Thermal Contraction Cracks in an Arctic Tundra Environment

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ABSTRACT. Field observations in the Mackenzie Delta area largely substantiate Lachenbruch's theoretical considerations of thermal contraction crack development. Frost crack patterns, representing the incipient stage of tundra polygons, were observed on both bare and vegetated surfaces of low alluvial flats and sandspits of three islands. Individual polygons, where developed, ranged in size from 20 to 30 metres diameter on bare surfaces to 2 to 3 metres on sedge-covered areas, and 80 per cent of the angular intersections measured were of the orthogonal type. Most cracks exhibited random orientations, except in close proximity to water bodies where tendencies toward normal and subparallel orientations occurred.

RÉSUMÉ. *Fentes de contraction thermique dans un milieu de toundra arctique.* Des observations sur le terrain, dans la région du delta du Mackenzie, appuient largement les considérations théoriques de Lachenbruch sur le développement des fentes de contraction thermique. Des figurés de fentes de gel, représentant le stade initial de polygones de toundra, ont été observés à la fois sur des surfaces nues et sur des surfaces recouvertes de végétation, sur des alluvions et des flèches sableuses de trois îles. Les polygones individuellement développés mesurent de 20 à 30 mètres de diamètre sur les surfaces nues, et de 2 à 3 mètres sur les surfaces peuplées de laîches; 80 pour cent des intersections angulaires mesurées sont de type orthogonal. La plupart des fentes sont orientées au hasard, sauf au voisinage de nappes d'eau, où apparaissent des tendances à des orientations normales et subparallèles.

РЕЗЮМЕ. *Термические контракционные трещины в условиях арктической тундры.* Полевые наблюдения, выполненные в дельте реки Макензи, в значительной степени подтверждают теорию развития контракционных термических трещин, предложенную Лахенбрухом. Структура мерзлотных трещин, представляющих начальную стадию тундровых полигонов, была исследована как на лишенных, так и обладающих растительностью низких аллювиальных береговых участках и песчаных косах трех островов. Размеры отдельных сформировавшихся полигонов колеблются от 20 до 30 метров в диаметре на голых, и от 2 до 3 метров на заросших камышом участках почвы. 80% всех обмеренных полигонов оказались ортогонального типа. За исключением случаев тесной близости к воде, когда наблюдается тенденция к параллельному или перпендикулярному расположению, большинство трещин обладает случайной ориентацией.

INTRODUCTION

Patterned ground in the Mackenzie Delta area is restricted primarily to non-sorted types (Washburn 1956). Although other factors may be involved, the absence of the sorted forms can largely be attributed to the fact that the mantle frequently lacks a sufficient concentration of stones to exhibit marked frost sorting (Mackay 1963, cf. Mackay 1967). Of the non-sorted forms, tundra or ice-wedge polygons constitute one of the most widespread types of patterned ground in the delta area, and this paper describes some aspects of thermal contraction cracks, which represent the incipient stage of tundra polygon development.

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Leffingwell (1915), working on the coastal plain of northern Alaska, was among the first to postulate that the networks of tundra polygons were generated by contraction cracks in the frozen ground, produced by intense stresses created as a result of pronounced seasonal changes in the ground temperature. His "thermal contraction" theory was outlined as follows (Leffingwell 1915):

> The permanently frozen ground contracts in the cold Arctic winter and cracks are formed which divide the surface into polygonal blocks. In the spring these frost cracks become filled with surface water which immediately freezes. In the expansion of the frozen ground as the temperature rises in summer, the vein of ice becomes more rigid than the country formation, and the readjustment takes place in the latter. The result is to bulge up the inclosed block either bodily or else locally along the sides of the ice. During the next winter's cold wave a new crack forms at the same locus so that a continually growing wedge of ground ice is formed. Thus the tundra becomes underlain by a network of ice-wedges, which inclose bodies of the original formation.

