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FROST CRACKING IN A MIDDLE-LATITUDE CLIMATE

INTRODUCTION

This paper describes frost cracks and hummocky microtopography formed at the Hanover Country Club golf course of Dartmouth College, Hanover, New Hampshire, during the winter of 1958—59. The climatic summary was prepared by Goddard; the field observations were made by Smith and Washburn while they were members of the Department of Geology at Dartmouth.

LOCATION AND CLIMATE

The golf course is located at the north edge of Hanover, which is in lat 43°42′ N., long 72°17′ W. (fig. 1). The golf course occupies part of a dissected plain, which was the floor of a former glacial lake. The plain has an altitude of 152—159 m (500—520 ft) and is underlain largely by laminated silt.

Weather records were started at Dartmouth College in November 1834, at Dartmouth's Shattuck Observatory in November 1855, and they have been continued uninterruptedly at the Observatory since 1867. Pertinent data are summarized in tables I—III (cf. also Goddard, no date). The mean annual temperature is 6,6 °C, the mean and the mean minimum for the coldest month (January) are −8,1° and −13,6 °C respectively, and the mean for the warmest month (July) is 20,3 °C. There are 5 months (May-Sept.) with a mean temperature above 10 °C. Thus the climate can be classed as a middle-latitude, humid continental climate with warm summers (Dfb zone of the Köppen classification) (Strahler 1960, p. 185—191).

DESCRIPTION OF CRACKS AND HUMMOCKY MICROTOPOGRAPHY

GENERAL

On 8 April 1959, while there were still patches of snow on the golf course, cracks were observed in several snow-free patches, especially on the southeast-facing slope between the second and third holes of the 18-hole course, and to a lesser extent on the opposite, northwest-facing slope near the 18th green. In the latter locality the ground also had a hummocky microtopography. Mr. Thomas Keene, Dartmouth golf coach and professional at the Hanover Country Club since 1921, did not recall having seen similar cracks before; however, he had noted the hummocky topography in the same place each spring and had observed that it flattens out upon completion of thawing. Mr. Harry Sanborn, golf-course superintendent for 24 years, reported having seen similar cracks before only in 1940.

CRACKS

The cracks tended to run parallel and at right angles to the contours, and they extended for several tens of meters where best developed, as on the southeast-facing slope (fig. 2). The cracks were hair thin to 0,5 cm wide at the surface, and in places cut the vegetation cleanly (pl. 1 and 3). Where they met, the angles of junction ranged from about 30° to as much as 120°. An excavation across a crack on 12 April encountered frozen sandy silt at a depth of 14 cm. A thin vein of clear ice reached a depth of at least 30 cm. At a depth of 40 cm the silt was somewhat sandier than above and not frozen hard, although its temperature was −5 °C. The turf at this locality was 1,5—2 cm thick.

Excavation of another crack in the same area 3 days later showed it to be open and 0,2—1 cm wide at the frost table, which lay at a depth of 26—32 cm; in places a wire could be freely inserted into the crack to 18 cm below the frost table. There was a sheathing of clear ice, 0,2—0,4 cm thick, on either side of the opening. The crack was coincident with the axis of a ridge in the frost table, the ridge being 10—30 cm wide and having a maximum relief of 7 cm (pl. 2). The temperature 2 cm beneath the ridge was −2 °C. Further excavation several days later showed that the crack reached to a depth of at least 50 cm, and judging from the fact that the hard-frozen silt underlying the ridge could be followed to a depth of about 1 m, the total vertical extent of the crack may have been similar. The grain size of the silt in this area is given by figure 3. The moisture

