ICE CAVES AND PERMAFROST ZONES IN SOUTHWEST ALBERTA

With 11 figures

STUART A. HARRIS

Zusammenfassung: Eishöhlen und Permafrost in Südwest-Alberta

Drei Typen von Eishöhlen kommen in Südwest-Alberta vor. Plateauberg-Eishöhlen sind für die Art typisch, die unmittelbar unterhalb der Zone ständigen Permafrostes gebildet werden, wo sich Eis an den Wänden aufgrund zurückgezogenen Permafrostes in Felsen bildet. Canyon-Creek-Eishöhlen sind charakteristisch für den zweiten Typ, der durch kalte Luft entsteht, die durch große Höhlen mit vielen Eingängen strömt. Das Klima ist kalt genug, daß Luft unter dem Gefrierpunkt sieben Monate im Jahr dort durchströmen kann, was von der sommerlichen Advektion nicht vollkommen aufgehoben wird. Die latente Wärme der Eisschmelze erzeugt eine Abflachung des Wärmeteils der Sinus-Kurven für Felstemperaturen auf der negativen Seite von 0 °C. Die dritte Art von Höhlen ist vom Typus der Castleguard Höhle (FORD et al., 1971), die eine großräumige Höhle innerhalb der Permafrost-Zone mit einem einzigen Eingang ist. Eis tritt in den äußeren 1000 m auf, wobei innerhalb des Berges wärmere, aber stabile Temperaturen herrschen.

Die Permafrost-Zonen in Südwest-Alberta bestehen aus einer oberen Zone ununterbrochenen Permafrostes bis zu einer vertikalen Ausdehnung von 100 m und schließlich einer 1200 m mächtigen, in der Eishöhlen auftreten können. Diese ist nördlich in Richtung der Zone sporadischen Permafrostes unterhalb peat north von 56° N ausgerichtet. Felsgletscher scheinen eher mit den Gletschern als mit den Permafrost-Zonen in Zusammenhang zu stehen.

Permafrost is defined as ground which remains below 0 °C for more than one season. It is commonly divided into two zones, viz: continuous and discontinuous (e.g., BROWN, 1967a), although the latter was earlier subdivided into discontinuous and sporadic in Canada (BAIRD, 1964).

Continuous permafrost is relatively easy to identify but discontinuous permafrost is another matter. The distribution of patches of perennially frozen ground is complicated by the fact that they take on several different forms. Recently, rock glaciers (WAHRHAFTIG & COX, 1959) and ice-cored moraines (ØSTREM, 1971) have been recognized as examples, and these tend to occur close to the limit of permafrost, together with glaciers.

A form of permafrost that has previously been ignored except by karst specialists is that of the ice-cave. This may be defined as a cave where the rock temperature is partly or wholly below 0 °C for more than one season. Such caves generally contain ice crystals in some form or another, and many examples may be found from Arizona to the Northwest Territories in the Rocky Mountains. This paper will examine the apparent distribution of these ice caves in southwestern Alberta, and their relationship to the lower limits of continuous and discontinuous permafrost further north.

Methods used

Dr. R. J. E. BROWN of the National Research Council and the writer have been carrying out research into the distribution of alpine permafrost in southwest Alberta for over three years. This has involved monthly visits to 18 ground temperature cables placed in drill holes at suitable sites between Plateau Mountain near Claresholm and Sunwapta Pass near the Columbia Icefield. The preliminary results of this study will be found in Harris and Brown, 1978.

Descriptions of ice-caves in the Canadian Rocky Mountains are conveniently summarized in THOMPSON, 1976. Since 1966, numerous expeditions by the Alberta Speleological Society and the McMaster University Caving Group have mapped these caves, but curiously enough, the relationship of these caves to permafrost appears to have been largely ignored. Instead, research has been concentrated on Uranium-speleothem dating, cave form, and cave temperatures based on isotope studies. The only exception is at Mt. Castleguard, where FORD et al. (1976) have determined the temperature profile of the cave. WIGLEY and BROWN (1971) have discussed the physics controlling seasonal temperatures in simple caves with a single entrance, and their system works satisfactorily in the case of the large Castleguard Cave. There the 1 km long frozen zone lies at the entrance and is believed to have formed since the area was deglaciated (FORD et al., 1976).

Other more complex types of ice caves can occur. Accordingly, two examples of such caves have been instrumented by the writer in an attempt to determine their annual temperature regimes and how the permafrost formed there. The first type occurs in an area of relic permafrost at Plateau Mountain (HARRIS and BROWN, 1978). Instrumentation started with monthly recording hygrothermographs and yearly recording water temperature recorders-placed in the Plateau Mountain ice cave by Brian Woods. Unfortunately, these proved too insensitive for detailed work, and the writer has since used thermocouples (accurate to ± 0.2 °C) and thermistors (accurate to ± 0.02 °C) which are placed in crevices in the rock. The thermistors gave the best results (except when removed or chewed by pack rats), but necessitate regular visits to obtain the data. This method has subsequently been used in the Canyon Creek ice cave, which is an example of a low altitude ice cave with at least five entrances through which air can circulate. There, the thermistors must be removed between observations due to the large number of tourists, especially on weekends.

Maps of the Canyon Creek ice caves had been prepared by cavers (see THOMPSON, 1976) but proved inaccurate. Accordingly, TOM BARTON made a new map of the Canyon Creek ice caves for the author, while BEN DANIELEWICZ and the writer made the map of the Plateau Mountain ice caves using a chain and prismatic compass. Unfortunately the time constraints imposed by the Alberta Government to protect the fragile ice environment prevented the construction of a more accurate map.

Results

1. The Ice Caves

THOMPSON (1976) describes a series of caves which contain ice in late summer in southwest Alberta and in the nearby ranges in British Columbia. These are the Glittering Ice Palace, Coulthard Cave, Cleft Cave, Ice Hall, Top of the World, Wedge Cave, and Flop Pot, all in the Crowsnest Pass; the Plateau Mountain ice cave west of Claresholm; the Canyon Creek cave on Moose Mountain; and the Disaster Point cave near Miette Hot Springs in Jasper National Park. Their locations are shown in Figure 1, and it will be seen that they are associated with a pronounced zone of thick Palaeozoic limestones which are widely distributed in the outer ranges of the Rocky Mountains. Additional ice caves were reported from Ainsworth, British Columbia, and Nahanni National Park, Northwest Territories. The caves were originally formed by solution by underground water, and some are > 275,000 years old (FORD et al., 1972).

