the road (Figure 1) from where the presently reported form was collected. This suggests that the local depositional environments in which the eleven cycles bearing *Yelma digitata* were deposited were relatively more turbulent than those in other sectors of the Kaladgi Basin. Recent studies[18,19] have indicated that significant rhythmicity, often controlled by synsedimentary basement tectonism has been preserved in the carbonates from the basal sequence of the Bagalkot Group. The presence of the cycles of ministromatolites in the lower beds of the Chitrabhanukot Dolomite near Yargatti further reaffirms this observation.

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ACKNOWLEDGEMENTS. We thank the Director, BSIP, Lucknow and the Head, Department of Geology, University of Pune for permission to undertake the joint study and for the facilities. S. N. and S. P. are grateful to CSIR for support in the form of Senior Research fellowship. Field-travel was partly supported through a UGC Research Scientistship Award to VSK.

Received 1 September 1997; revised accepted 10 November 1997

Downslope soil movement in a periglacial region of Garhwal Himalaya: Rates, processes and climatic significance

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Soil-movement rates, processes and landforms were studied in periglacial zone of Central Crystalline, Garhwal Himalaya. Maximum rates of downslope movement measured in solifluction lobes and terraces range from 3.0 to 4.0 mm/yr. Rates of displacement were strongly influenced by differences in moisture availability and gradient. Three years of study indicate that movement is currently confined to the upper 60 cm of soil. Solifluction is a more effective process in the saturated axial areas of solifluction lobes in wet sites, but is less effective than frost creep at their edges. Solifluction lobes and terraces are the results of intense solifluction beneath a cover of vegetation; they form where downslope movement is impeded, and are normally associated with a decrease in gradient as they occur on concave lower slopes.

IN India, periglacial features are restricted to the Himalayas and the limits of periglacial landscape are from 4700 m.a.s.l to 6000 m.a.s.l, covering an area of about 5% of the total Himalayan area[1]. The snow, ice cover and glaciers in Himalayas have fluctuated between wide limits in the past and this phenomenon is being observed even today. The snow–ice and glacier regime influences the climate of the region and the vegetation cover and landscape features. Above the timber-line is the region of gelifluction lobes with turf-banked fronts and gliding boulders, with shrubs like *Rhododendron, Clematis, Berberis, Hypericum* and *Salix*. Common herbs of this zone are *Thalictrum, Paeonia, Copsella, Viola* and *Spiraea*. Above this is a zone characterized by stone-banked terraces, stone stripes and vegetation, consisting of cushion plants, tussock grasses, tall herbs and many shrubs; higher still is the 'frost-shatter zone' with much bare rock, extensive block fields and patterned ground. In high alpine belt, vegetation grows in patches and on debris. *Corydalis, Sedum, Berginia, Pernassia, Leontopodium, Polygonium, Genm elatum, Iris, Juncus* and *Luzula* are important species of this zone. Stability of the periglacial slopes is controlled mainly by the strength of slope materials. Lobes and terraces are the results of intense solifluction beneath the cover of vegetation. They form where downslope movement is impeded, and are normally associated with decrease in gradient, viz. on concave lower slopes. Much of the