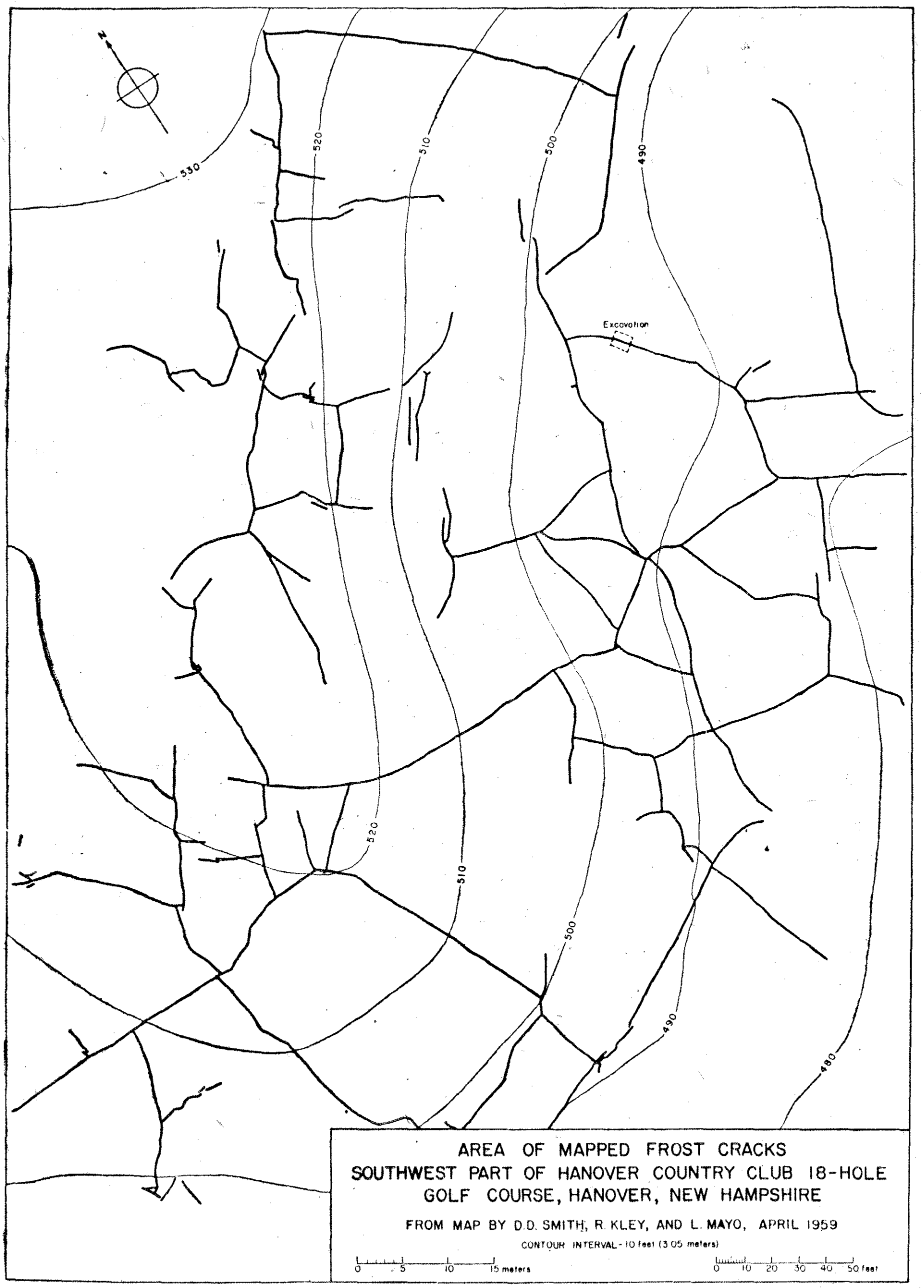
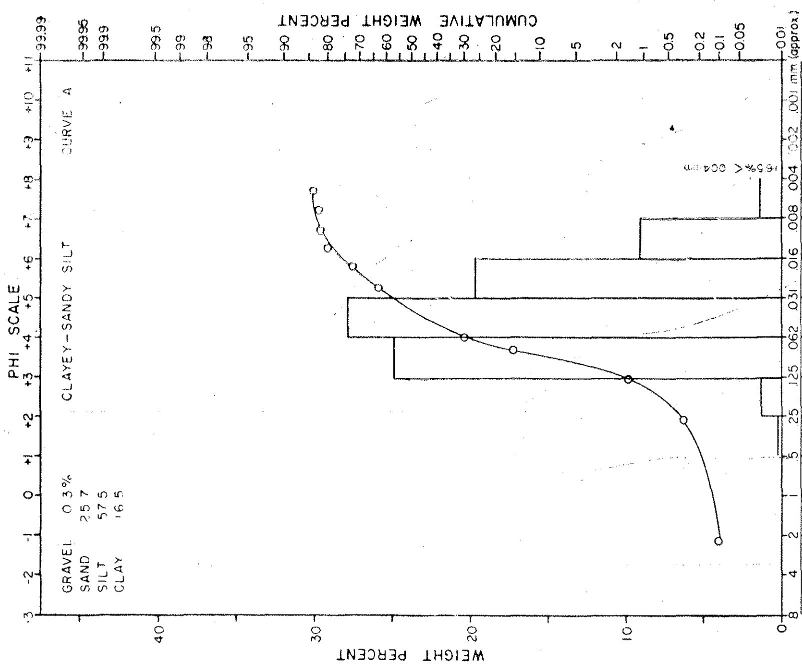
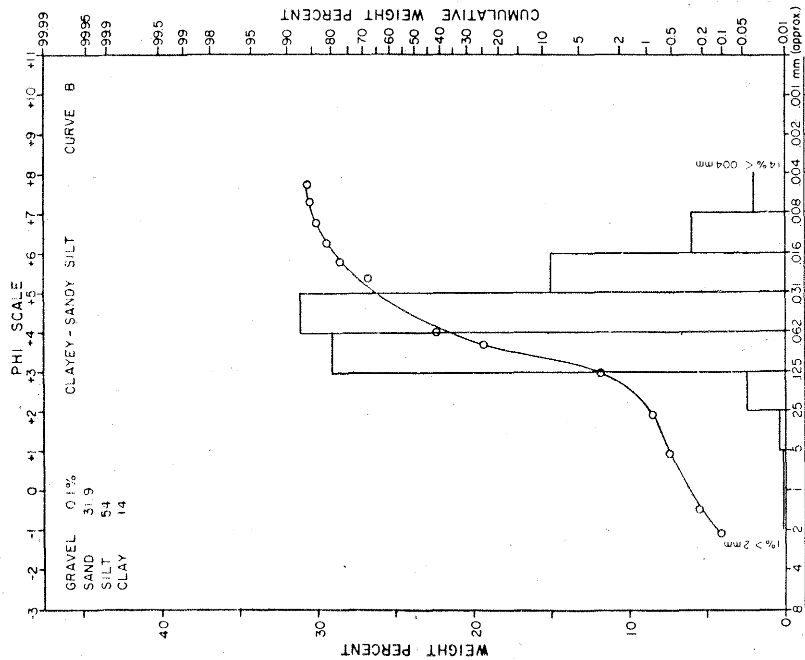