The general principles of Leffingwell's contraction theory have been accepted by most of the subsequent research workers investigating tundra polygons. Despite the voluminous literature on this subject, however, the precise details of their origin are still imperfectly understood. Black (1952) and Lachenbruch (1962) attribute some of this ignorance to an absence of quantitative, rather than qualitative, data but it may also reflect the paucity of observations describing the initial development of the frost crack patterns.

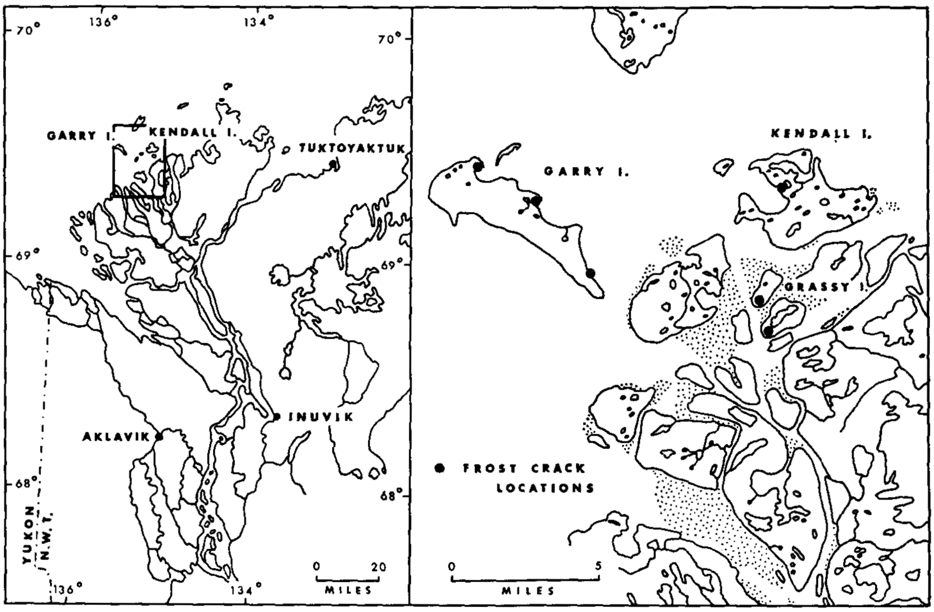

FIG. 1. Location Map.

INCIPIENT FROST CRACK PATTERNS

An examination of the literature pertaining to tundra polygons reveals abundant references to, and descriptions of, the polygonal ground in relatively advanced stages of development, but surprisingly little relating to the formation of the initial frost crack patterns. Leffingwell (1919) shows illustrations of incipient cracks on the coastal plain of northern Alaska, and Black (1952) also makes brief reference to similar features. Lachenbruch (1962) has made a theoretical study of frost crack patterns in his examination of Leffingwell's thermal contraction hypothesis from the point of view of mechanics, but he does not cite any field evidence to corroborate his conclusions. Washburn *et al.* (1963), to my knowledge, have produced one of the few papers describing the occurrence of frost cracks, albeit in a non-arctic environment.

Observations in the Mackenzie Delta area during the summers of 1964 and 1965 revealed 3 locations where incipient frost cracks had developed on the ground surface. The locations, each characterized by an absence of any major relief features and elevations of less than 1 metre (3 feet) above mean sea level, included lake-strewn, alluvial flats on Kendall and Grassy Islands and the flats bordering the lagoons enclosed behind sandspits on Garry Island (Fig. 1). All of these sites are frequently inundated during periods of high water, especially during storm surges. The frost cracks were found to be equally well developed on bare