GEIGER (1966) has emphasized the importance of the number of entrances to caves in determining air flow, calling those with single entrances „static" and those with several entrances „dynamic" caves. WIGLEY and BROWN (1976) have objected to these names, pointing out that air movement occurs in both types. They give a good summary of their earlier paper (WIGLEY and BROWN, 1971) dealing with the temperature regime in single-entrance caves. In southwest Alberta, an additional complication is the presence or absence of permafrost in the zone occupied by the ice caves. The Castleguard cave is an example of one in the zone of post-glacial climatically controlled permafrost apparently in equilibrium with the present-day climate. However, this is not typical of all the ice caves in the region.

The Plateau Mountain and Canyon Creek ice caves were chosen for study because they represent respectively a cave with a single entrance close to the zone of continuous permafrost, and one with at least five entrances and lying some 400 metres below it. Plateau Mountain cave has generally still air in it, whereas the Canyon Creek cave usually has wind blowing through

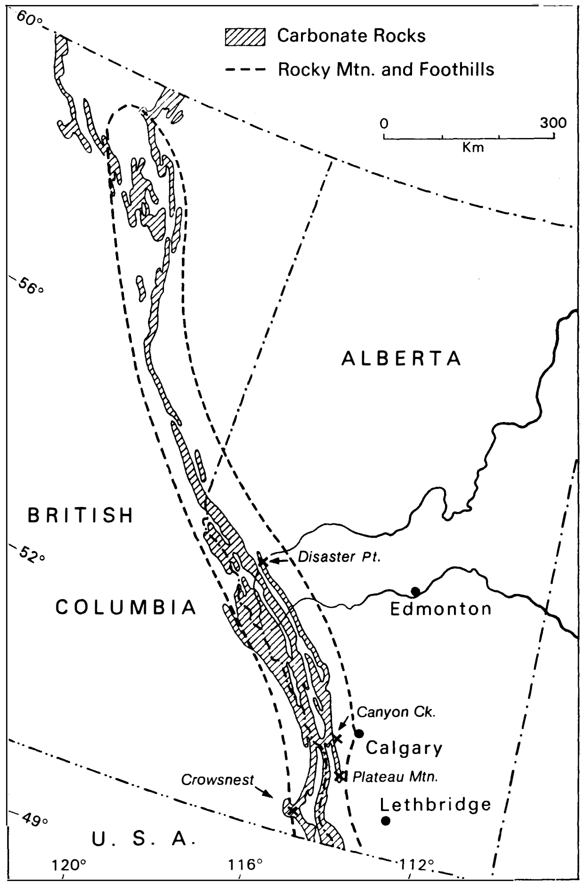


Figure 1: Distribution of Palaeozoic carbonate rocks (after DOUGLAS, 1970) and sinificant ice cave areas in the Southern Rocky Mountains

it. Direction of movement of the air at the Canyon Creek cave varies from visit to visit and is apparently independent of season.

(a) Plateau Mountain Ice Cave. This cave has its entrance on a south-facing cirque wall at 2,225 m (7,300 ft) near the north end of Plateau Mountain. The cave probably contains the largest hexagonal plate-like ice crystals of any cave so far described in Canada. They currently measure up to 25 cm in diameter (see WIGLEY and BROWN, 1976, Plate 9.2, p. 342). Over-use of the cave by the public resulted in severe melting, and the cave was gated in 1972 to prevent further damage to the ice crystals. It is now under the control of the Alberta Provincial Parks system. Ice thickness on the walls exceeds 1 m in places. Nearby ground temperature cables indicate that the permafrost is relic, so that the ground temperature continues to decrease to at least 30 m depth (HARRIS and BROWN, 1978).

Figures 2 and 3 show the form of the cave and the location of the temperature measuring stations, while Table 1 shows the temperatures of the cave wall at

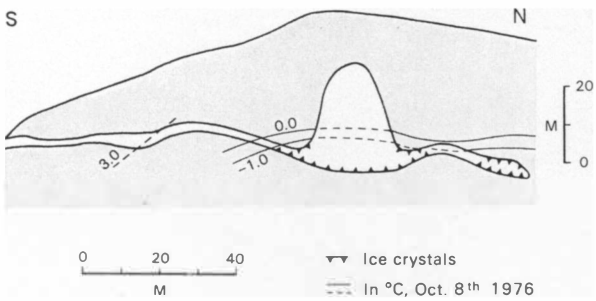


Figure 2: Cross-section of the Plateau Mountain ice crave showing the rock temperatures on October 8th, 1976 (from HARRIS and BROWN, 1978)

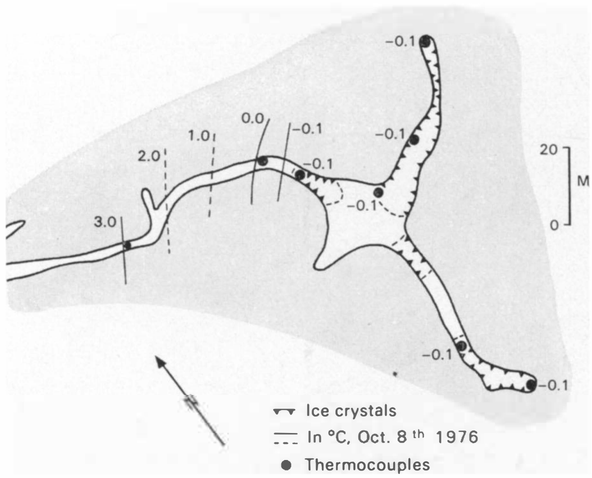


Figure 3: Plan of the Plateau Mountain ice cave showing the rock temperature measuring stations and location of ice

various times of the year. The relaxation zone of 60 m which has fluctuating temperatures and no permenent ice accumulation is consistent with that predicted from the approximate pipe radius of the narrowest part of the entrance (see WIGLEY and BROWN, 1971). It will be seen that there is only a very minor fluctuation in the temperature of the rock in the deeper parts of the cave and that the permafrost is very marginal. The increase in cold with depth agrees with data obtained from the nearby boreholes and it appears that the low temperatures are the result of an earlier colder period. The data from the monthly and yearly temperature recorders confirm this constancy of temperature. Heat is currently slowly dissipating this cold, but in the meantime, conditions are suitable for the formation of ice on the walls of caves. The air inside the cave is cold, and is kept saturated with water vapour by ground water dripping from the roof. In the back chamber, these drips are currently forming ice pillars. Hexagonal ice crystals are growing once again over the melted remnants of earlier crystals in the middle portion of the cave and the cave is slowly but steadily recovering its former grandeur. Eventually latent heat from freezing of water vapour will use up all the available cold in the rock and the cave will cease to be an ice cave.