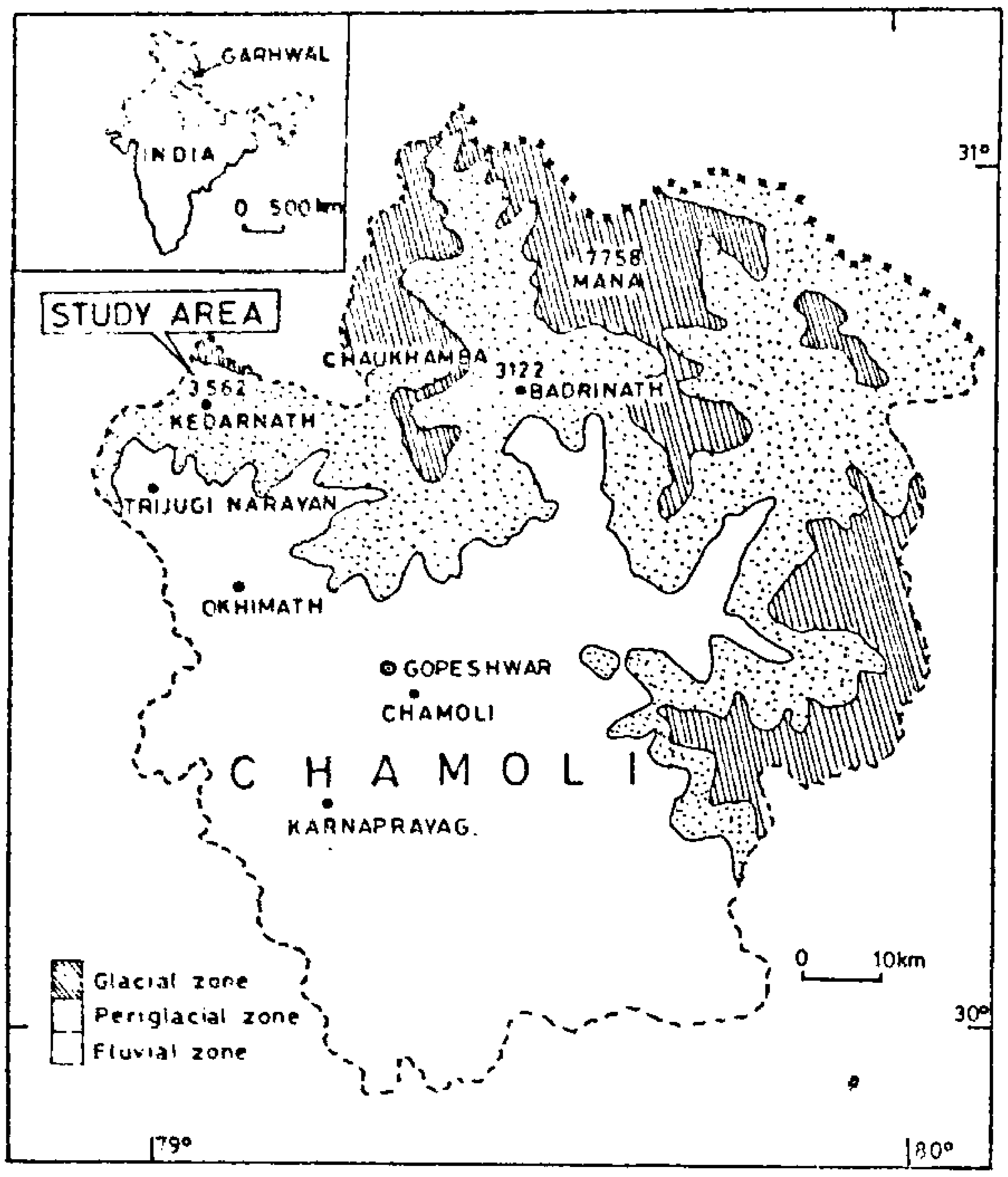

Figure 1. Location map of the study area.

Table 1. Classification of landforms produced by downslope soil movements around Kedarnath area

	No. surface expression	Lobate	Terrace-like	Location
Unsorted	Unsorted sheet	Solifluction lobe	Soil terrace	Around Kedarnath and Vasuki Tal area
Sorted	Blockfield	Stone-banked lobe	Stone-banked terrace	Around Panya Tal and north of Kedarnath

alpine region is saturated during the spring thaw, and significant solifluction occurs only in areas where the water table remains high enough during the fall freeze to permit thick ice-lens development.

The area of investigation is located below the perpetual snow line around Kedarnath (Figure 1), with development of landforms which are the results of polycyclic endogenic and exogenic processes operating with varying intensities through time. The area comes under the Central Crystalline belt of Garhwal Himalaya, mainly comprising folded and faulted, medium- to high-grade metamorphic rocks. The periglacial zone lies at an average elevation of about 2760 m to 4920 m in this region. The total rainfall (average of 1994 to 1996) from May to September is 2150 mm. The mean monthly temperature in open, ranges between 0 and 7°C in May and 8 and 20°C in July. Daily melting of the snow keeps the rocks throughly soaked with water at zero temperature, hence the action of frost is more than usually effective in splitting them into pieces. Several features related to the work of frost, nivation and gelifluction characterize areas of past and present periglacial activity. On a fairly flat ground, patterned ground occurs, while on steeper slopes (36°–45°) of moderate gradient (26°–35°), steps and stripes are observed. Depositional features include protalus ramparts at the foot of relatively steep slopes, and gelifluction terraces below more gently sloping snow patches. Cryoplanation terraces represent the main erosional features, often structurally-controlled whose edges are marked by cliffs and tors.

Most landforms produced by downslope soil movements are polygenetic. In classification of landform, we have adapted a descriptive terminology based on the parameters used by Washburn[2] in his classification of pattern ground. These are surface expression and the presence or absence of sorting (Table 1, Figure 2). The flow-dominated failures are most common and could be classified according to speed of movements and surface forms, into the following three categories[3]; solifluction, skinflows and ground ice slumps.

Solifluction is a slow, downslope movement of saturated, nonfrozen earth material, behaving apparently as a viscous mass, over a surface of frozen material and affecting the whole or a part of active layer[4,5]. Solifluction involves two closely related though distinct processes, gelifluction and frost creep[6].