Fig. 2. Area of mapped frost cracks, southwest part of Hanover Country Club 18-hole golf course, Hanover, New Hampshire

Excavation at upper right of map is that illustrated by pl. 2


PHI SCALE
GRAVEL 0.3%
SAND 25.7
SILT 57.5
CLAY 16.5
CLAYEY-SANDY SILT
CURVE A
WEIGHT PERCENT
CUMULATIVE WEIGHT PERCENT
16.5% < .004 mm
mm (approx.)
Gravel
Sand
Silt
Clay size
MODIFIED WENTWORTH SCALE


PHI SCALE
GRAVEL 0.1%
SAND 31.9
SILT 54
CLAY 14
CLAYEY-SANDY SILT
CURVE B
WEIGHT PERCENT
CUMULATIVE WEIGHT PERCENT
1% > 2 mm
14% < .004 mm
mm (approx.)
Gravel
Sand
Silt
Clay size
MODIFIED WENTWORTH SCALE

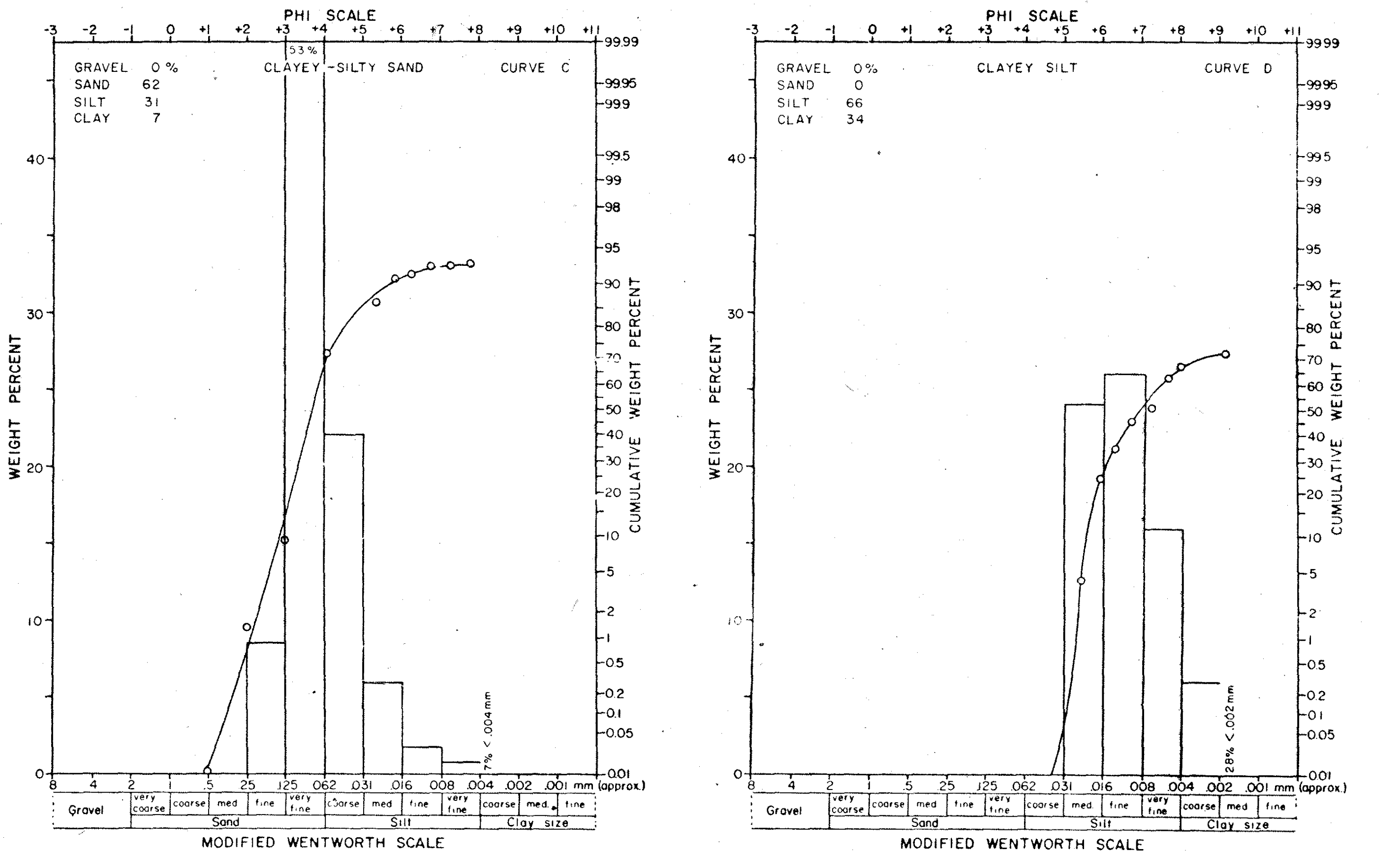


Fig. 3. Grain-size curves of silt and sand from Hanover golf course

Curves A, B, and C are of material from frost-crack excavation on southeast-facing slope (pl. 2); Curve A — silt from depth 45 cm at crack; Curve B — silt from same depth, 15 cm from crack; Curve C — sand from about 10 cm vertically below B; Curve D — silt from hummocky topography on northwest-facing slope, depth about 10 cm content of the frozen silt ranged from 27 to 48 percent of the dry weight. The highest moisture was immediately adjacent to the crack, and the amount decreased progressively away from it, reaching the lowest measured value some 15 cm distant.