(b) Canyon Creek Ice Cave. The Canyon Creek ice cave has its entrance at about 1,768 m (5,800 feet) on the south-facing slope of Moose Mountain. It is about 210 m (700 feet) above the canyon floor, and probably some 500 m below the main zone of permafrost in the outer range of the mountains. Figure 4 shows the plan of the cave and location of the temperature measuring stations on the new map by Tom Barton, while Figure 5 shows an approximate cross-section based on the 1968 and 1970 surveys of the Alberta Speleological Society.

Table 1: Rock temperatures in the Plateau Mountain ice caves as meaured by thmermocouple (Tc) and thermistor (Th). For measuring stations, see Figure 2.

Measuring Station	8 Oct., 1976		1 July, 1977		2 Aug., 1977		30 Aug., 1977		7 Oct., 1977		Ice present in dish for 1 year without melting
	Tc	Th	Tc	Th	Tc	Th	Tc	Th	Tc	Th	
1	3.0	n.d.	−0.2	n.d.	0.4	0.61	0.3	0.52	0.4	0.51	No
2	0.0	n.d.	−0.2	n.d.	−0.2	0.04	0.0	0.05	0.1	0.06	No
3	−0.1	n.d.	n.d.	n.d.	−0.2	−0.01	−0.15	0.0	0.1	0.03	No
4	−0.1	n.d.	n.d.	n.d.	−0.1	−0.04	−0.2	−0.02	−0.05	−0.02	Yes
5	−0.1	n.d.	0.0	n.d.	−0.1	−0.17	−0.2	−0.10	−0.1	−0.07	Yes
6	−0.1	n.d.	−0.25	n.d.	−0.25	n.d.	−0.2	−0.17	−0.2	−0.18	Yes
7	−0.1	n.d.	−0.2	n.d.	n.d.	−0.10	n.d.	−0.09	n.d.	−0.11	Yes
8	−0.1	n.d.	−0.2	n.d.	−0.3	−0.18	−0.2	−0.18	−0.1	−0.17	Yes

Tc Thermocouple, accurate to ± 0.2
Th Thermistor, accurate to ± 0.02
n.d. No determination

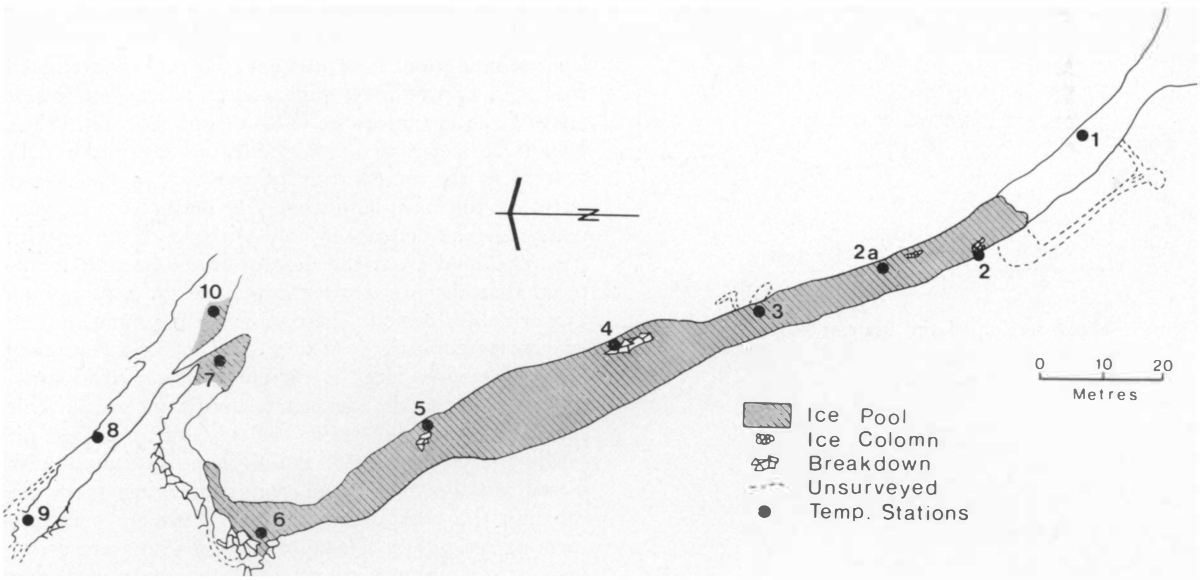


Figure 4: Plan of the Canyon Creek ice caves showing the rock temperature measuring stations and location of ice (modified from THOMPSON, 1976)

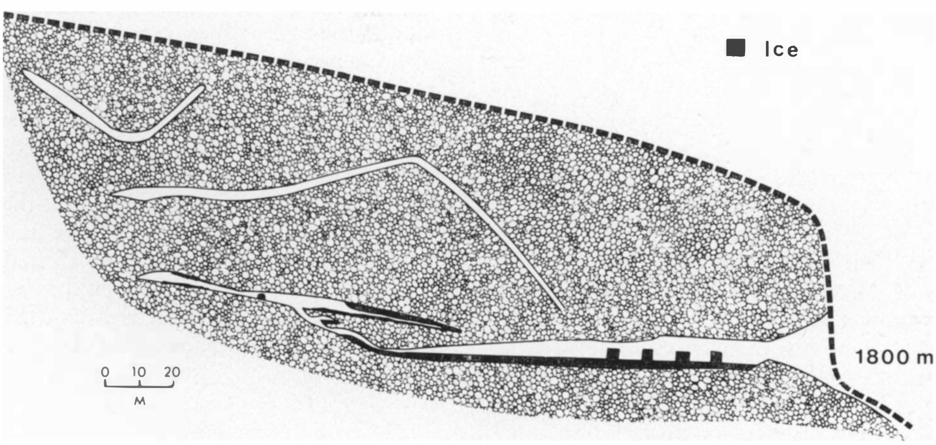


Figure 5: Schematic cross-section of the Canyon Creek ice caves showing the location of the gallieres with permafrost

This cave has wind blowing through it throughout the winter, even when the outside air is still. It also commonly has wind in it in summer. The first chamber is ice-floored and exhibits spectacular ice columns near its entrance. These partly melt in summer under the influence of dripping water, and reform in the fall and winter. The ice floor becomes a shallow lake in August and September. Ground temperatures vary considerably with season, being coldest in spring and warmest in late summer (Table 2). Degree of cooling varies enormously from winter to winter, and is closely related to the outside air temperature (Figure 6). Unlike the fragile Plateau Mountain ice cave, the hundreds of visitors a month have negligible apparent effect on the regime.