Gelifluction is described as a downslope flow of saturated soil associated with thawing of frozen ground[7] (Figure 3). Permanently or seasonally frozen subsurface layers prevent downward percolation of moisture. The upper layer affected by seasonal thawing (the 'active layer') becomes soaked with water from melting snow, from melting of any temporary segregations of ice within it or from rainfall. In the study area, the melting of ground ice is the principle source of moisture. The effect of excess water in the active layer is to reduce its shear strength. The shear strength of a material depends on internal friction and cohesion. Soaking of debris with water thus reduces both internal friction and cohesion, and also increases the weight of material. Snow patches resting on the active layer may also contribute to instability by their weight. In the first place, ice layer formation will disrupt frost-susceptible material, forming discontinuities at the ice surface which serves as significant plane of weakness when the ice melts. Secondly, it increases the void ratio and therefore permeability, and in turn reduces cohesion between the particles. These conditions persist during thaw, and allow the material to absorb more water, if it is not already saturated.

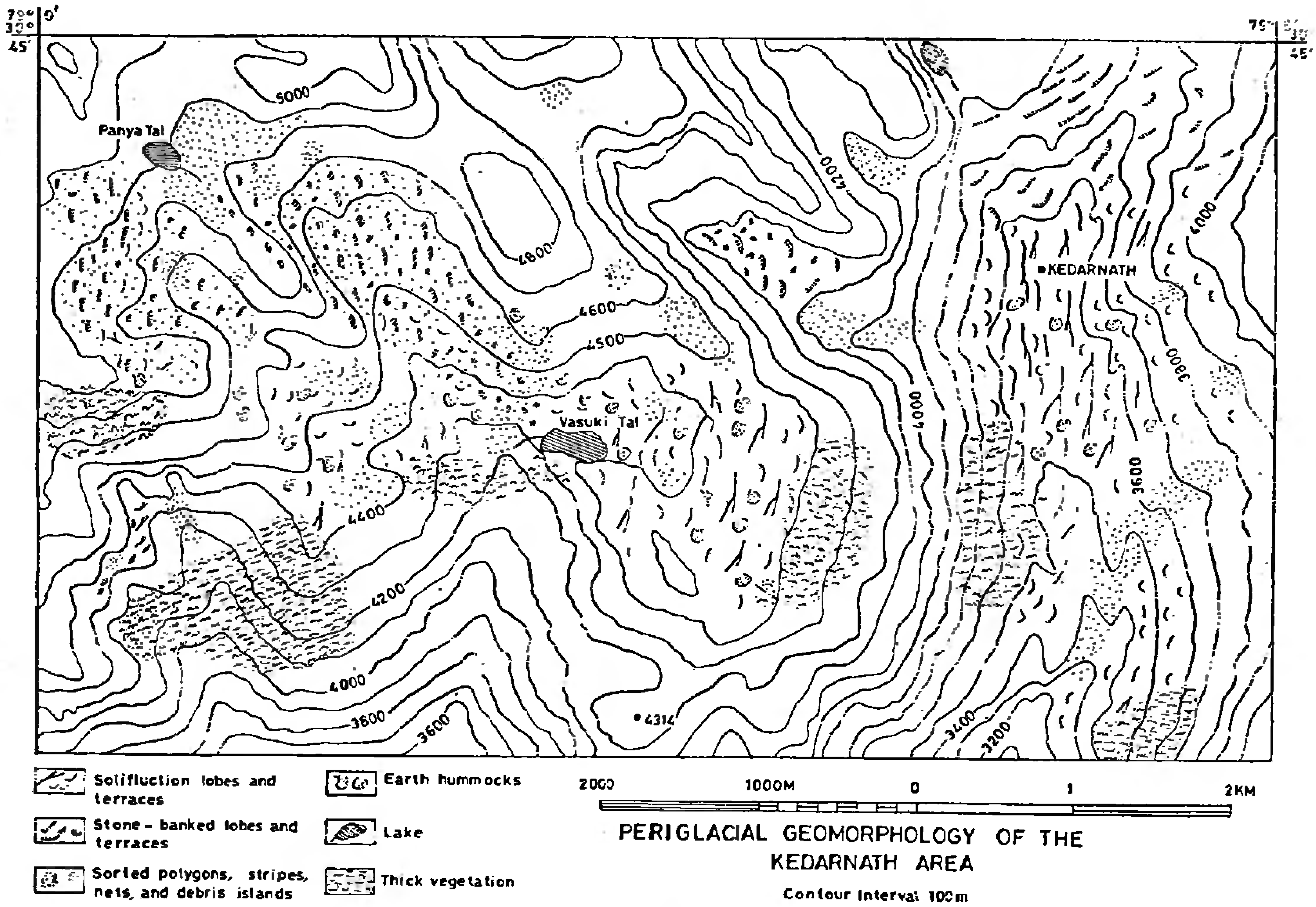

Figure 2. Map showing the periglacial geomorphic features of the study area.

Frost creep may be defined as the ratchet-like downslope movement of particles as a result of frost heaving of the ground and subsequent settling on thaw[8]. Gelifluction and frost creep may occur in areas of frozen ground, seasonal or diurnal[9]. Gelifluction and frost creep on a large scale are more characteristic of areas not experiencing warm summers and where the mean annual air temperature is not higher than 1°C (ref. 10).

