Biuletyn Peryglacjalny, no. 39, 2000

C. G. WOUDSMA*, J. F. N. JENSEN*, S. A. HARRIS*
Calgary

MODELLING PERMAFROST DISTRIBUTION IN THE CANADIAN ROCKY MOUNTAINS: A GIS-BASED APPROACH

Abstract

The vastness in size of permafrost regions in North America, together with the country's harsh climates and rugged terrain, present considerable problems for determining permafrost distribution. Direct methods for determining distribution are expensive and time consuming, so there is a need for indirect methods of prediction.

This study addresses the problem of predicting permafrost distribution. It represents a preliminary effort to develop an indirect method of predicting permafrost distribution in a mountainous region of Western Canada. The study area is Plateau Mountain, which is located about 80 km southwest of Calgary, Alberta, Canada in the outer ranges of the Rocky Mountains.

The problem is addressed by using spatial analysis conducted within the geographical information system ARC/INFO. Specific criteria used to predict the probable location of permafrost are primarily derived from 1) a digital elevation model of Plateau Mountain and 2) a landcover classification. The results of the analysis are tested against known locations of permafrost to establish accuracy of the methodology. Results suggest 70% accuracy. This study is the impetus for further development of the methodology to predict permafrost distribution in Jasper National Park, Alberta, Canada – a project currently in progress.

INTRODUCTION

Predicting permafrost distribution in mountainous regions is a task of both commercial and academic interest. Commercial developments in areas underlain by permafrost require specialized planning and use of construction techniques that are designed to cope with the delicate thermodynamic regime associated with permafrost (HARRIS, 1986; HAEBERLI, 1992). Proper identification of the distribution of permafrost is important for hazard assessment and to minimize construction costs and environmental impacts. Methodologies (e.g., HAEBERLI, 1973, 1975; HARRIS, 1981, 1995; JORGENSON, KREIG, 1988; KELLER, 1992; KING, *et al.*, 1992; HOELZLE, *et al.*, 1993; HOELZLE, M. 1996; FRAUENFELDER, *et al.*, 1998) developed for the prediction of permafrost can also be adapted for use with a variety of

* Department of Geography, University of Calgary, 25000 University Drive N.W., Calgary, Alberta, Canada T2N IN4.

research topics such as geomorphology, environmental modeling and vegetation studies (e.g., FRANKLIN, 1995).

The 1990s have seen a move towards the use of computers as a tool to solve the problem of predicting permafrost distribution. Considerable modelling of permafrost distribution has been carried out in the Swiss Alps. KELLER (1992) developed a method to predict the distribution of mountain permafrost there, using the application PERMAKART. PERMAKART, an executable program for use in the geographical system ARC/INFO, applies an empirical model of permafrost distribution based on a relationship between slope, aspect and altitude to a digital terrain model (FRAUENFELDER, *et al.*, 1998). HOELZLE (1994 as cited in FRAUENFELDER, *et al.*, 1998) developed the model PERMAMAP in ARC/INFO. In PERMAMAP, the spatial relation between BTS measurements, mean annual air temperature, and potential direct solar radiation is used to derive permafrost distribution. FRAUENFELDER (1997, as cited in FRAUENFELDER, *et al.*, 1998) developed a model PERMAMOD based on field data from the Swiss Alps and a set of permafrost rules of thumb (HAEBERLI, 1975; HAEBERLI, *et al.*, 1996). The model joins topo-climatic information with bio-geographical data and other permafrost indicators to derive permafrost distribution. FRAUENFELDER, *et al.* (1998) evaluated the three models against empirical field data. They found that PERMAKART and PERMAMAP correspond well at high altitudes, but with diminishing accuracy towards lower altitudes. PERMAMOD appeared to show the most accurate estimation of permafrost distribution, but concern was expressed that combining different approaches in one model may result in the loss of independent variables. Loss of independent variables is an issue in model calibration.

Computer modelling of alpine permafrost distribution outside of Europe (e.g., JORGENSON, KREIG, 1988; GRANBERG, 1989; PEDDLE, FRANKLIN, 1992, 1993; LI, CHENG, 1999) began earlier, but appears to be somewhat less prolific. This may partly be due to a paucity of detailed data about regional permafrost features and landforms in comparison to data compiled for Europe – especially for the Swiss Alps.