The outside air temperature tends to follow the usual sine-curve form, whereas the rock temperatures follow a truncated sine-curve. The truncation occurs on the cold side of 0 °Celsius and appears to be maintained by the failure of the air in the cave to supply enough heat to completely melt the large volumes of ice present on the cave floor. This is presumably due to the latent heat of melting of ice (80 cals/g).

Several changes also occur in the form of water in the cave. In winter, the bulk of the water is frozen, the only exceptions being at the pillar nearest the entrance where the low sun causes some melting of the outer side of the pillar for a short period each day from late October to the end of February, and some

Table 2: Rock temperatures by thmermistor (accurate to ±*0.02 °C) in Canyon Creek ice cave.* See Figures 4 and 5 for the locations of the measuring stations

Measuring Station	22 Feb. 1977	15 April 1977	14 July 1977	4 Sept. 1977	30 Sept. 1977	11 Nov. 1977	26 Dec. 1977	22 Feb. 1977
1	1.40	0.40	n.d.	1.48	1.02#	n.d.	−2.41	−3.52
2	−1.56ϕ	−2.33ϕ	0.28#	0.03#	0.03#	−1.44ϕ	−7.57	−5.18
2a	n.d. ϕ	n.d. ϕ	n.d.	n.d.	n.d. #	−1.04ϕ	−6.95	−5.37
3	−1.78ϕ	−2.35ϕ	−0.09	0.03*#	0.00#	−0.85ϕ	−6.80	−4.92
4	−1.71	−2.25	−0.27#	0.05*#	−0.04*	−0.68△	−6.40	−5.22
5	−2.13	−2.40	−0.51	−0.27*	−0.13*	−0.98	−5.97	−5.27
6	n.d.	−2.28	−0.38	−0.11*	−0.08*	−1.06	−5.84	−5.53
7	n.d.	−2.37	−0.39	−0.22*	−0.22*	−0.57	−6.43	−4.65*
8	n.d.	−1.92*	−0.47*	−0.12*	−0.20*	−0.62	−5.37	−4.26*
9	n.d.	−2.14	−0.33*	–	−0.12*	−0.67	−4.06	−4.41*
10	n.d.	−1.61	−0.12*	–	−0.33*	−0.68	−4.92	−3.69*
2–10 mean	−1.75	−2.22	−0.25	−0.09	−0.12	−0.82	−5.76	−4.85

Dripping water with ponds in low spots
* Ice crystals growing on wall
ϕ Columns growing
△ Last place for water in ponds to freeze

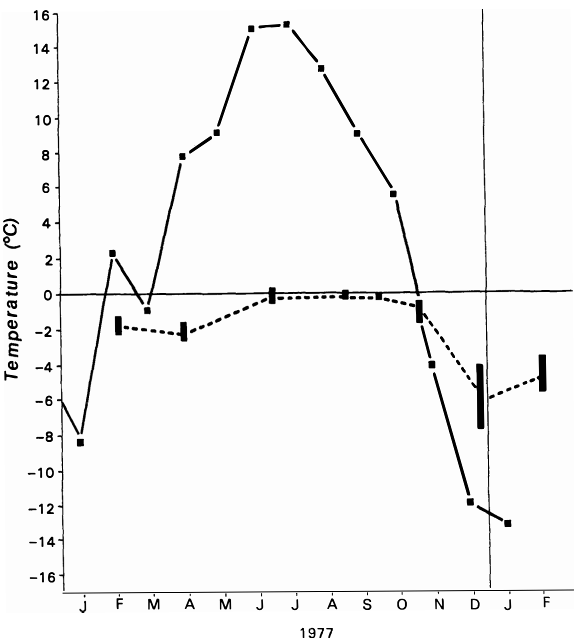


Figure 6: Comparison of temperatures at the University of Calgary and in the Canyon Creek ice cave. The bars represent the range of rock surface temperatures encountered from stations 2 to 10 within the cave, while the central mark on the bar indicates the mean of these observations on the date. Although the ice cave lies 600 m above the elevation of the weather station, the general correspondence between air temperature and temperatures on the rock surface in the ice cave is clear.

water dripping on to the tops of the ice pillars and columns which are growing. The inner chambers are dry and there are only a few places with small ice crystals on the wall.

The air inside the cave tends to be similar in temperature to the surrounding rock, although it is clearly moving into and through the cave from the cold air outside. This movement is probably by a combination of the chimney effect of Wigley and Brown (1976) with gravity (cold air drainage into cracks) when the air is still, and has the effect of cooling the entire cave by advection from late October until the end of April.

In summer, water dripping from the roof tends to form pools on the ice on the floor, and it may also melt the outer layers of the columns and ice fall. It is undoubtedly aided by warmer air passing through the cave from other openings, although this air is not much above freezing point when it reaches the inner chambers. It brings with it moisture which forms small ice crystals on the cold rock walls until the latter reach 0 °C. The extent of the cover of ice crystals indicates which areas never became unfrozen the previous summer. The sun is too high to shine into the cave at this time of year. When no wind is blowing, the air tends to be still in the cave, so that the amount of advection of cool air in winter may be greater than that of warm air in summer.

The entire cave lies in the zone of seasonal temperature fluctuation (Figure 7) although this is not entirely consistent with the theory of Wigley and Brown (1971). However it is problematic to arrive at a reasonable estimate of the pipe radius in this cave due to the fact that the air enters from multiple cracks, many of them far too small to explore. Added to this is the considerable addition of heat in summer from percolating groundwater dripping from cracks in the roof.

Figure 7 emphasizes the point. Instead of finding a cold zone just inside the cave entrance and a warmer zone of constant temperature beyond this, the temper-

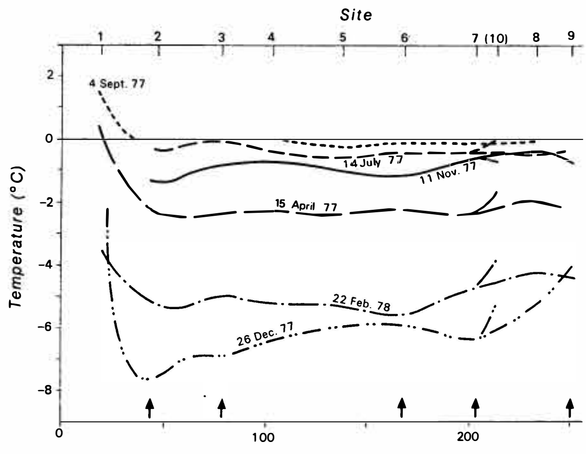


Figure 7: Variation in rock surface temperatures in different parts of the ice cave as measured at different seasons of the year in Canyon Creek ice cave. The thick arrows indicate some of the main locations of cracks through which air in the cave enters or exits from the cave, apart from the entrance.

ature regime varies throughout the cave. In general, the colder places in winter approximate to the location of the places where air enters via cracks. In summer, these tend to be the locus of the warmer zones.

