal snowfall and is probably nourished primarily by the avalanches which fall onto it constantly from the summit plateau of Mount Logan and the other surrounding peaks.

The low water-equivalent value measured at 2,200 m. on the upper Ogilvie Glacier is somewhat surprising as, at an equivalent elevation on the divide between the Hubbard and Kaskawulsh Glaciers, 40 km. to the northeast, the 1964-65 accumulation exceeded 1 m., which was over 4 times as much (Marcus 1965; unpublished data). Since the temperature gradient in the snow at the Ogilvie Glacier pit site was not yet isothermal at 0°C., it is unlikely that any significant mass loss due to melt had occurred. This would suggest that the northwest flank of Mount Logan is a desert in terms of annual precipitation. If this is so, it is probably because the bulk of Mount Logan is in the path of the prevailing storms from the Gulf of Alaska. If these storms follow the *path of least resistance* through the range, the Hubbard, Seward and Kaskawulsh Glacier systems should receive a disproportionately larger amount of the precipitation falling on the range as a whole than would the Logan or Walsh Glacier systems. To some extent, this is borne out by the available aerial photography of the range, which shows far more bare rock and morainal material to the northwest of Mount Logan than to the northeast, in the direction of the Hubbard and Kaskawulsh Glaciers.

2) Before melt starts, temperatures in the annual snow layer are related to the near-surface air temperature regime.

Fig. 4 shows the snow temperatures measured at a depth of 2 m. for all the pits excavated to that depth plotted against their respective elevation.

It is assumed that the trend exhibited by the 2 m. snow temperatures is in some way related to the lateral air temperature gradients existing in the King Trench. It can be seen that this temperature distribution consists of two inflected segments, the upper being very close to the dry adiabatic lapse rate of 1°C./100 m. and the lower being an inverted lapse rate with a variation of approximately 1.3°C./100 m.
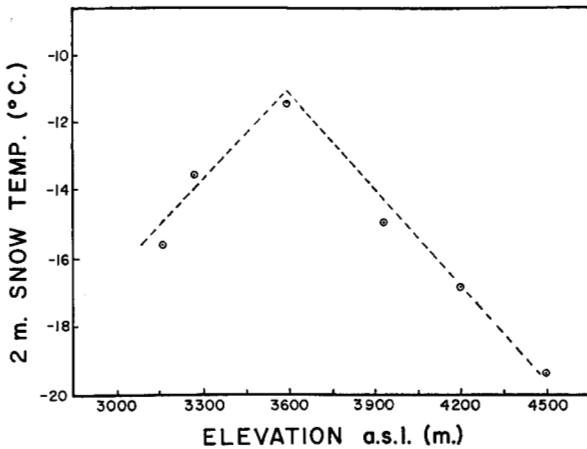
FIG. 4.   Snow temperatures at a depth of 2 metres along the traverse line.

3) Because of its low resistance to wind erosion, the snow surface gives some indication of the relative wind speed at any point along the slope. The existence of sastrugi, hard slab or the exposed edges of individual depositional laminae is interpreted as being indicative of intensive surface-wind scour, whereas a soft, smooth snow surface is assumed to indicate relatively calm conditions. Evidence of surface-wind scour was best developed on, and immediately below, the 2 icefalls in the Trench. Below the upper icefall, in the relatively flat, central portion of the Trench, evidence of surface wind scour died out rapidly down the slope, virtually disappearing within less than 100 vertical metres. The zone of most intense surface-wind scour was in the immediate vicinity of Camp IV (Pit 5) suggesting that the highest, near-surface wind speeds occurred at that point.