BTS (bottom snow temperatures) measurement is another method widely used in Europe to establish the presence of permafrost (HAEBERLI, 1973, HOELZLE, *et al.*, 1993), but the mean winter snow cover of 50–60 cm is too shallow for the method to be widely used in western Canada (c.f., KING, 1983). The method is labour intensive and only suitable for use in small areas, whereas Canada is vast.

A need has been expressed for the development of an indirect method to predict permafrost distribution in the mountainous regions of western North America. HARRIS (1981) indicates that a reconnaissance tool capable of predicting permafrost distribution would help focus fieldwork and equipment more effectively and efficiently. The vastness in size of North

American permafrost regions, together with harsh climates and rugged terrain, present considerable problems for determining distribution. Direct methods (see e.g., KING, *et al.*, 1992) for determining permafrost distribution are expensive and time-consuming, so there is a practical application for indirect methods of prediction (HARRIS, 1983). PEDDLE and FRANKLIN (1992, 1993) have developed software for evidential classification of landcover and permafrost in mountainous terrain in the southwest Yukon Territory, Canada, using remote sensing imagery, but there is still room for more work in computer modelling of permafrost distribution in the Rocky Mountains.

This paper presents a preliminary effort to develop methodology to predict permafrost distribution in a mountainous region of Western Canada. This will form the basis for a more extensive project currently being undertaken in Jasper National Park, Alberta, Canada.

STUDY AREA

The study area is Plateau Mountain (Fig. 1), located about 80 km southwest of Calgary, Alberta, Canada in the outer ranges of the Rocky Mountains (50°13'N and 114°31'W). It has been extensively studied over the past two decades (e.g. HARRIS, BROWN, 1978; HARRIS, 1997) and the availability of a considerable amount of field data makes it an ideal choice for a study area.

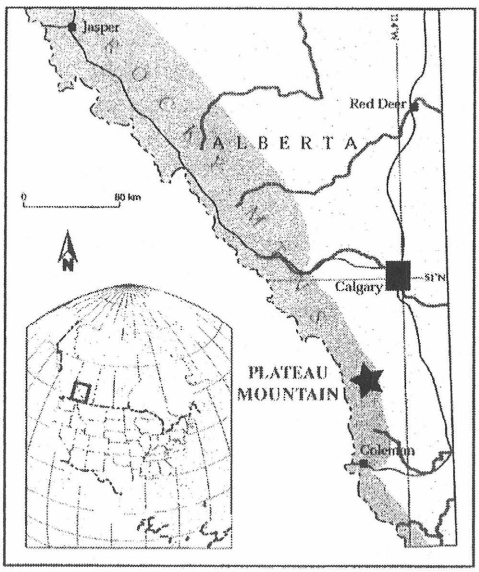

Fig. 1. Location of Plateau Mountain in southwest Alberta, Canada

The mountain has a flat top approximately 13 km^2 in size and a maximum elevation of 2519 m. Plateau Mountain is formed from the core of an anticline tilted downwards towards the north and west (HARRIS, 1997). Typical landcover includes forest below the treeline and grassy alpine meadow at higher elevations. Treeline averages 2290 m in elevation on the west side (BRYANT, SCHEINBERG, 1970 as cited in HARRIS, 1997). Vegetated areas are broken up by the presence of block slopes, which surround much of the mountain.

Plateau Mountain lies in the rain shadow east of the Continental Divide. Most snowfall received generally blows off the exposed top and accumulates in forested areas and in cirques on the southern and eastern sides of the mountain. Mean winter snow cover is 12 cm on exposed sites and approximately 95 cm in the adjacent forest. Mean annual air temperature (1974–1995) at 2500 m is –2.22°C (HARRIS, 1997).

METHODS AND ANALYSIS

The problem of predicting permafrost distribution on Plateau Mountain is addressed using spatial analysis conducted within the geographical information system ARC/INFO. Criteria specifically related to Plateau Mountain were established to identify potential locations of permafrost in the study area. The criteria were then applied to landscape data and a digital elevation model of Plateau Mountain. Landscape data was acquired from the ALBERTA VEGETATION INVENTORY (1991), a comprehensive landcover database for the province of Alberta. A digital elevation model with a 20 m grid was interpolated from a topographic map of Plateau Mountain. Spatial analysis consisted of 1) isolating areas that met the criteria, and 2) combining individual outputs using overlay procedures to produce a prediction of permafrost distribution in the study area. The criteria were applied to landscape data and the digital elevation model as summarized briefly in the following illustrations.