From this study, it would appear that this ice cave occurring well below normal climatic permafrost is due to special conditions where large caves with multiple entrances or cracks to the surface occur. In this case, cold air drainage in winter causes more cooling of the inner chambers than can be warmed by air entering during the shorter summer period, even on south facing slopes in the chinook belt of Alberta. The type of ice crystals is limited to small granular crystals due to periodic remelting, while ice falls, ice lakes and ice columns also occur. In some cases where there are vertical cracks to the surface, snow may be an added source of ice, but this is not usually the case. At Canyon Creek, the solution of limestone produced a suitable cave, but near Idaho Falls, an ice cave occurs in basaltic lava flows in the caverns left by draining of fluid magma or the escape of trapped gases. Since that site is also at an unexpectedly low altitude, it must also be of this type. Thus any suitably cavernous rock could contain a pocket of permafrost if subjected to a sufficiently cool continental climate in the mid latitudes.

2. *Relationship to Other Forms of Permafrost*

When Brown (1967) realized that permafrost must extend southwards along the higher parts of the Rocky Mountains, he tried to map its probable extent by using the −1 °C (30 °F) isotherm interpolated from the limited climatic data from the Cordilleran region that was then available. The −1 °C boundary was derived from experience in northern Canada. When this boundary is plotted together with height of the tree-line, location of known active rock glaciers, ice cored moraines, glaciers, and ice caves (Figure 8), it clearly lies within the distribution of ice caves, but much lower than the rest of the permafrost features in this part of the mountains. The picture is not helped by the fact that the apparent tree line fluctuates considerably in height with latitude. This is generally regarded as indicating changes in elevation of the critical isotherm (A. F. Mark, personal communication, 1974), and this may well be the case in Nahanni.

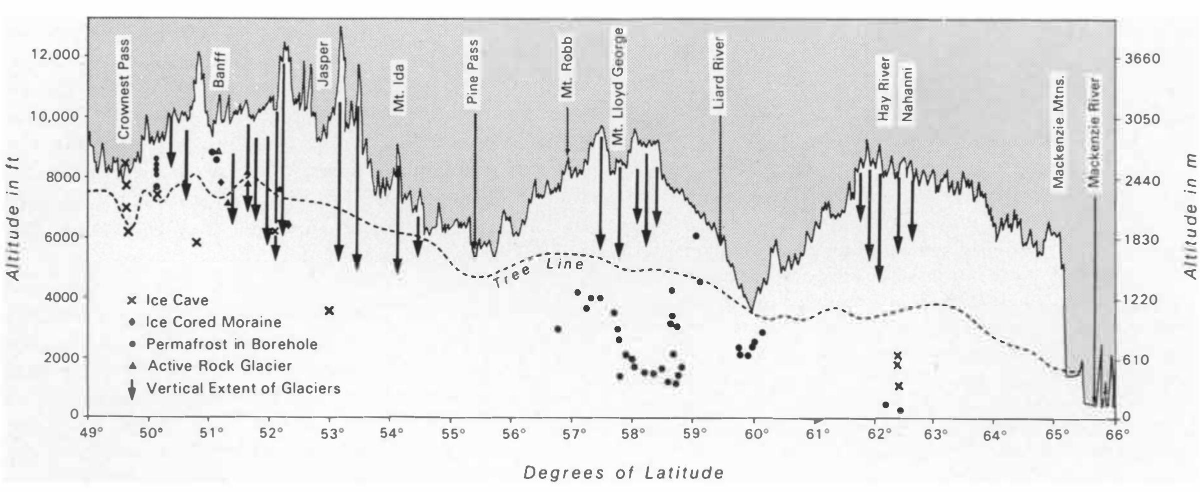


Figure 8: Distribution of tree line, permafrost in boreholes, ice caves, ice-cored moraines, active rock glaciers and glaciers along the Continental Divide in the eastern ranges of the Rocky Mountains from the 49th parallel to 66° N. Included is data from Harris & Brown, 1978; Ogilvie & Baptie, 1967; Osborne, 1975; Østrem & Arnold, 1970; Scotter, 1975; and Brown, 1967 (a) and (b).