In winter, frost heaving normal to the slope is dominant, and during summer, gelifluction gradually takes over and particles move parallel to the surface. October is the month when both gelifluction and frost creep occur, while later in the year frost heaving again becomes dominant, although the movements are slow.

Skinflows, active layer glides[11] or active layer detachment[12] are more rapid failures, involving the detachment of a thin veneer of vegetation and soil which flows or slides down the slope over a frozen subsoil. Skinflows are usually ribbon-like in plan and result from a sudden disturbance of thermal conditions in the active layer due to heavy rainfall (Figure 4), high air temperatures and high day–night temperature fluctuations. Skinflows generally occur on slopes of 25° to 10° gradient.

Ground ice slumps result from rapid thawing of ice-rich permafrost[13]. Basal erosion of valley sides frequently initiates such failures when exposed to ground ice on a scarp and ablates back, releasing sediments as it retreats. The sediment flows and slides to the base of the scarp where it flows away as a mudflow apron or a lobe of much lower gradient.

Figure 3. Gelifluction lobe, associated with thawing of frozen ground. Melting of ground ice is the principle source of moisture.

Stone-banked terraces are defined as terraces or garland-like accumulations of debris overlying a

Figure 4. Active layer detachment on slope side caused by heavy rainfall. On the background of the slope, perpetual snow-line exists.

Figure 5. Periglacial features include stone-banked lobe (occur average 17° slope) (1), solifluction lobes (2), Scree deposits (3), cirque (4), etc. in the Vasuki–Panya Tal area. Altitude approximately 3500–5100 m.

relatively free-moving subsoil. Stone-banked terraces in the study area occupy south and east-facing slopes with an average gradient of 18°. There is a partial overlap between the slope and exposure requirements of solifluction and stone-banked terrace; where both occur on the same slope, the latter commonly overrides the former, suggesting a difference in time or rate of movement. The fronts of stone-banked terraces are lobate, steep and rocky. The material at the rear of the tread is a mixture of soil and rock fragments, covered with vegetation. Fragments of tabular gneisses and blocky granites, amphibolites and quartzites are rock types occurring in stone-banked terraces.

Stone-banked lobes are defined as lobate masses of rocky debris underlain by relatively stone-free, fine-textured, moving soil. Stone-banked lobes occur on south- and east-facing slopes with gradients of 10° to 25° (Figure 5). Stone-banked lobes and terraces frequently occur together in the same area, and many of the terraces have developed on the merger of closely-spaced stone-banked lobes. Stone-banked lobes also occur at the front of isolated 'stone streams' and along the lower margins of scree slopes below persistent snow banks. The treads of stone-banked lobes are composed of rock debris without a visible fine material.

The experimental site is located on the rise of a large and relatively stable solifluction terrace on the right bank of Mandakini (Figures 6 and 7). Its elevation is 3558 m, and slope is towards northeast at 8°. The surface of the slopes southeastward is at an angle of about 8°, steepening near the front, where it bulges outward. Winter snow accumulation is heavy all along this site. The rapid movements on this solifluction terrace, are caused by a small stream that originates on the interconnected borders of sorted polygons over the terrace surface, and it leaves the terrace through a rocky stripe and across this surface. The stream derives its water from melting snow, and ground ice. It flows throughout the warmer months of the year, keeping the central portion of the terraces saturated during the critical spring thaw and fall freeze periods.

Annual rates of movements were measured on solifluction terraces. This study was conducted to evaluate the processes involved in downslope movement, to determine flow pattern, and to measure the differences in movement rates with depth.

Monthly movement recordings were initiated in May 1994, when 16 stone stakes were installed along a theodolite line crossing the axis of terraces. Benchmarks for monitoring consisted of 1.5 m long wooden pegs, cemented in concrete up to a depth of 60 cm and surrounded by coarse sand and gravel. Stakes were inserted to the depths of 30 and 60 cm. Displacement was measured parallel to the ground surface between a reference line drawn on each stake and a vertical straight edge positioned on the theodolite range line. Stakes were monitored between May 1994 and July 1996.

The results of this monitoring are shown in Figure 8. During three recordings, average rate of movements varied from 3 mm/yr at the edge of the terrace, to 40 mm/yr along its axis.The depth of buried stakes becomes progressively shallower as a result of frost heaving. Data from the first year of study indicates greater displacement of 30 cm than of 60 cm stakes. This suggests that the surface soil is moving more rapidly than the soil at depth.

Heaving of stakes relative to the ground surface is proportional to the total thickness of segregated ice lenses in the layer of soil surrounding the stakes[14]. As a result, stakes driven to depths of 60 cm were thrust up further out of the ground than stakes driven to depths of 30 cm.