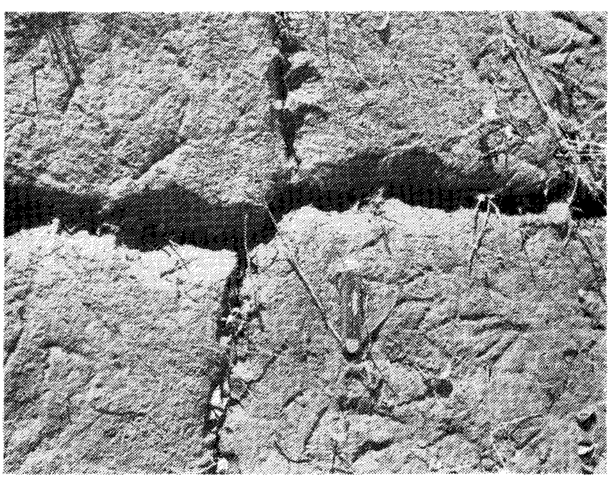

FIG. 2. Orthogonal intersections of frost cracks on bare alluvial surface of Grassy Island, Mackenzie Delta, N.W.T.

ground surfaces (Fig. 2), and on flats supporting a dense cover of grasses and sedges 20 to 40 cms. (8.0 to 15.5 inches) tall (Fig. 3). In these latter areas, the vegetation was flattened, presumably by a combination of prevailing winds, snowfall and flood surges in the preceding fall. The vegetation was cut by sharp, knife-like fractures and was probably frozen to the ground surface at the time of the frost cracking to produce the clean break. In many places, the cracks were observed to extend beneath the surfaces of shallow lakes, though none was traced entirely across the lake floor. This indicates that the water, at least in the shallower parts of the lakes, was frozen to the bottom although water in the central

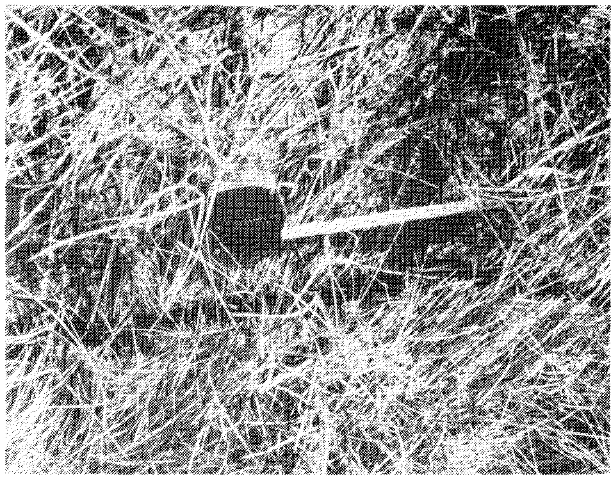

FIG. 3. Frost cracks developed through a layer of vegetation on Kendall Island. N.W.T.

sections of the lakes may have remained unfrozen at depth. The fact that the fissures on Kendall Island cut through the vegetation into the underlying mineral soil, would appear to substantiate the view that the cracks were produced by intensive frost action. The cracks on the bare ground surfaces were interpreted as having originated in a similar manner, although the possibility that they were produced by desiccation of the soil cannot definitely be excluded.

Excavations in one of the sandspit-lagoon areas on Garry Island revealed that the frost cracks were best developed in organic-rich silts and silty loams. Mechanical analyses of the soils showed that they were composed of 59.2 per cent silt, 21.3 per cent sand, and 19.5 per cent clay (Wentworth classification categories). The soils were mantled by a thin layer of organic material, and the organic content of the soil samples averaged 5.5 per cent by weight of the dried sample. The surficial organic layer and the organic matter at depth, often in the form of thin intercalations, probably represent washed peat derived through erosion of the adjacent coastal bluffs. The soils also possessed a high moisture content, with frozen samples having an average ice content of 91.7 per cent (expressed as weight of ice to dry soil). Mackay (1965) has already documented the granulometric composition of the soils underlying the sedge-covered flats on Kendall Island, where the proportions of clay and sand were slightly lower (silt 79 per cent, sand 13 per cent and clay 8 per cent).