Normally, timberline acts as the lower limit of widespread permafrost in rock or soil (e.g., GRAY, BROWN, 1982; HARRIS, 1982; HAEBERLI, *et al.*, 1996; HOELZLE, 1996; FRAUENFELDER, *et al.*, 1998). GRAY and BROWN (1982) suggest that treeline may provide a reliable index for regional mapping of permafrost in place of altitudinally derived temperature isotherms. Adiabatic lapse rates would be a preferred method to derive temperature isotherms on Plateau Mountain. HARRIS (e.g., 1995) has done considerable work with adiabatic lapse rates and freeze/thaw indices, but the data are insufficient to permit the derivation of at least four different lapse rates, one for each of the four principle aspects. An empirical model of permafrost distribution used by KELLER (1992) received consideration; however, climatic differences between the Swiss Alps and the western

Canadian Rockies (HARRIS, 1995) raise concerns about the model's transferability. Treeline (Fig. 2) was established using aerial photographs and overlay analysis of elevation, aspect and landcover.

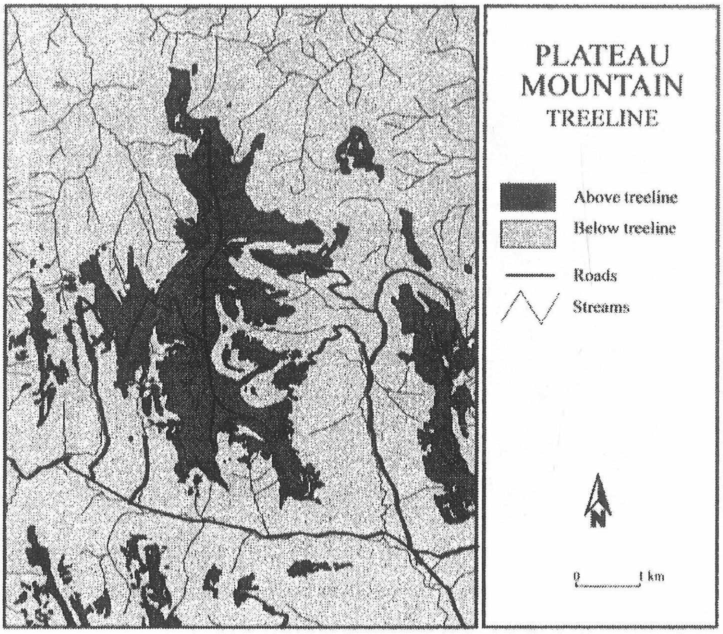

Fig. 2. Treeline, Plateau Mountain

The probability of occurrence of permafrost in areas of well-developed vegetation is under 25%, but increases to above 75% in unvegetated areas covered with debris (HAEBERLI, 1975; HOELZLE, *et al.*, 1993; HOELZLE, 1996). This characteristic of permafrost distribution is supported by HARRIS and PRICK (1997) and HARRIS and PEDERSEN (1998), who find that annual ground temperatures are 4–7°C cooler in coarse blocky material on Plateau Mountain than in adjacent mineral soils. This condition provides one explanation as to why isolated zones of permafrost can occur below treeline. Plateau Mountain is characterized by grassy alpine meadow above treeline in the lower part of the alpine zone, grading into lichen-covered rocks on the flat summit (HARRIS, 1997). The mountain is also surrounded by block slopes, which extend down below treeline. A landcover classification was derived based on SQL query of the Alberta Forestry Vegetation Inventory database (1991) (Fig. 3).