Data for 1994 to 1996 shows that rates of soil movement increase downslope along the axis of the

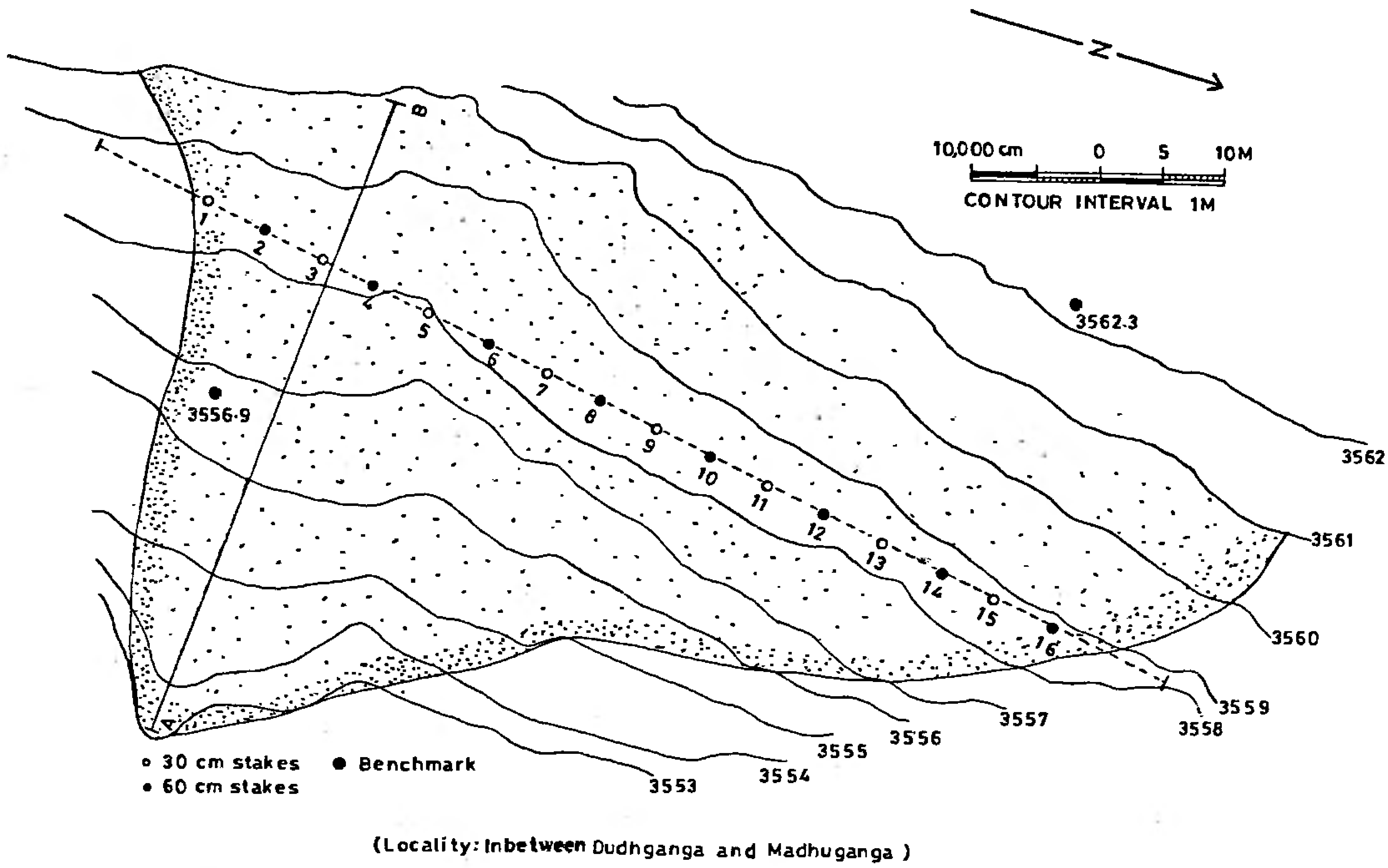

Figure 6. Map showing the positions of movement marker in solifluction terrace.

Figure 7. Measurement of surface soil movement rates (experimental site) on solifluction terrace, on right bank of Mandakini in Kedarnath area. The line of pegs traverses the upper part of the terrace.