Most of the frost cracks exhibited little or no topographic expression at the ground surface, but some of the larger fissures traversing the unvegetated areas were marked by the presence of shallow troughs 30 to 70 cms. (12.0-27.5 inches) across and 10-20 cms. (4-8 inches) deep. When examined in early August 1964, the frost cracks on Garry Island exhibited a wedge-like form extending down through the active layer and into the frozen ground at depths of 50 cms. (19.5 inches) below the ground surface. At the surface, the open fissures were up to 4 cms. (1.5 inches) across, and they remained open to depths of 15 to 25 cms. (6 to 10 inches) but narrowed to only a few millimetres in width at the level of the frost table. In many localities, the cracks were infilled at depth by sand-size material that had probably been blown or washed in from the ground surface. These miniature sand-wedges are similar in form to the larger scale features described by Péwé (1959) in the McMurdo Sound area of Antarctica. Below the level of the frost table, the cracks were occupied by small veins of ice, approximately one millimetre across, which could be traced to a depth of 76 cms. (30 inches) below the ground surface.

Rarely did the frost cracks in the sandspit-lagoon areas of Garry Island reveal any arrangement into a definite polygonal network. The majority of the fissures appeared to be randomly distributed over the ground surface, and showed no preferred directional orientation except for a weak tendency to occur along lines developed at right angles and parallel to the margins of the lagoons. The only other salient feature of the distribution was the contrast in the density of the pattern between the silty loam and coarser sand areas of the sandspit. Although the frost cracks were present in both of these areas, the density was much higher in the silty loam sections.

The distribution of the frost cracks on Kendall and Grassy Islands showed a much greater tendency to be organized into crude polygonal patterns. Fig. 4 shows the spatial arrangement of the frost cracks on a part of the sedge-covered flat on Kendall Island. As may be seen, the ground surface was subdivided into a number of highly irregular polygons of variable size but averaging 2 to 3 metres (6.5 to 10.0 feet) across. The majority of these irregularly-shaped polygons were 4- or 5-sided, and hexagonal forms were notably conspicuous by their absence. Most of the fissures on Kendall Island also exhibited little preferred directional orientation except in the vicinity of the larger water bodies.

The spatial distribution of the frost cracks on Grassy Island demonstrated the existence of a much more regular polygonal network, although on a considerably larger scale. On these bare alluvial flats the individual polygons averaged 20 to 30 metres (65 to 100 feet) across, and tetragonal forms were predominant. The pattern of these frost cracks moreover revealed much stronger trends in their preferred directional orientation. The larger fissures, up to 5 cms. (2 inches) wide and located in the floors of shallow troughs in the ground surface, were oriented at right angles to the bank of a distributary of the Mackenzie River. The smaller cracks, less open and having almost no topographic expression on the ground surface, on the other hand, were aligned more or less parallel to the same river bank. These preferred orientations were especially noticeable within distances of approximately 50 to 60 metres (165 to 200 feet) from the edge of the channel, but became less distinct with increasing distance from the bank.

ANGULAR INTERSECTION PATTERNS

It is generally agreed that frost cracks originate as a result of large thermal stresses created by a sudden cooling of the ground (Lachenbruch 1962):

> When the tensile strength (of the ground) is exceeded near the surface, a tension crack forms and propagates downward. . . . The formation of a crack causes a local relief of tension in the surficial materials. . . . Each