No cracks were observed on this slope in the early spring of 1961 immediately after the snow disappeared (Mr. John Scully, oral communication, April 1961) and no surface indications of former cracks were observed by one of us (ALW) when walking over the slope in June 1961.

HUMMOCKY MICROTOPOGRAPHY

The hummocky microtopography of the northwest-facing slope near the 18th green was characterized by irregular mounds in clayey silt. Many mounds were without clearly defined form or diameter, but as nearly as could be determined the majority were 1—3 m long, 0,5—1 m wide, and had a relief of 7—8 cm. The best developed ones were clearly elongate up and down the slope (pl. 4), which had a gradient of about 12°.

On 8 April when the area was first visited, the ground crunched underfoot and excavation showed ice 0,5 cm thick and composed of vertically oriented crystals beneath 2,5 cm of turf. Four days later the frost table had dropped to a depth of 8 cm over mounds and depressions alike, but the depressions were springy to walk on and „soupy" at depth, whereas the mounds were relatively firm — probably because of better drainage. Irregular ice lenses up to 2 cm thick, one with a bulge 4 cm thick and 3 cm wide, were noted immediately beneath the frost table. The ice in the thick lenses had a vertical structure, due at least in part to vertically alined air bubbles. The ice was porous in places, especially adjacent to the 4-cm bulge, and several vuglike openings showed incomplete ice crystals.

In an excavation made on 18 April, the frost table was at a depth of 11—12 cm beneath two mounds and the intervening depression. Four ice lenses up to 1 cm thick, interspersed with numerous tiny lenses up to 0,1 cm thick, were observed below the mounds but none below the depressions. Another excavation showed similar relations, although here one lens was observed beneath the depression. This excavation showed also that the thicker lenses dipped away from the depression, whereas the tiny ones were more nearly parallel to the surface. The clayey silt was distinctly finer grained than the silt of the opposite, southeast-facing slope, and the moisture content was correspondingly higher, ranging from 60 to 76 percent of the dry weight at a depth of 25—30 cm. Only one clearly defined crack (it extended up and down slope) was noted in the hummocky area.

Hummocks were observed in the spring of 1961 after the snow disappeared (Mr. John Scully, oral communication, April 1961), and a trace of an up-and-downslope linear pattern where the slope was steepest was observed by one of us (ALW) in June.

INTERPRETATIONS AND CONCLUSIONS

Frost cracking is reported to be common in polar and subpolar regions (cf. Washburn 1956, p. 850—852), and the Hanover cracks are also explained as frost cracks resulting from contraction of frozen ground at low subfreezing temperatures.

The description of the hummocky microtopography and Mr. Keene's observation that the hummocks tend to form annually show that severe frost action is common. In Hanover the mean minimum temperature for January, which is normally the coldest month, is —13,6 °C. The absolute minimum is —39,7 °C (16 Feb. 1943). Frost cracking has been reported at a temperature of —10 °C (or slightly higher) in Iceland (Spethmann 1912, p. 246), and were it not for insulating snow cover or vegetation, frost cracking would probably be more common in cold regions than it is. The snowfall in Hanover was unusually low for the first part of the winter in 1958—59, the total for October through January being 71,4 cm, compared to the normal total for these months, which is 94,8 cm (table I). Even more significantly, December, the coldest month of the winter of 1958—59, had a mean temperature of —15,3 °C (1,7 °C lower than normal) and the lowest December mean of any for the period 1931—60 (table II), combined with a total snowfall through December of 41,9 cm and a mean snow cover in December of only 13,0 cm (table I). That freezing penetrated unusually deeply was confirmed by the late Mr. Phillip Coykendale of the Hanover Water Works Company, who reported that the ground froze to a depth of as much as 1,4 m (4,5 ft) in sandy clay and to about 2 m (6 ft, 4 in) in „gravel soil", whereas Company records show that freezing normally reaches a depth of only some 0,6 m (2 ft) in clay and up to 0,9 m (3 ft) in sand or gravel (Fred F. Parker, written communication, 18 Oct. 1961).

A similar combination of low temperatures and unusually slight snow cover is recorded for the winter of 1939—40, when frost cracks were also observed by Mr. Sanborn. During that winter the mean minimum temperature of the coldest month, which was January, was —16,4 °C (2,8 °C lower than normal), and the mean monthly temperature is the second lowest for January in the period 1931—60 (table II), differing

Table I

Climatic summary, Hanover, N. H.
(Data from Dartmouth College Shattuck Observatory)