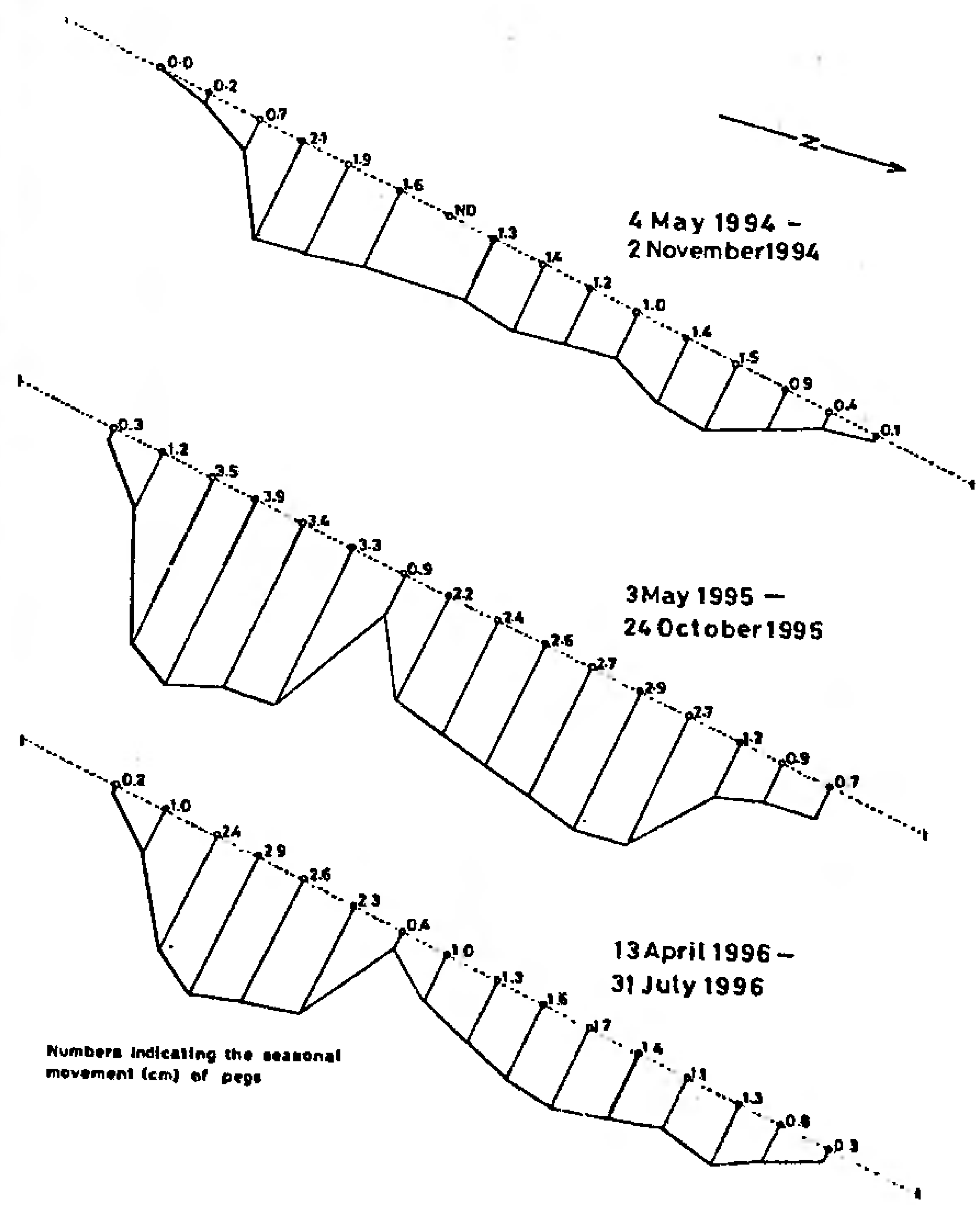

Figure 8. Displacement (cm) of stakes. Black dots represent stakes inserted to a depth of 60 cm, and open circles represent stakes inserted to a depth of 30 cm.

lobe, reaching maximum values a few meters behind the front (Figure 9 *a*). Closer to the front, the lower water table and restraining turf layer cause movement to the retarded.

Direction of soil movements has been inferred from the orientations of plants roots that penetrate deeply into the moving soil and estimated from the positions of plants with respect to their root tips. Additional information was obtained from annual measurements of tilting of movement pegs.