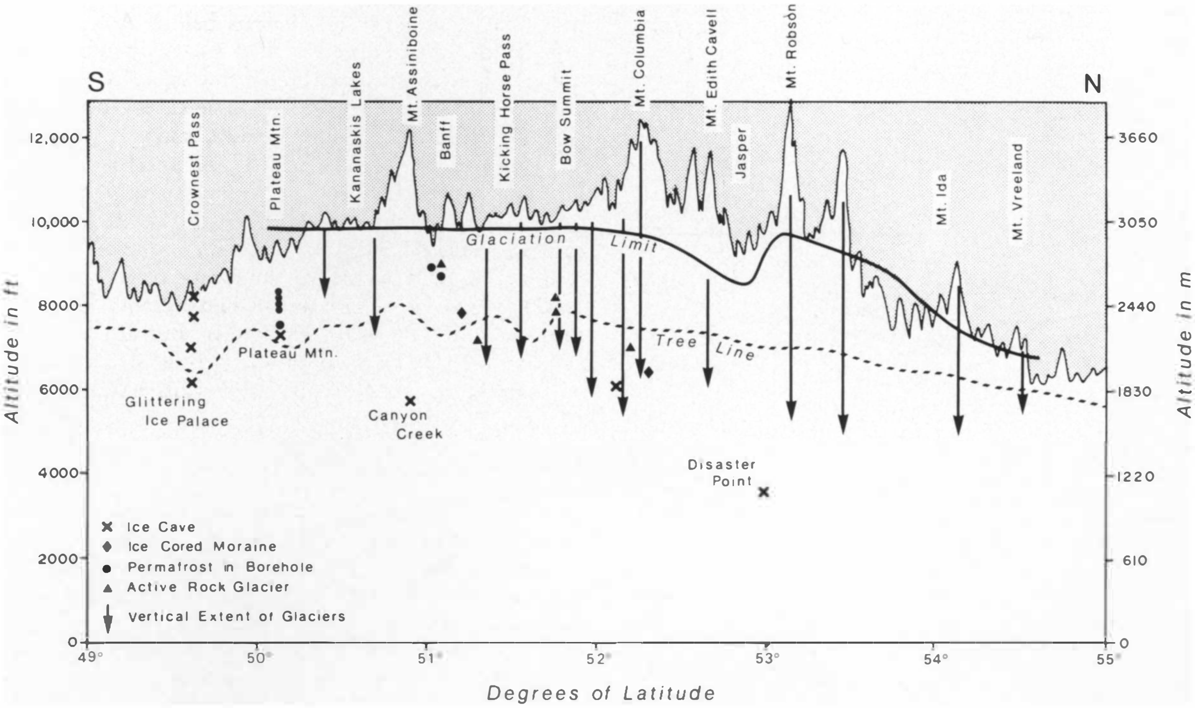


Figure 9: Distribution of tree line, permafrost in boreholes, ice caves, ice cored moraines, active rock glaciers and glaciers along the highest part of the eastern ranges of the Rocky Mountains from the 49th parallel to 55° N. This is the zone east of the Continental Divide, and also shown is the height of the highest mountains. It includes data from Harris and Brown, 1978; Ogilvie & Baptie, 1967; Osborne, 1975; Østrem & Arnold, 1970; and Scotter, 1975.

However, Cordes and Gill (1974) have presented evidence that wind can also reduce the height of the tree line, e.g., in the Crowsnest Pass.

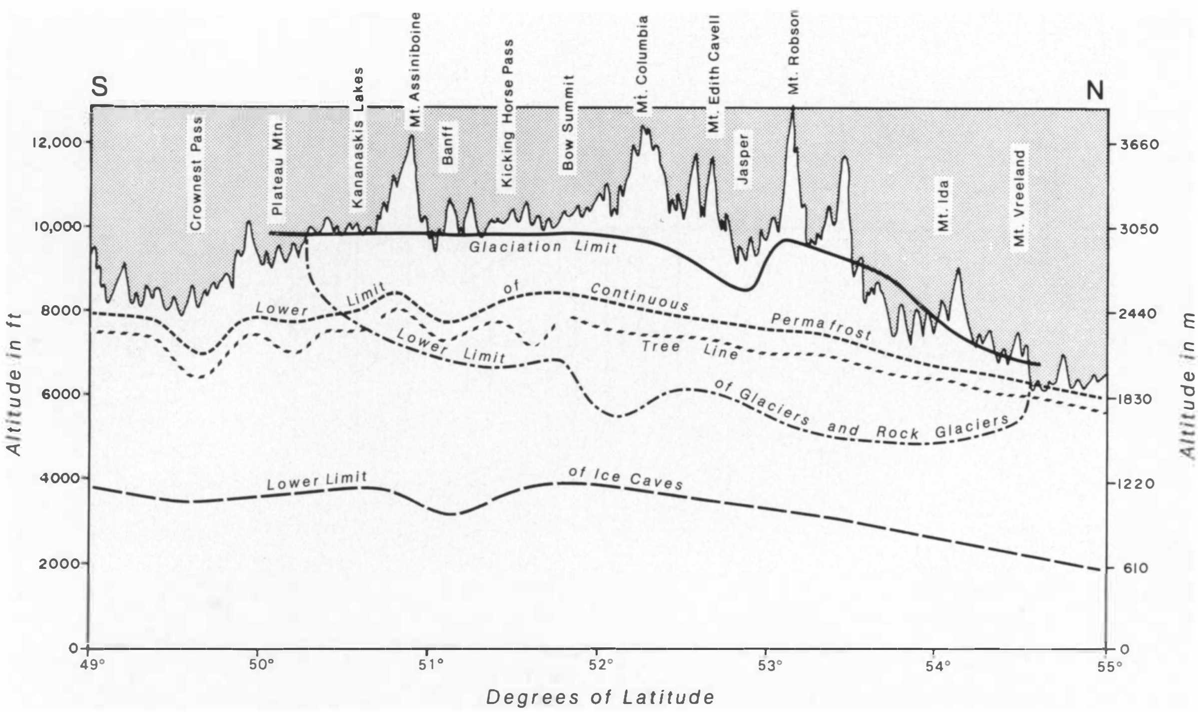
Particularly noteworthy is the fact that the zone of discontinuous permafrost with considerable vertical extent recognized by Brown (1972) along the Alaska Highway along the eastern mountain slopes appears to grade laterally southwards into the zone of ice caves at about latitude 55° N. Ice caves occur north of this boundary, but the permafrost beneath peat bogs disappears to the south. Presumably this is due to longer and warmer summers. By 53° N, permafrost is absent in peaty swamps at elevations of up to 2,100 m, though at this altitude, the swamps are in alpine situations with spring water flowing through them.

Concentrating on the situation in southwest Alberta (Figure 9), it appears that the limit of continuous permafrost may lie 50–200 m above the tree-line (Harris and Brown, 1978). In the higher mountains, a zone of ice cored moraines, rock glaciers and glaciers extends down to 600 m below this, although they are absent where the mountains lie below the glaciation limit (Østrem, 1966). However, in all areas, a zone of ice caves extends down to at least 1,200 m below the zone of continuous permafrost, although this is also controlled by the presence of caverns of suitable form. This contrasts with patches of frozen ground occurring in drill-holes down to a mere 100 m below the zone of continuous permafrost on Plateau Mountain (Harris and Brown, 1978). Thus permafrost zonation in the alpine regions of southwest Alberta can be summarized as: –

1. A zone of continuous permafrost and ice caves at high altitude with or without glaciers, rock glaciers, and ice-cored moraines.
2. A zone of discontinuous permafrost and ice caves up to 100 m in vertical extent, with or without glaciers, rock glaciers, and ice-cored moraines.
3. A zone of scattered ice caves up to 1,200 m in vertical extent, with or without glaciers, rock glaciers and ice-cored moraines.

These zones are shown schematically for the mountains of southwest Alberta in Figure 10.

It can be argued that the zone of ice caves includes most of the mountains of southwest Alberta. While this is certainly true, the lower limit of this zone rises in height as it is traced southwards. Thus in Wyoming, Hill et al. (1976) found only 13 caves with perennial ice probably present in them out of a total of 245 caves they describe. The lowest altitude of these ice caves was 7,400 feet (2,257 m) which is over 1,100 m above the elevation of the lowest cave in the State.