4) The variation in average snow density along the traverse route is shown in Fig. 5. While snow density fluctuations may result from the interaction of a complex of environmental influences, it has been suggested (Schytt 1958) that perhaps the most important of these in terms of values measured in the near-surface layers are wind speed and air temperature. Wind may be expected to increase densification by mechanically breaking up the original snow crystals
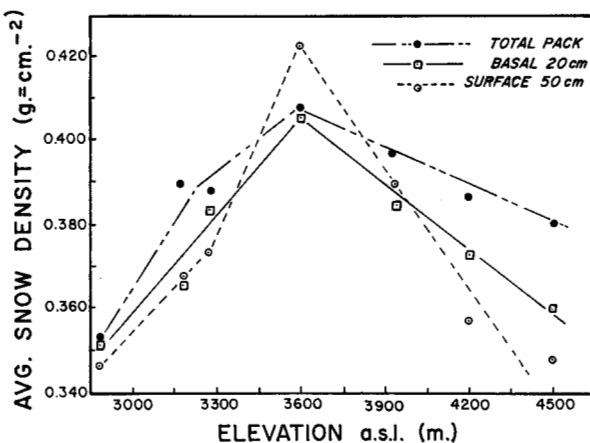

FIG. 5.   Average snow density values for selected snow thicknesses in the 1964-65 winter accumulation layer as a function of pit elevation.

into forms which are more susceptible to close packing. Temperature increases will increase the instability of the initial crystal forms, promoting the formation of a grain with fewer crystallographic faces and greatly decreased area per unit mass (Bader *et al.* 1939; Bader 1962; de Quervain 1945). The third major factor contributing to dry metamorphism is plastic deformation under the load of overlying layers, but this is assumed to occur only at depths greater than 10 m. (Benson 1962), so should not affect the values obtained in this study.

In addition to the average density of the total annual layer, values for a basal layer 20 cm. thick and the upper 50 cm. of the pack at each pit site on the traverse route are also shown in Fig. 5. It is assumed that this basal zone represents some time period at the beginning of the 1964-65 accumulation while the surface 50 cm. represent an event, or events, much closer in time to the study period.

The relationship between average snow density and elevation shown in Fig. 5 has several implications. These may be summarized:

- The trend of density with elevation has not been determined by a single event during the period of deposition but appears to be the result of processes which influence the snowpack more-or-less continuously during accumulation.

- Maximum densities were measured in that part of the King Trench which showed evidence of greatest wind scour and where the warmest 2 m. temperatures were obtained. This lends some credence, however indirect, to the hypothesis relating dry metamorphism of the surface layers to variations in the influence of wind and temperature.

- Snow deposited at or near the beginning of the 1964-65 accumulation season exhibits essentially the same trend as that deposited immediately before the study period, some 8 or 9 months later. This implies that the geographical distribution of the factors influencing snow densification in the King Trench is reasonably constant with time. It should be noted that this latter point requires a much more thorough understanding of the efficiency of the energy transfer process below the level of the surface layers before it can be accepted or rejected.

5) No pits were dug above 4,500 m. The following were noted between this elevation and 6,000 m. during a reconnaissance of the upper portion of the mountain:

- Snow accumulation fell off rapidly above 5,000 m. and on the summit plateau, new snow of any appreciable depth was observed only in sheltered areas. The remaining areas were hard-packed and wind-sculptured.

- The snow plume blowing from the summit ridge of Mount Logan streamed away to the north, indicating that the prevailing winds at an elevation of 6,000 m. were from the south.

- No evidence of riming was seen below 4,500 m. At this elevation it was observed as small "frost feathers" on the tent guy ropes. On the summit ridge, large "mushroom" formations of snow were seen and ascribed to the combined action of rime deposition and wind erosion.

The writers are indebted to P. Lev for the latter observations.

CONCLUSIONS

The primary difficulty in using the annual snow layer as a recording climatological station is our present inability to relate absolutely a single climatic element to a specific snow property. In all probability, this will never be possible on an absolute basis because any one property is affected by several climatic elements. In the case of the Mount Logan data, however, it is believed possible to construct a simple climatological model which will successfully account for the observed variations in stratigraphic parameters.

Snow-covered surfaces are particularly conducive to the formation of strong "inversions" i.e., temperature increasing with height above the surface (Wexler 1936). These are caused by the fact that the snow surface radiates approximately like a black body for all wavelengths in the absence of short-wave solar radiation. The atmosphere radiates with black-body intensity only in certain bands of the spectrum, which are mainly due to water vapour. Also, the air loses energy both upward and downward but the snow surface radiates upward only. As a result of these conditions, the snow surface will be in equilibrium with the air above when its temperature is lower than that of the air. In the high latitudes, it can be expected that this process will be effective even in summer because the sun never rises high above the horizon and much of its short-wave energy is reflected by the snow surface. While snow acts nearly as a black body for terrestrial long wave radiation, it has a high albedo for solar radiation.