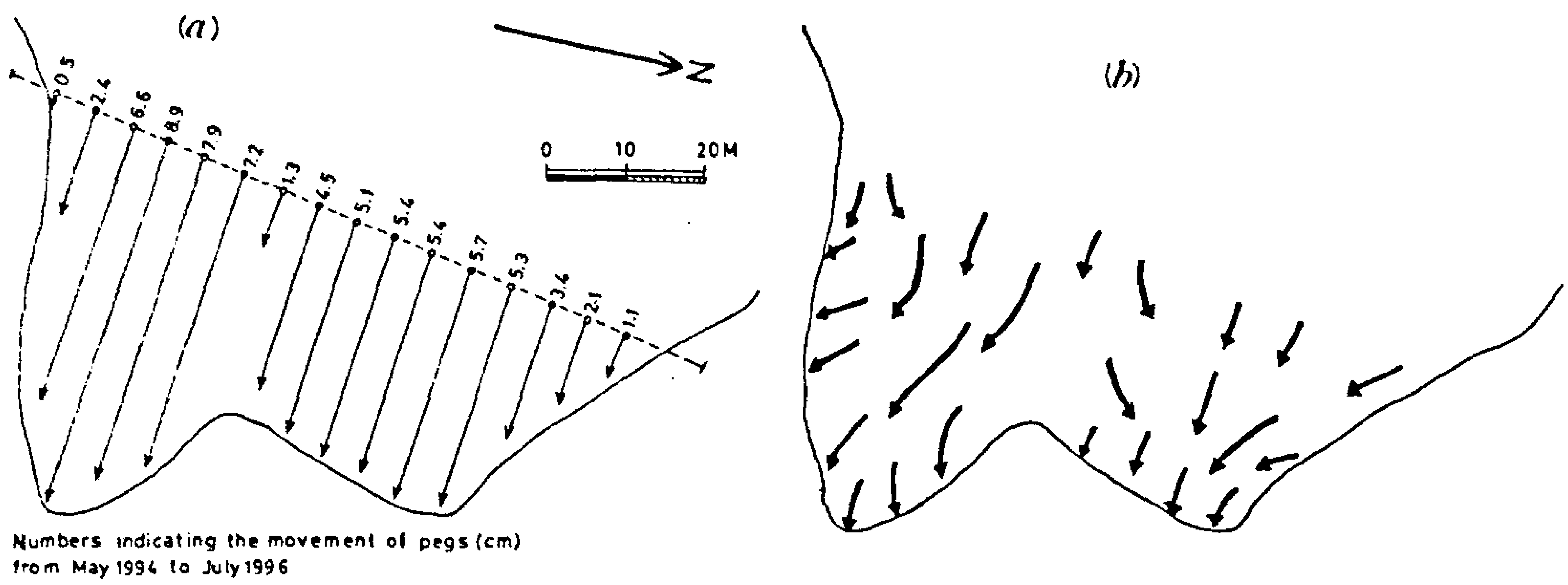

Figure 9. Rates and inferred directions of soil movement. ***a***, Measured rates of movement (cm) are greater along the axis of the lobe; ***b***, Directions of soil movement inferred from the tilting of pegs and the orientations of plants.

Both lines of evidence suggest that movement at the rear of lobe is directed obliquely downslope and towards the axis of the lobe (Figure 9*b*). Nearer the front, directions of movement shift so that the soil is flowing away from the lobe axis. The directions of movement are directly related to variations in velocity; wherever the movement along the axis accelerates, the ground surface subsides and depression develops. Soil moves inwards from the edges of the lobe to replace soil that has moved out of the axial area. Near the front of the lobe, where movement is related, the ground surface bulges upward, creating a local slope away from the axis of the lobe and the soil moves outward in response to this gradient, resulting in maintaining equilibrium surface profile.

A distinctive suite of periglacial mass movement processes may be defined, since all the characteristically associated with the thawing of frozen ground[13]. A periglacial mass movement is associated with the thawing of frozen ground. The initiation of instability and subsequent movement velocities depend more on the ice content of the thawing soil and its rate of thaw than on slope gradients[13]. Since ice contents of frozen material are often extremely high, thawing may lead to the release of a greater volume of water than what can normally be accommodated by the soil pore space. Under these circumstances, slope failures are likely even over very gentle slopes.

The presence of frozen subsoil (at depth 60 cm) results in the mass movements described as solifluction and skinflow, and ground ice slump appears to be largely translational rather than rotational in character. However, some deep-seated rotational slides also occur through frozen ground, and the base of such failures generally pass through underlying unfrozen material[15]. Four factors may be cited as being of particular significance in affecting the amount of ice segregation during soil freezing: (i) the pore spaces of the soil, (ii) the moisture supply, (iii) the rate of heat extraction and (iv) the confining pressure. It appears that the susceptibility of a soil to ice segregation increases as pore space decreases. The rate of heat extraction is a major factor in controlling the rate of penetration of the freezing front. This in turn is directly related to the rate of frost heaving and is inversely related to the heaving ratio (heave per unit depth). The high freezing rates reduce the time available for water migration to the freezing front, so that the extent of heaving is reduced, resulting simply from freezing of *in-situ* pore water[16–18]. The reduction in frost heave results from increasing confining pressure.

In the study area, solifluction takes place mainly during late summer at the time of the maximum thaw penetration. The most recent slides may be because of high-pore water pressure due to the thaw consolidation in an active layer over permafrost. Year-to-year variation in movement rates as a factor of 8, with high values in years with little snow, deep freezing of soil, early clearance of snow in spring, and subsequent thawing from surface. Low-movement rates resulted from high snowfall, shallow freezing, and late clearance of snow resulting in thawing of the frozen soil largely from the bottom upwards.

Gelifluction and frost creep may affect a wide range of material, ranging from alluvial silts and clays, and the diamictons of glacial or periglacial origin, to scree. The talus shift involves creep movements of individual scree fragments due to disturbances by such agencies as rockfall, needle ice, localized sliding, etc.[19,20], and affects the slopes close to their angle of repose. On gentler periglacial slopes, residual soils and till often suffer frost sorting which brings coarser material to the surface, leaving finest at depth[21]. This fine-grained substrate may well be frost susceptible, leading to frost heaving in winter and solifluction during summer thaw. The sorted stripes, stone-banked lobes on steeper slopes, shallow lobate slides, represent the morphological expression of downslope movements.