Figre 10: Main permafrost zones from the Rocky Mountains of Southwest Alberta depicted in Figure 9, compared with the glacial zone. Note that the two sets of zones are quite indepent of one another.

By the latitude of Arizona, the ice caves are confined to the tops of the mountain ranges even though caves extend down to low elevations, e.g. the Carlsbad Caverns. Thus the concept of there being a distinct zone of ice caves is quite defensible.

It should be noted that on theoretical grounds, it might be expected that rock glaciers would be more closely related to ice-caves in a zonal permafrost distribution if the Balch effect were the main cause of their existence and activity (see WAHRHAFTIG and COX, 1959). It may be that as more data are accumulated in their distribution, this may turn out to be the case, but at the moment, the available data suggests a distribution parallelling that of glaciers and ice-cored moraines. This is in accordance with the concept that they are often derived from former glaciers, or the ice in them is based on suitably high snowfalls (see Figure 11, after CURREY, 1968). If it were otherwise, most talus slopes in the mountains would change into rock glaciers.

Conclusions

In southwestern Alberta, ice caves appear to be of at least three types. The first is due to ice formation on the walls of caves in the zone of relic permafrost. The moisture is supplied by percolating water and the ice crystals are very fragile. They are characterized by temperatures in the deeper portions remaining just below zero throughout the year and by the absence of wind. The Plateau Mountain ice cave is an example, and they occur close to or within the zone of continuous permafrost. The ice often takes the form of large hexagonal plates encrusting the cave walls to thicknesses in excess of 1 m.

The second type occurs under cool continental climates where there are large caverns with many entrances. Cold air passing through the cave for seven months of the year cools the rock walls to temperatures below −2 °C through most of the cave. In summer, warmer air circulates but this advection of heat is too small to fully counteract the winter cooling. Ice is formed in winter from percolating ground water and in summer by crystal growth on the cold cave walls from the warmer air circulating in the cave. Ice columns form below dripping ceilings, ice falls develop where water seeps out of the cave floor on inclines, and small ice crystals form on walls in summer.

The third type is the cave with a single entrance occurring in the zone of climatically adjusted present-day permafrost. Castleguard Cave is an example and is characterized by an outer permafrost zone with ice crystals extending about 1,000 m, with an inner warmer unfrozen zone characterized by seasonally stable temperatures (FORD et al., 1972). The length of the cold zone fits the predictions of WIGLEY and BROWN (1971; 1976).

Comparing the latitudinal and altitudinal zones of glaciers, continuous permafrost, ice caves, ice-cored moraines and rock glaciers in southwest Alberta (Fig-

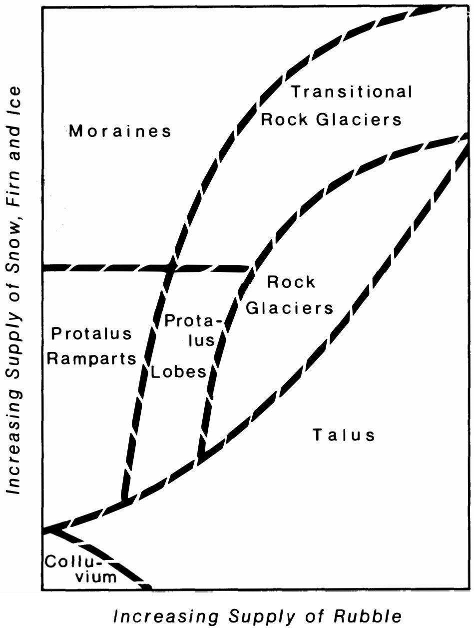


Figure 11: The relationship of the various landforms found in alpine cirques to the balance between the supply of snow, firm and ice, and the supply of rock debris (after CURREY, 1968).

ures 9 and 10), it appears that the glaciers and ice-cored moraines form a group related to the intersection of the glaciation limit with the mountains, whereas continuous permafrost and ice caves tend to parallel the tree line. It is therefore suggested that the alpine permafrost in the area takes the form of an upper zone of continuous permafrost up to 100 m in vertical extent, and then a zone up to 1,200 m thick in which ice caves may occur. This latter zone grades northwards into the zone of isolated patches of permafrost below peat, north of 56° N, documented by BROWN, 1976 (b). The evidence as to the status of rock glaciers is limited but present indications are that they are more closely related to glaciers (CURREY, 1968), and that the Balch effect is not their primary cause nor control.

Acknowledgements

The writer is indebted to many people for various forms of help. The Assistant Deputy Minister, Alberta Recreation, Parks and Wildlife, Mr. James Potton, and Dr. Stuart Loomis kindly provided the permission to visit the Plateau Mountain ice caves, while several Park Rangers kindly took time out from their other duties to escort the caving party. Brian Woods, John Morneau, Tom Barton, Ben Danielewicz, and Stephen and Kevin Harris accompanied the writer in the field or helped with the research at different times, regardless of weather. Dr. R. J. E. Brown provided the water temperature recorders, introduced the author to the use of thermistors, and has discussed the problem of the relation of ice caves to the permafrost zones on several occasions. Without his support and that of the National Research Council, Building Research Division, we would still know virtually nothing about the distribution of alpine permafrost in the area. The field work was also aided by N.R.C. grant #A-7843.

References

BAIRD, P. D.: The Polar World. Longmans, Green and Co., Toronto, 1964, 328 p.

BROWN, R. J. E.: Permafrost Map of Canada. Natl. Res. Council, Div. Bldg. Res., N.R.C. 9767, and Geol. Surv. Can., Map. 1246 A. 1967 (a)).

– : Permafrost investigations in British Columbia and Yukon Territory. Natl. Res. Council, Div. Bldg. Res., N.R.C. 9762, 1967 (b), 55 p.

CORDES, L. D. and GILL, D.: Low-elevation Krummholz in the Foothills of Southern Alberta. In "The Kootenay collection of Research Studies in Geography", B. M. BARR, ed., B.C. Geographical Series No. 18, Tantalus Res., Ltd., Vancouver, 1974, pp. 83–93.

CURREY, D. R.: Neoglaciation in the Mountains of the southwestern United States. Unpubl. Ph.D. thesis, Dept. of Geography, University of Kansas, 1968, 171 pp.

DOUGLAS, R. J. W.: (Ed.). Geology and Economic Minerals of Canada. Economic Geology Rept. No. 1, Geol. Surv. Can., 1970, 833 p.