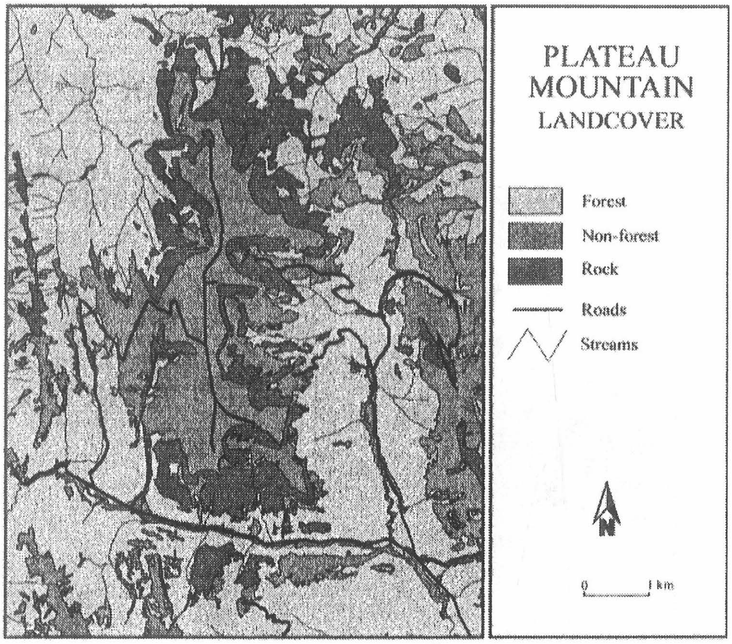

Fig. 3. Landcover classification, Plateau Mountain

Permafrost should be expected in areas with perennial or persistent snow deposits (Fig. 4). Winter snow covers over 50 cm thick have the effect of inhibiting frost penetration (HARRIS, BROWN, 1978) and favour higher sub-nival winter temperatures. However, persistent snow cover prevents the penetration of heat during the thawing season (HAEBERLI, 1978; GOODRICH, 1982; GRAY, BROWN, 1982). Most snowfall received on Plateau Mountain generally blows off the exposed top, accumulating in forested areas and in cirques on the southern and eastern sides of the mountain. Mean winter snow cover is 12 cm on exposed sites and approximately 95 cm in adjacent forest (HARRIS and PRICK, 1997). A classification of persistent snow cover was derived based on SQL query of the Alberta Forestry Vegetation Inventory database (1991), classification of Landsat imagery, examination of aerial photography, and analysis of a DEM for concavity, slope and aspect (Fig. 4).

Extremely shaded debris has a propensity to contain permafrost (HAEBERLI, 1978). Conditions of extreme shade may cause permafrost occurrences at altitudes where mean annual air temperatures exceed 0°C (e.g., PANCZA, 1989 as cited in HAEBERLI, *et al.*, 1993). The degree of sun/shade experienced by a surface element was calculated for the entire