Solifluction terraces in the study area occupy slopes of 3° to 18°, with an average gradient of 10°. The terraces are largely restricted to east- and west-facing slopes, where moisture is abundant and evenly distributed along the contour and where the deposition of windblown soil (loess) eroded from exposed west-facing slopes.

Wherever the winter snow accumulation is thick, sorting processes are ineffective, and solifluction terraces are covered with dense vegetation. On the other hand where the winter snow is shallow, the moist treads of the terraces show effects of intense frost activity. Elsewhere in the study area, sorted polygons, 3 to 10 m in diameter, occur near the front of terraces at the northwestern end of Vasuki Tal area. Small active polygons, 1 to 4 m in diameter, occupy the floor of shallow ponds on terrace treads. Most of such ponds are irregularly shaped, but some are elongated parallel to the prevailing wind direction. Hummocks occur where winter snow is thick enough to provide protection from wind erosion, but thin enough (generally 10–50 cm) to permit deep frost penetration. At less protected sites, the hummocks are replaced by frost boils, which form narrow, relatively snow-free zones over the rise of the terraces. Parallelling fronts of the terraces, and associated with frost boils, are tension cracks caused by differential heaving.

The above discussion has shown that the most important aspect of periglacial slopes formed in unconsolidated soils is the presence of ice-rich frozen ground. Thawing of such frozen ground is liable to release excess water and promote significant loss of strength in the newly-thawed soil as normal stresses are transferred to the pore water during consolidation. Mass movements on very gentle slopes may result. Solifluction represents the annual, widespread, slow, mass movement of the active layer during thaw. Sporadic localized failures producing rapid flows and slides are generally superimposed on slopes suffering some degree of solifluction. They usually result from accelerated thawing initiated by such events as abnormally high temperatures or high rainfall.

Downslope movements in the Kedarnath area reflect the difference in gradient and availability of autumn moisture. Since the gradient has remained virtually constant through time, periods of rapid downslope movements are inferred to have been at times when moisture was in plenty at the beginning of freezing.

Soil-moisture distribution is intimately related to the availability of snow during winter seasons.

The relative importance of frost creep and solifluction varies with the moisture content of soil. Frost creep is generally associated with upper slope, and solifluction with lower slope positions. The line separating the zone dominated by each of these two processes shifts upward and downward with changes in climate. During late Pleistocene, solifluction was the dominant movement process whereas under present-day climate, solifluction occurs only in specialized, saturated microenvironment. Frost creep is the dominant movement process now on upper, middle and lower slopes.

Sorted landforms, characteristic of frost creep are often superimposed upon landforms of solifluction. The occurrence of sorted polygons and stripes, stone-banked lobes, and stone-banked terraces on the treads of turf-banked lobes and terraces, reflects a general decline in the availability of moisture.

Three main processes of periglacial downslope movement are identified, namely solifluction (including gelifluction and frost creep), skinflow and ground ice slumps. In case of gelifluction, the excess of water reduces shear strength of the material, and relatively rapid movements may result if vegetation is unable to prevent them. While in the case of frost creep, frost-heave produces planes of weakness within the material and reduces cohesion between the particles. Gelifluction and related deposits show evidence of flow orientation and sorted structures caused by movements. Stone-banked, solifluction lobes and terraces are common morphological features which result from differential rates of movement over slope of 5°–25°. Skinflows are resulted from a sudden disturbance of thermal conditions in the active layer, while the ground ice slumps results from rapid thawing of ice-rich permafrost. Experimental results show that the soil movement has varied from 3 mm/yr at the edge of the terraces, to 40 mm/yr along its axis. Data from the first year of study indicates greater displacement of 30 cm of 60 cm stakes and suggests that the surface soil is moving more rapidly than at depth.

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ACKNOWLEDGEMENT. A. K. N. thanks the CSIR for generous financial support.

Received 19 April 1997; revised accepted 20 October 1997

MEETINGS/SYMPOSIA/SEMINARS

National Seminar on Plant Biotechnology for Sustainable Hill Agriculture

Date: 6–8 May 1998
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Sessions on the following themes will be organized during the conference: Air pollution and its impact on human respiratory/cardiac/CNS systems, water pollution and its impact on human health issues, noise pollution and its impact on human health, soil pollution and solid waste management.

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Fourth International Conference on Vibration Problems

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Place: Calcutta

Topics include: Nonlinear dynamic analysis of structures; vibrations of beams, plates and shells, vibration due to thermal and mechanical loading, shock-induced vibrations, random vibrations, buckling and post-buckling behaviour, etc.

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