	1835—1952 (Brocken record)	1876—1950							1866—1956	1935—1949	1939—1940						1958—1959					
			Warmest month (July)		Coldest month (Jan.)								Winter 1939—1940						Winter 1958—1959			
		Mean annual	Mean	Mean max.	Mean	Mean min.	Absolute max. (July)	Absolute min. (Feb.)	Mean total	Mean depth coldest month (Jan.)	Mean annual 1939	Mean annual 1940	Mean min. coldest month (Jan.)	Absolute min. (Feb.)	Total	Mean depth coldest month (Jan.)	Mean annual 1958	Mean annual 1959	Mean min. coldest month (Dec.)	Absolute min. (Dec.)	Total	Mean depth coldest month (Dec.)
Temperature (°C)		6.6	20.3	26.8	—8.1	—13.6	38.5	—39.7			6.6	5.9	—16.4	—27.8			6.5	7.8	—15.3	—28.9		
Precipitation (rain and snow) in cm	90.35																					
Snow (in cm)									185.4	25.0					193.8	13.8					192.3	13.0

by only 0,5 °C from the lowest (1945 and 1957), but differing significantly in being combined with a considerably lower snowfall. The latter from October through January was 39,2 cm and the mean snow cover in January was only 13,8 cm. Moreover, the mean January temperature in 1940 is the third lowest of any month in the period, the lowest being in February 1934 when there was much more snow.

Although the absolute minimum temperature is normally in February, the February snowfall in both the winters of 1939—40 and 1958—59 exceeded the normal, with the result that the maximum snow cover for the winter (64,3 cm in 1940, 54,1 cm in 1959), and hence the maximum insulating effect, was reached in that month. The mean temperature and the total snowfall for these two winters were near normal. Thus the combination of low temperatures and unusually thin snow cover during the first months appears to have been the critical characteristic distinguishing these two winters from most in the Hanover area. On the slopes discussed, deep freezing would have been further promoted by increased conductivity of the snow as a result of compaction by skiing.

It might be argued that the cracks were due to earthquake shocks that have been known to jolt the area, or to jarring by trains that pass on the Vermont side of the Connecticut River and do shake houses on Occum Ridge near the golf course. However, no severe earthquake shocks occurred here in the winter of 1958—59, and the fact that the cracks have been so rarely observed by those working on the golf course in the spring argues against jarring by trains as a factor. That the cracks occurred during the winter and are unrelated to desiccation cracking of the previous autumn is indicated by an observation by Mr. Sanborn that he was able to follow a crack from bare ground adjacent to a small temporary pond into the ice of the pond. This observation is the more significant because both the summer and autumn in 1939 and 1958 were drier than usual. Considering June to September, inclusive, for the period 1931—60 (table III), 1939 with 57,4 mm, and 1958 with 64,3 mm, had the second and third lowest precipitation totals (1953 had 48,1 mm). However both 1947 and 1950 also had totals of less than 70 mm. Moreover, considering June to October totals for the same period (the more critical period in view of the fact that the mean October temperature is well above freezing so that frost cracking would not be a factor), 1947, 1950, and 1953 all had lower precipitation totals and thus greater potential for desiccation cracking. Also, neither 1939 nor 1958 had the minimum precipitation for any of the months cited. Since 1940 and 1959 are the only years when cracking has been observed, it would seem that desiccation as the primary cause can be eliminated. The correlation of cracking with low temperature

Table II

Mean temperature (°C) at Hanover, New Hampshire, for the period 1931—1960
(Data from Lautzenheiser, 1961, but converted to °C)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1931	− 8.0	− 5.8	+ 0.9	+ 7.3	+ 13.1	+ 17.6	+ 22.1	+ 19.0	+ 16.7	+ 10.0	+ 5.1	− 3.8	+ 7.8
1932	− 1.1	− 5.3	− 2.6	+ 5.2	+ 13.0	+ 17.1	+ 18.9	+ 20.2	+ 15.7	+ 10.4	+ 1.0	− 2.7	+ 7.5
1933	− 1.6	− 3.6	− 2.0	+ 6.2	+ 13.9	+ 19.0	+ 21.1	+ 19.4	+ 15.9	+ 8.1	− 1.3	− 8.6	+ 7.2
1934	− 7.0	− 13.3	− 2.3	+ 7.0	+ 13.6	+ 18.5	+ 21.1	+ 17.4	+ 17.4	+ 7.2	+ 4.1	− 6.7	+ 6.4
1935	− 10.8	− 7.3	− 0.7	+ 5.8	+ 10.6	+ 17.9	+ 21.6	+ 19.8	+ 13.4	+ 8.7	+ 4.4	− 7.2	+ 6.3
1936	− 8.6	− 10.4	− 3.1	+ 5.2	+ 14.6	+ 18.2	+ 19.4	+ 18.9	+ 15.8	+ 8.8	− 0.2	− 3.7	+ 6.8
1937	− 2.4	− 3.6	− 3.7	+ 5.2	+ 13.7	+ 18.0	+ 21.2	+ 22.2	+ 14.9	+ 8.2	+ 2.3	− 6.1	+ 7.5
1938	− 8.5	− 4.7	+ 0.6	+ 8.0	+ 12.2	+ 19.0	+ 20.9	+ 21.1	+ 13.2	+ 10.3	+ 2.6	− 4.0	+ 7.6
1939	− 8.3	− 6.2	− 3.9	+ 3.8	+ 13.0	+ 18.1	+ 20.9	+ 21.6	+ 15.3	+ 8.6	+ 0.4	− 4.9	+ 6.5
1940	− 11.0	− 6.7	− 2.7	+ 3.8	+ 13.2	+ 17.1	+ 20.4	+ 18.7	+ 14.4	+ 6.8	+ 2.1	− 5.1	+ 5.9
1941	− 9.4	− 6.1	−3.4	+ 9.7	+ 13.2	+ 18.8	+ 21.1	+ 17.6	+ 15.6	+ 8.0	+ 3.9	− 3.8	+ 7.1
1942	− 7.2	− 7.9	+ 1.9	+ 7.8	+ 14.8	+ 17.9	+ 19.9	+ 19.1	+ 15.2	+ 9.6	+ 1.1	− 7.1	+ 7.1
1943	− 10.4	− 6.3	− 2.4	+ 2.8	+ 12.1	+ 19.1	+ 20.2	+ 18.3	+ 13.8	+ 9.1	+ 1.2	− 8.3	+ 5.7
1944	− 7.3	− 7.8	− 3.6	+ 3.8	+ 15.4	+ 17.7	+ 20.8	+ 21.1	+ 16.0	+ 7.8	+ 1.7	− 6.9	+ 6.6