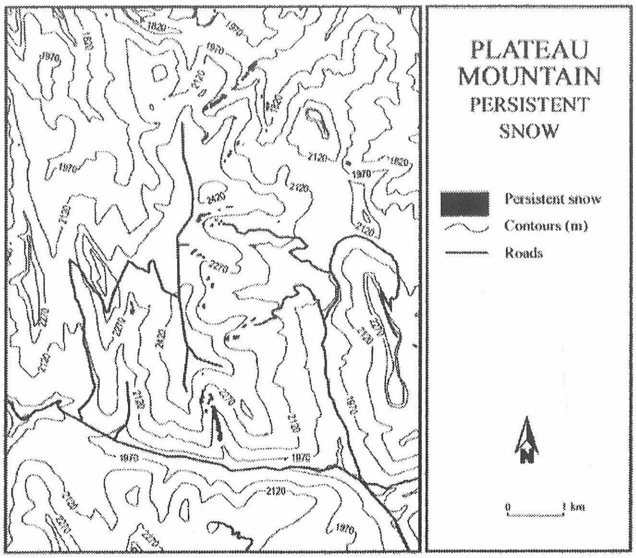

Fig. 4. Persistent snow classification, Plateau Mountain

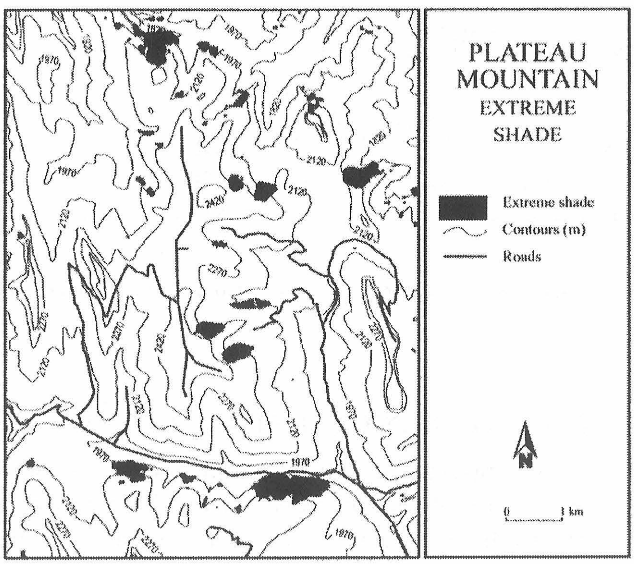

Fig. 5. Areas of extreme shade, Plateau Mountain

study area on the basis of a digital elevation model utilizing hillshade analysis and with tabular input of positive solar altitude and azimuth for 50°N latitude as the light source (Fig. 5). This output was further adjusted using overlay procedures to isolate extremely shaded debris (Fig. 6). The adjustment was made to reflect the results of colder ground temperatures in block slopes noted by HARRIS and PRICK (1997) and HARRIS and PEDERSEN (1998). They also indicate that typical slopes of block fields are approximately 30°, while steeper slopes tend to be solid rock.

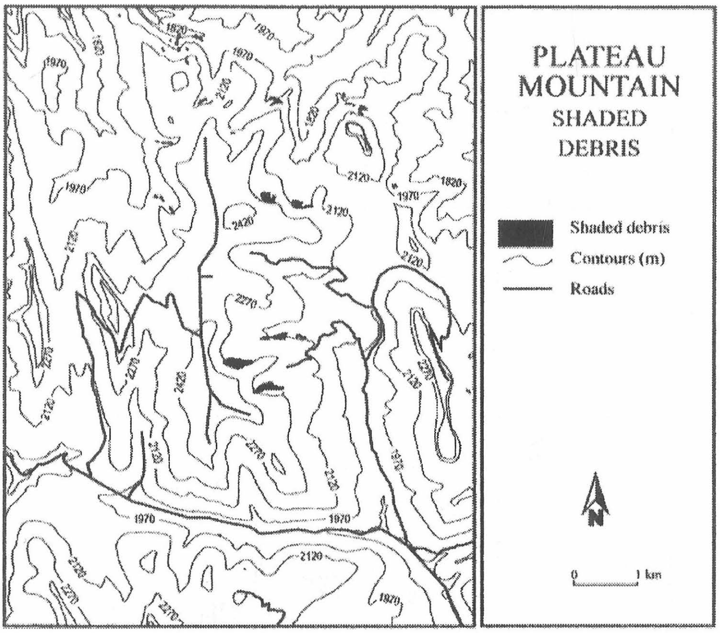

Fig. 6. Extremely shaded debris filtered to reflect block fields, Plateau Mountain

APPLICATION TO THE OCCURRENCE OF PERMAFROST

The results of the analyses briefly summarized above were integrated to establish a binary prediction of permafrost distribution in the study area (Fig. 7). The predicted distribution was compared to known points identifying permafrost presence or absence on Plateau Mountain as well as with other information about permafrost distribution in the study area (e.g., HARRIS, BROWN, 1978; HARRIS, 1997) in order to arrive at a measure of accuracy (Fig. 8). 70% of the known points were correctly identified using the GIS methodology. Overall, the prediction indicates that permafrost underlies 2,113 hectares (20%) of the study area. A total of 49 hectares (2%) of the predicted permafrost lies as isolated bodies in debris below the treeline.