FORD, D. C., THOMPSON, P., and H. P. SCHWARCZ: Dating cave caliche deposits by the Uranium Disequilibrium Method: some preliminary results from Crowsnest Pass, Alberta. In: Research Methods in Pleistocene Geology, YATSU, E., and FALCONER, A., eds. Proc. Second Guelph Symposium on Geomorphology, University of Guelph, 1972, pp. 247–255.

FORD, D. C., R. S. HARMON, H. P. SCHWARCZ, T. M. L. WRIGLEY and P. THOMPSON: Geohydrologic and thermometric observations in the vicinity of the Columbia Icefield, Alberta and British Columbia, Canada. J. Glaciol. v. 16, 1976, pp. 219–230.

GEIGER, R.: The climate near the ground. Harvard Univ. Press, Cambridge, Mass., 1966.

HARRIS, S. A. and R. J. E. BROWN: Plateau Mountain: A case study of alpine permafrost in the Canadian Rocky Mountains. Proc. Third Internat. Conf. Permafrost, Edmonton, Alberta, 1978. In the Press.

HILL, C., W. SUTHERLAND, and L. TIERNEY: Caves of Wyoming, Geol. Surv. Wyoming Bull, 59, 1976, 229 p.

OGILVIE, R. T. and B. BAPTIE: A permafrost profile in the Rocky Mountains of Alberta. Can. J. Earth Sci., v. 4, 1967, pp. 744–745.

OSBORNE, G. D.: Advancing rock glaciers in the Lake Louise area, Banff National Park, Alberta, Can. J. Earth Sci., v. 12, 1975, pp. 1060–1062.

ØSTREM, G.: The height of vhe glaciation limit in southern British Columbia and Alberta. Geogr. Annaler, v. 48 (A), 1966, pp. 126–138.

– : Rock Glaciers and ice-cored moraines. A reply to D. Barsch. Geogr. Annaler, v. 53 A, 1971, pp. 207–213.

ØSTREM, G. and K. ARNOLD: Ice-cored moraines in southern British Columbia and Alberta. Geogr. Annaler, v. 52 A, 1970, pp. 120–128.

SCOTTER, G. W.: Permafrost profiles in the Continental Divide region of Alberta and British Columbia. Arctic & Alpine Res., v. 7, 1975, pp. 93–95.

THOMPSON, P.: Cave Exploration in Canada. Special Edition of The Canadian Caver, Dept. of Geography, University of Alberta, 1976, 183 p.

WAHRHAFTIG, C., and A. COX: Rock glaciers in the Alaska Range. Bull. Geol. Soc. Amer., v. 20, 1959, pp. 383–436.

WIGLEY, T. M. L. and M. C. BROWN: Geophysical applications of heat and mass transfer in turbulent pipe flow. Boundary-Layer Meteorology, v. 1, 1971, pp. 300–320.

WIGLEY, T. M. L. and M. C. BROWN: The Physics of caves. In "The Science of Speleology", T. D. FORD and C. H. D. CULLINGFORD, Eds., Academic Press, London, 1976, pp. 329–358.

GREAT CIRCLES ON THE GREAT PLAINS: THE CHANGING GEOMETRY OF AMERICAN AGRICULTURE*)

With 3 figures, 5 photos and 3 tables

TOM L. MCKNIGHT

Zusammenfassung: Große Kreise auf den Great Plains: die sich wandelnde Geometrie der amerikanischen Landwirtschaft

Das in der ganzen Welt berühmte Bild der ausgeprägten Rechtwinkligkeit (75–80%) der Agrarlandschaft der USA wird in den letzten 20 Jahren zunehmend durch eine neue Form abgelöst. Große Kreisflächen legen sich exakt über die Rechtecke wie die runden Steine auf einem Damebrett. Diese Wandlung der landwirtschaftlichen Geometrie ist die Folge einer Entwicklung, die man die bedeutendste mechanische Neuerung in der Landwirtschaft seit der Einführung des Traktors genannt hat: die zentrierte Drehbewässerung (center pivot irrigation).

The farm landscape of the United States is famous throughout the world for its overwhelming rectangularity. More than three-fourths of the total national area was surveyed in systematic cadastral surveys that established a regular pattern of grid lines enclosing squares[1]). These surveys, most of which actually preceded settlement, set a pattern for property lines, transportation routes, and even field borders that is an enduring rectilinear legacy in the landscape.

Circling the Square

Within the past two decades, however, a new shape has begun to appear. Right-angled rectangular regularity is being modified by the closed curvature of circles. The North American agricultural landscape has often been likened to a gigantic checkerboard; increasingly great circular forms are being superimposed neatly upon the sqares, like checkers being placed on the board.

These great circles are simply large irrigated fields. However, the regularity of their patterns, the abruptness of their introduction, and the rapidity of their diffusion are clear indications that more as involved than a simple change in field shape. Indeed, this striking metamorphosis of agricultural geometry represents a development that has been called the most significant mechanical innovation in farming since the introduction of the tractor[2]).

The phenomenon is termed center pivot irrigation. Its design is simple in concept but complex in construction. In essence it involves a self-propelled, moving pipe (a "lateral" in irrigation parlance), dotted with sprinkler heads, mounted on wheels, and anchored at the center of the field (the pivot point). It moves in a circular arc, dispensing water in a regular pattern that is capable of almost infinite variation.

After a few years of trial-and-error experimentation, center pivot irrigation was introduced to the agricultural scene with little fanfare in the late 1950s

*) The writer was stimulated, encouraged, and instructed by Dr. LESLIE F. SHEFFIELD, Extension Co-ordinator for Irrigation of the University of Nebraska-Lincoln, who is probably the leading professional authority on center pivots, and by Dr. PHILIP VOEGEL of the University of Nebraska-Omaha, who is perhaps the geographer most knowledgeable about center pivots.

[1]) Major geographical studies of this phenomenon include WILLIAM D. PATTISON: Beginnings of the American Rectangular Land Survey System, 1784–1800, (Department of Geography Research Paper No. 50, University of Chicago, Chicago, 1964); NORMAN J. W. THROWER: Original Land Survey and Subdivision, (Monograph Series, Association of American Geographers, Rand McNally & Co., Chicago, 1966); and HILDEGARD BINDER JOHNSON: Order Upon the Land: The U.S. Rectangular Land Survey and the Upper Mississippi Country, (Oxford University Press, New York, 1976).

[2]) WILLIAM E. SPLINTER: "Center-Pivot Irrigation", Scientific American, Vol. 234 (June, 1976), p. 90.