Table II (cont.)

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1945	−11.1	−5.6	+4.2	+8.9	+10.8	+17.7	+20.2	+19.3	+16.2	+7.7	+2.5	−8.0	+6.9
1946	−8.1	−8.8	+4.9	+5.7	+11.9	+17.5	+19.8	+17.7	+16.3	+10.3	+3.9	−4.3	+7.2
1947	−6.4	−7.2	−1.3	+4.7	+12.0	+16.8	+21.7	+21.2	+15.7	+12.4	+0.2	−7.9	+6.8
1948	−10.7	−9.1	−1.2	+6.8	+11.4	+16.9	+20.3	+19.9	+15.3	+8.1	+5.6	−2.4	+6.7
1949	−3.2	−3.9	+0.7	+7.7	+13.4	+20.7	+22.3	+20.5	+14.2	+11.0	+1.1	−3.1	+8.4
1950	−3.7	−8.2	−3.9	+4.6	+12.8	+17.7	+19.6	+18.5	+12.4	+9.9	+2.7	−3.2	+6.6
1951	−5.2	−3.7	+0.1	+7.3	+13.2	+17.3	+20.6	+18.9	+14.9	+9.4	+0.1	−4.9	+7.3
1952	−5.7	−4.3	−0.5	+7.6	+10.9	+18.6	+22.2	+20.0	+16.2	+7.3	+2.8	−2.9	+7.7
1953	−4.3	−3.7	+1.2	+6.9	+14.1	+19.2	+21.4	+19.4	+15.6	+9.8	+4.8	−0.5	+8.7
1954	−9.3	−2.5	−0.7	+7.1	+11.7	+17.9	+19.2	+17.9	+13.9	+11.1	+3.1	−3.9	+7.1
1955	−8.3	−4.7	−1.1	+7.7	+15.0	+18.2	+22.8	+21.4	+14.7	+9.4	+1.6	−8.6	+7.3
1956	−5.1	−4.3	−3.7	+4.1	+10.1	+18.1	+18.9	+18.7	+13.1	+9.3	+3.6	−2.9	+6.7
1957	−11.1	−3.3	+0.6	+8.0	+12.8	+19.7	+19.9	+17.8	+16.3	+9.4	+4.3	−0.9	+7.8
1958	−6.0	−8.6	+1.8	+7.4	+11.2	+14.9	+20.2	+19.7	+15.2	+8.1	+3.1	−9.7	+6.4
1959	−7.3	−8.9	−1.2	+7.2	+15.0	+17.8	+21.9	+21.1	+17.1	+9.1	+2.8	−2.3	+7.7
1960	−6.5	−2.7	−3.6	+7.1	+15.3	+18.0	+19.4	+19.7	+15.9	+7.9	+4.1	−7.2	+7.3

Table III

Total and mean precipitation (mm) at Hanover, New Hampshire, for the period 1931—1960
(Data from Lautzenheiser, 1961, but converted to mm)

Year	Total													Mean		
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann'l	May-Oct.	June-Sept.	June-Oct.
1931	41.4	29.5	50.3	60.5	108.2	148.6	187.5	62.7	122.7	71.4	35.8	8.31	1001	116.8	130.3	118.6
1932	100.6	50.8	82.3	62.6	28.2	61.5	70.6	113.0	85.6	79.5	121.7	29.5	886	73.2	82.8	82.0
1933	49.3	65.8	86.4	159.0	46.5	149.9	34.8	126.0	71.4	97.0	41.2	79.5	1006	87.6	95.5	95.8
1934	57.7	51.8	48.3	124.7	60.2	86.6	99.8	33.3	124.0	45.0	106.7	79.3	916	74.7	83.3	77.7
1935	129.8	52.1	36.3	65.5	51.3	115.8	111.8	73.7	106.7	23.6	114.1	25.4	905	80.5	102.1	86.4
1936	120.4	54.9	143.0	101.1	66.0	55.6	95.0	112.3	35.8	127.3	53.6	105.4	1070	82.0	74.7	85.1
1937	81.3	54.1	88.7	78.2	163.6	106.7	169.9	50.0	27.4	94.0	78.5	76.7	1068	101.9	88.7	89.7
1938	85.1	51.8	34.8	58.2	47.5	53.3	151.4	124.7	225.6	56.1	71.6	101.6	1063	109.7	138.7	122.2
1939	77.2	75.7	59.9	102.4	45.5	58.9	48.8	57.7	64.5	113.8	25.4	62.5	792	64.8	57.4	68.8
1940	25.4	72.4	99.1	88.1	116.8	46.2	131.8	36.1	118.1	21.3	114.6	76.5	945	78.5	83.1	70.6
1941	39.4	38.9	51.6	12.5	61.2	56.4	232.9	78.2	25.4	75.7	57.9	65.0	795	88.4	98.3	93.7
1942	48.0	33.0	105.7	65.3	89.9	94.5	70.6	16.8	111.5	52.1	122.9	72.4	882	72.6	73.4	69.1
1943	57.2	32.5	44.5	83.1	105.9	91.4	125.7	149.1	47.8	125.5	136.1	15.5	1015	107.7	103.6	108.0
1944	43.2	61.0	74.7	70.1	64.5	131.8	61.2	22.9	120.9	77.5	61.5	42.9	831	79.8	84.3	82.8