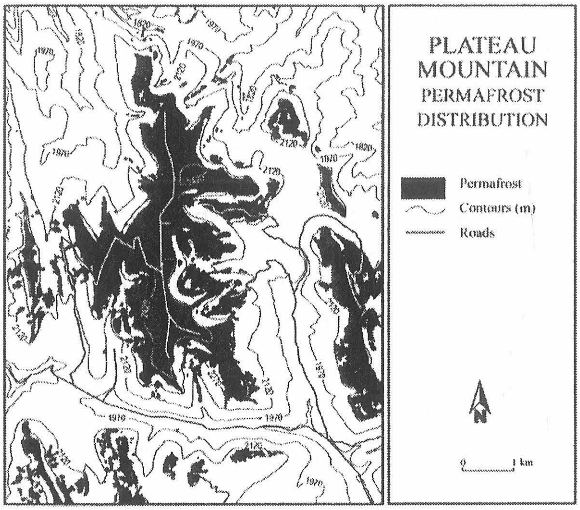

Fig. 7. Total permafrost distribution, Plateau Mountain

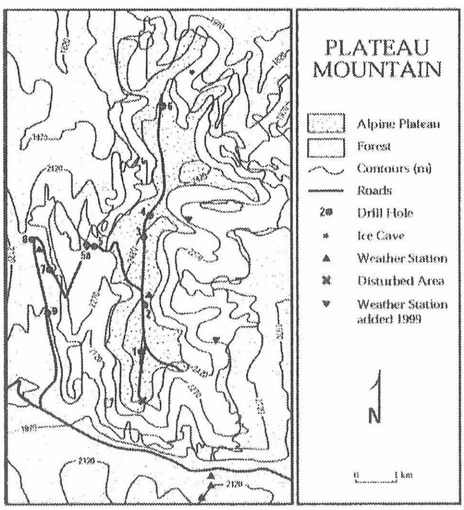

Fig. 8. Location of ground temperature cables and weather stations on Plateau Mountain (modified from HARRIS and BROWN)

CONCLUSION

Research interests and commercial developments are creating a demand for information about the distribution of alpine permafrost. The vastness in size of mountainous regions, together with their harsh climates and rugged terrain, pose numerous problems for determining distribution. Direct methods for determining permafrost distribution are expensive and time-consuming, so there is a need to develop indirect methods.

Considerable work has been carried out in the Swiss Alps to address this problem, but there is still a need for more work in the western Canadian Rocky Mountains. In this preliminary study, we used spatial analysis within the geographical information system ARC/INFO to arrive at a prediction of a permafrost distribution of 2,113 hectares on Plateau Mountain, Alberta, Canada (see Fig. 7). Based on specific criteria describing the probable location of permafrost, which were primarily derived from a digital elevation model and a landcover classification, we were able to predict the probable location of permafrost with a 70% accuracy. We were also successful in identifying a number of isolated permafrost bodies in debris below the treeline.

This study will form the basis for a more extensive study currently being undertaken in Jasper National Park, Alberta, Canada.

References

Alberta Forestry, Lands and Wildlife Land Information Services Division, Resource Information Branch, 1991 – Alberta Vegetation Inventory Standards Manual, version 2.1.

Franklin, J., 1995 – Predictive vegetation mapping: geographic modeling of biospatial patterns in relation to environmental gradients. *Progress in Physical Geography,* 19; p. 474–499.

Frauenfelder, R., Allgower, B., Haeberli, W., Hoelzle, M., 1998 – Permafrost investigations with GIS – a case study in the Fletchhorn area, Wallis, Swiss Alps. *Proceedings of the 7th International Conference on Permafrost,* Yellowknife, NWT, Canada; p. 291–295.

Granberg, H. B., 1989 – Permafrost mapping at Schefferville, Québec. *Physical Geography,* 10; p. 249–269.

Gray, J. T., Brown, R. J. E., 1981 – The influence of terrain factors on the distribution of permafrost bodies in the Chic-Choc Mountains, Gaspésie, Québec. *Proceedings Fourth Canadian Permafrost Conference,* Ottawa: National Research Council of Canada, The Roger J. E. Brown Memorial Volume; p. 23–35.

Goodrich, L. E., 1982 – The influence of snow cover on the ground thermal regime. *Can. Geotech J.*, 19; p. 421–432.

Haeberli, W., 1973 – Die Basis-Temperatur der winterlichen Schneedecke als möglicher Indikator für die Verbreitung von Permafrost in den Alpen. *Zeitschrift für Gletscherkunde und Glazialgeologie*, IX (1–2); p. 221–227.

Haeberli, W. 1975 – Untersuchungen zur Verbreitung von Permafrost zwischen Flüelapass und Piz Grialetsch (Graubünden). *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich,* 17; p. 221.

Haeberli, W., 1978 – Special aspects of high mountain permafrost methodology and zonation in the Alps. *Proceedings of the Third International Conference on Permafrost,* NRC – Ottawa, vol. 1; p. 378–384.

Haeberli, W., 1992 – Construction, environmental problems and natural hazards in periglacial mountain belts. *Permafrost and Periglacial Processes,* 3; p. 111–124.