The existence of an inversion will develop a very stable stratification of the air in contact with the snow surface which will inhibit vertical mixing because the higher density air layers are closest to the surface. If the slope on which the inversion is forming is sufficiently steep, these denser bottom layers will eventually flow downhill. This will give rise to the katabatic winds which are a common feature of snow-covered slopes (Benson 1962; Geiger 1965). In areas where this katabatic air drainage is impeded by a topographic barrier, the inversion layer will be much more persistent. As the katabatic winds flow down the slope, they will warm at approximately the dry adiabatic rate of 1°C./100 m. Because katabatic winds are flowing primarily in response to gravitational attraction, it can be expected that, in the absence of topographic *funneling,* they will reach their greatest speed on the steepest slopes. Evidence of wind scouring should be most apparent on slopes under the influence of the katabatic air flow and should be largely absent where this movement is absent or greatly restricted, assuming that the slopes are protected from the prevailing winds related to the more general regional circulation.

In the King Trench, all of the stratigraphic observations suggest that the climate on the slopes between 3,500 and 4,500 m. is strongly influenced by persistent katabatic winds. The close agreement of the measured snow-temperature lapse rate to the dry-adiabatic rate, the evidence of surface-wind scour in the lower portion of this region and, indirectly, the gradual decrease in average snow density with increasing elevation all point to katabatic winds as the primary climatological control. Between 3,500 and 3,000 m., on the other hand, the snow temperature lapse rate was inverted, there was little evidence of surface wind erosion and average snow density decreased with decreasing elevation. This is

interpreted as indicating that the inversion layer which forms in this region of the Trench is prevented from flowing downhill, and that a semi-stable inversion develops which controls the climate in the central portion of the Trench. Geiger (1965) refers to the high viscosity of the near-surface air layer and it is assumed that it is this viscosity, together with the virtually level floor of the glacier, that contributes to the formation of an inversion layer at this point. Below 3,000 m., the slope again becomes quite steep, the snowcover of much of the lower icefall is hardpacked and windblown and the limited temperature data indicate that a nearly dry adiabatic lapse rate exists at this elevation. On the basis of these observations, it seems justifiable initially to divide the King Trench region of Mount Logan into 3 climatological sections, the highest and lowest of which are largely the result of normal katabatic wind flow while the intermediate section is characterized by a semi-stable inversion layer resulting from the obstruction of this katabatic drainage; very likely this obstruction is the result of topographic control.

The limited geographical extent of these data does not warrant extensive conclusions concerning the near-surface climate which may be found in other large mountain ranges or even in other parts of the St. Elias Range. However, they do suggest directions for future study of the alpine climate. These are presented here in the form of a tentative hypothesis.

- Topography is perhaps the most important control in determining the areal distribution of near-surface climatic elements in the mountains. While the climate of any mountain range is largely determined by factors related to general atmospheric circulation and geographic location, local variations may be much more accurately inferred from pronounced inflections in slope angle.

- Extrapolation of climatological parameters such as wind speed and air temperature to mountain slopes from nearby valley climatological stations or free-air soundings, as is commonly done, is not a valid approach. This is due to the strong control which is felt to be exerted by the composition and geometry of the surface on the near-surface climate. While the end result is undoubtedly conditioned by free air values, these will be primarily significant in determining the general climatological characteristics of the area in question, which will then be modified to a greater or lesser extent by local surficial properties.

- While much work remains to be done, this study suggests that an analysis of the pertinent stratigraphic parameters of the alpine snow pack, such as density and temperature, may be a useful approach to the study of local mountain climates.

of IRRP; and Messrs. Philip Upton and Jack Wilson who made a total of 10 landings with ski-equipped aircraft on and near Mount Logan in support of the expedition. The authors would like to thank Drs. Arlin Super and Valter Schytt for their useful criticisms of the paper. The writers are, of course, solely responsible for the final form the paper has taken.

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