Table III (cont.)

Year	Total													Mean		
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann'l	May-Oct.	June-Sept.	June-Oct.
1945	89.7	65.0	40.4	127.5	124.0	105.9	153.9	17.8	103.6	111.0	134.6	82.0	1155	102.6	95.3	98.6
1946	56.9	54.9	32.0	62.5	107.4	75.2	71.1	120.1	118.9	68.6	42.4	96.8	907	94.0	96.3	90.7
1947	91.4	55.1	61.7	46.7	128.3	117.6	99.8	38.1	19.8	11.4	117.1	58.7	846	69.1	68.8	57.4
1948	67.8	45.2	61.2	84.6	111.5	70.9	116.1	72.6	33.3	55.6	133.6	75.2	928	76.7	73.2	69.6
1949	78.0	51.3	43.2	54.9	60.7	78.0	120.4	78.2	92.0	62.7	47.0	49.3	816	82.0	92.2	86.4
1950	96.8	59.9	76.5	49.5	36.8	63.5	74.7	100.1	39.4	45.0	122.2	54.4	819	59.9	69.3	64.5
1951	43.9	113.0	103.4	111.3	62.7	65.5	134.9	86.4	74.2	89.4	113.3	107.7	1105	85.6	90.2	90.2
1952	65.3	93.7	52.6	89.4	81.3	132.3	93.2	32.5	63.8	51.8	30.5	118.6	904	76.0	80.5	74.7
1953	106.9	47.5	126.5	98.3	111.3	10.9	50.6	80.3	50.0	93.7	55.4	73.4	904	66.0	48.0	57.2
1954	70.4	95.0	89.9	110.7	173.2	126.5	110.2	78.7	121.9	38.4	110.0	65.3	1190	108.2	109.5	95.3
1955	25.2	83.3	71.6	62.2	85.9	81.5	112.0	226.6	45.0	75.7	70.4	16.0	955	104.4	116.3	108.2
1956	80.0	62.2	112.8	77.5	85.6	70.4	102.4	56.4	125.0	25.2	55.1	96.8	948	77.5	88.7	76.0
1957	42.2	30.0	37.3	36.8	57.4	89.2	124.2	23.1	92.5	45.5	124.7	113.0	815	71.9	82.3	74.9
1958	168.2	89.2	53.1	82.3	82.8	32.5	89.9	67.1	67.1	87.6	70.1	26.7	917	71.1	64.3	68.8
1959	84.1	68.8	80.3	42.7	43.9	81.8	41.9	159.8	70.6	141.5	146.3	81.8	1042	89.9	88.7	99.1
1960	65.8	91.7	60.2	113.8	107.4	57.4	97.8	41.7	170.4	84.3	49.3	38.9	978	93.2	92.0	90.4

and low snowfall, discussed above, is clearly much closer than the correlation with desiccation.

Although frost cracking of the ground is commonly regarded as confined to polar and subpolar regions, it is not a purely polar or subpolar process. Low winter temperatures are by no means confined to those environments, nor are sudden drops of temperature, which promote frost cracking (Lachenbruch 1960, p. B406). However, it is unlikely that cracks of the kind described from the Hanover golf course would become filled with adjacent material in a manner to simulate ice-wedge casts, especially those recording former ice-wedge polygons, which are necessarily associated with permafrost (cf. Washburn 1956, p. 831—833). Nevertheless freezing penetrated the ground to a depth of about 2 m (6 ft, 4 in) in Hanover during the winter of 1958—59, and was accompanied by appreciable frost cracking; in some middle-latitude environments seasonal frost extends even deeper. A maximum depth of 2,7 m (9 ft) has been reported in Minnesota, and maximum depths of 1,8—2,7 m (6—9 ft) are mapped as probable in neighbouring northern states (*Heating* & *Ventilating*, 1938).

Hopkins, Karlstrom and others (1955, p. 139; pl. 39) reported frost-crack polygons in Alaska in areas free of permafrost. If seasonal frost can produce such structures in Alaska, the possibility must be recognized that deep seasonal freezing in middle-latitude climates may develop similar, though smaller, frost-crack structures that might not only simulate those associated with seasonal frost action in a high-latitude environment, but perhaps also simulate those commonly regarded as characteristic of permafrost.

In summary it is concluded that:

(1) Frost cracking occurred at Hanover, New Hampshire, during the winters of 1939—40 and 1958—59, but is rare there compared to development of hummocky microtopography by frost action.