Haeberli, W., Cheng, G., Gorbunov, A. P., Harris, S. A., 1993 – Mountain permafrost and climatic change. *Permafrost and Periglacial Processes,* 4; p. 165–174.

Haeberli, W., Hoelzle, M., Dousse, J. P., Ehrler, C., Gardaz, J. M., Imhof, M., Keller, F., Kunz, P., Lugon, R., Reynard, E., 1996 – Simulation der Permafrostverbreitung in den Alpen mit geographischen Informationssystemen. Arbeitsbericht im Rahmen des Nationalen Forschungsprogrammes NRP31 "Klimaänderungen und Naturkatastrophen"; p. 58.

Harris, S. A., 1981 – Climatic relationships of permafrost zones in areas of low winter snow-cover. *Arctic,* 34; p. 64–70.

Harris, S. A., 1982 – Permafrost distribution along the Rocky Mountains in Alberta. *Proceedings of the Fourth International Conference on Permafrost,* Alaska, Washington, D.C.: National Academy Press; p. 59–67.

Harris, S. A., 1983 – Comparison of the climatic and geomorphic methods of predicting permafrost distribution in western Yukon Territory. *Proceedings of the Fourth International Conference on Permafrost,* Alaska, Washington, D.C.: National Academy Press; p. 450–55.

Harris, S. A., 1986 – The permafrost environment. London & Sydney: Croom Helm; p. 74–218.

Harris, S. A., 1995 – Temperature conditions in permafrost areas of the mountains of southwestern Alberta and the European Alps. *Ztschr. f. Geomorph. N.F.,* 39 (2); p. 211–235.

Harris, S. A., 1997 – Relict late quaternary permafrost on a former Nunatak at Plateau Mountain, S.W. Alberta, Canada. *Biuletyn Peryglacjalny,* 36; p. 47–72.

Harris, S. A., Brown, R. J. E., 1978 – Plateau Mountain: a case study of alpine permafrost in the Canadian Rocky Mountains. *Proceedings of the Third International Conference on Permafrost,* Ottawa: National Research Council of Canada, 1; p. 386–91.

Harris, S. A., Prick, A., 1997 – The periglacial environment of Plateau Mountain: overview of current periglacial research. *Polar Geography,* 21; p. 113–136.

Harris, S. A., Pedersen, D. E., 1998 – Thermal regimes beneath coarse blocky materials. *Permafrost and Periglacial Processes,* 9; p. 107–120.

Hoelzle, M., 1996 – Mapping and modelling of mountain permafrost distribution in the Alps. *Norsk Geografisk Tidsskrift,* 50; p. 11–15.

Hoelzle, M., Haeberli, W., Keller, F., 1993 – Application of BTS-measurements for modelling mountain permafrost distribution. *Proceedings of the 6th International Conference on Permafrost,* Beijing, S. China, University of Technology Press; p. 272–277.

Jorgenson, M. T., Kreig, R. A., 1988 – A model for mapping permafrost distribution based on landscape component maps and climatic variables. *Proceedings of the 5th International Conference on Permafrost,* Trondheim, 1; p. 176–182.

Keller, F., 1992 – Automated mapping of mountain permafrost using the program PERMAKART within the Geographical Information System ARC/INFO. *Permafrost and Periglacial Processes,* 3; p. 133–138.

King, L., 1983 – High mountain permafrost in Scandinavia. *Proceedings of the 4th International Conference on Permafrost*, Alaska, Washington D.C.: National Academy Press; p. 612–617.

King, L., Gorbunov, A. P., Evin, M., 1992 – Prospecting and mapping of mountain permafrost and associated phenomena. *Permafrost and Periglacial Processes,* 3; p. 73–81.

Li, X., Cheng, G., 1999 – GIS-aided response model of high-altitude permafrost to global change. *Science in China Series D: Earth Sciences*, 42; p. 71–79.

Peddle, D. R., Franklin, S. E., 1992 – Multisource evidential classification of surface cover and frozen ground. *Int. J. Remote Sensing*, 13; p. 3375–3380.

Peddle, D. R., Franklin, S. E., 1993 – Classification of permafrost active layer depth from remotely sensed and topographic evidence. *Remote Sens. Eviron.*, 44; p. 67–80.