(2) Since frost cracking can occur in a middle-latitude climate, some „fossil" frost-crack structures, too, may have originated in such a climate.

(3) Frost cracking unrelated to permafrost may produce structures simulating ice-wedge casts (especially, narrow and shallow ones) associated with former permafrost; this would be particularly likely in subpolar climates but the possibility cannot be excluded that it may also happen in middle-latitude climates characterized by deeply penetrating frost.

(4) It is possible to make significant errors in reconstructing climates from „fossil" frost-crack and related structures unless there is clear proof of their specific significance for distinguishing between a permafrost, subpolar, or even middle-latitude climate.

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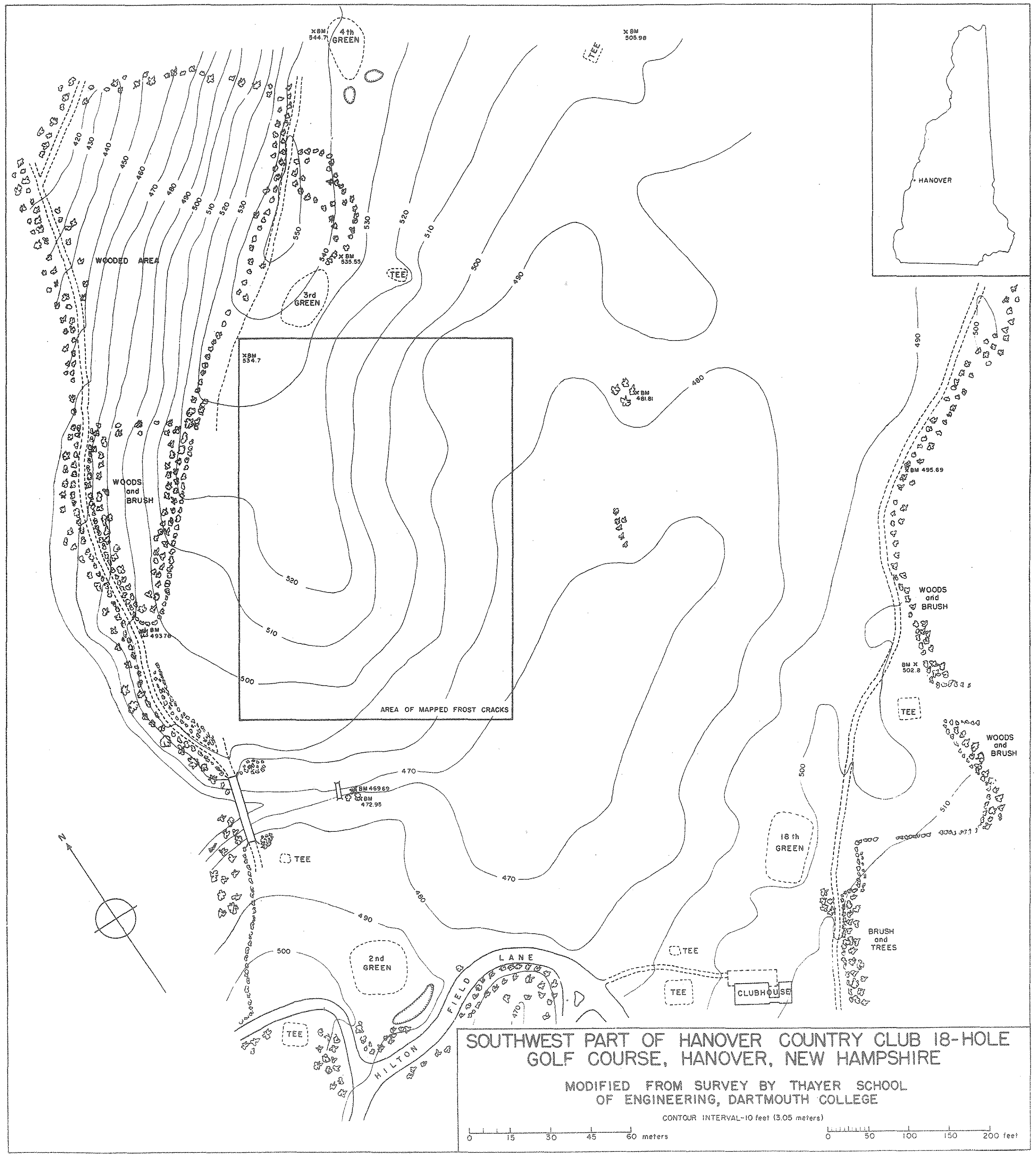

Fig. 1. Southwest part of Hanover Country Club 18-hole golf course, Hanover, New Hampshire

Pl. 1. Frost crack on southeast-facing slope, Hanover golf course

View diagonally upslope. Scale given by 17-cm rule at center

Pl. 2. Excavation along frost crack on southeast-facing slope, Hanover golf course (cf. fig. 2)

View upslope. Scale given by 17-cm rule. Rule lies at base of vertical back wall of pit; bottom of pit in foreground is parallel to surface of slope

Pl. 3. Intersecting frost cracks on southeast-facing slope, Hanover golf course

Scale given by pocket knives and rule in cracks

Pl. 4. Hummocky microtopography on northwest-facing slope, Hanover golf course

View upslope. Scale given by 17-cm rule adjacent to excavation at left