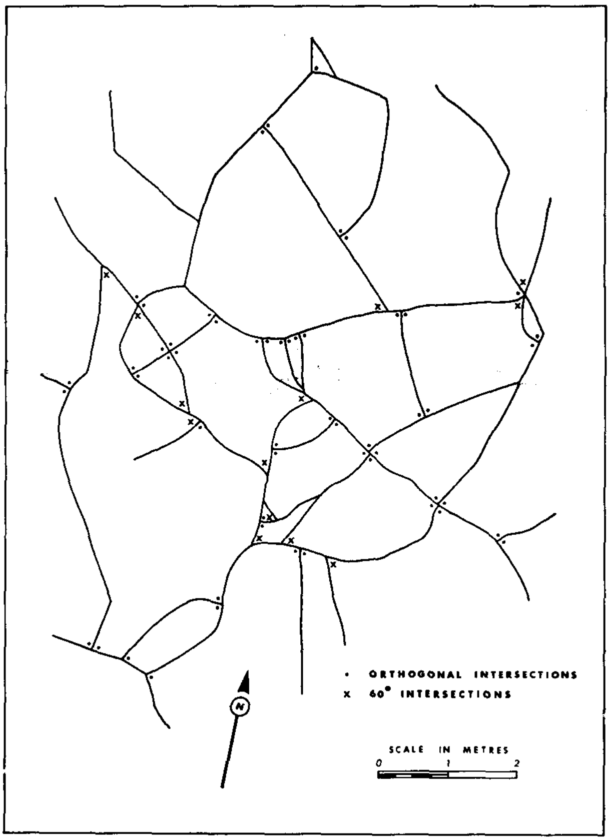

FIG. 4. Incipient frost crack pattern on Kendall Island, N.W.T.

crack is, therefore, surrounded by a band in which cracking has caused appreciable reduction of horizontal tension — the "zone of stress relief". . . . The component of thermal tension at the ground surface in the direction parallel to the crack is relieved only slightly by the cracking and, thus, large horizontal stress differences occur within the zone of stress relief. A second crack entering this zone tends to align itself perpendicular to the direction of greatest tension, and, hence, tends to intersect the first crack at right angles. Conversely, the occurrence of an orthogonal intersection generally implies that one of the cracks predated the other.

Lachenbruch's conclusion that the angular intersections of a polygonal network of frost cracks will exhibit a preferred tendency towards an orthogonal pattern, contrasts with many descriptions of polygonal ground in which authors have expressed a tendency for hexagonal forms and angular intersections of 120 degrees to predominate (Leffingwell 1915; Conrad 1946; Black 1952). The implications of the hexagonal pattern, and angular intersections of 120 degrees, are that the frost cracks originated at a series of points and each crack developed more or less simultaneously. In an attempt to determine the validity of Lachenbruch's conclusion, particular attention was paid to the nature of the angular

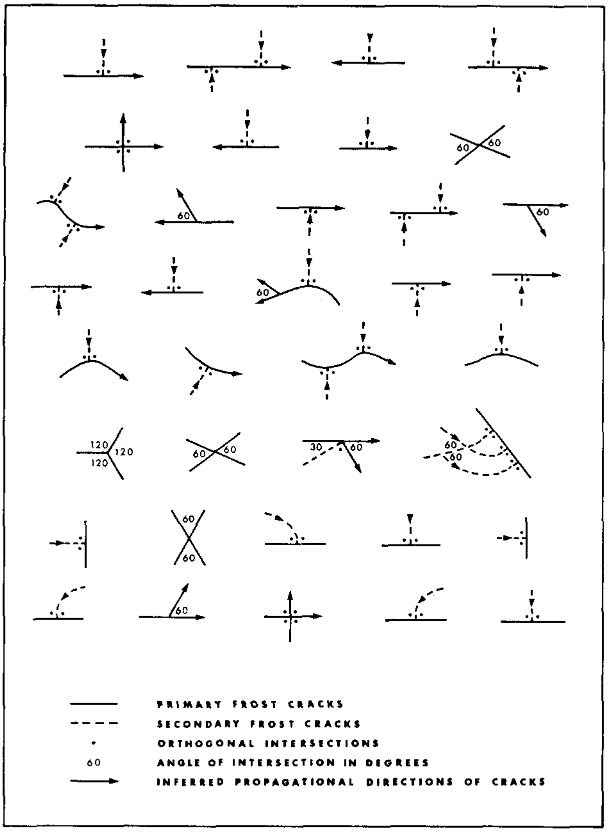

FIG. 5. Diagrammatic sketches of frost crack intersection patterns.

intersections of the frost crack patterns on Garry and adjacent islands. A total of 101 angular measurements was recorded including those shown in Fig. 4. An additional fifty intersection patterns are illustrated diagrammatically in Fig. 5, where an attempt has also been made to indicate the relative order of occurrence and propagational direction of each of the fissures. Primary frost cracks, usually the larger, are defined as those which originated first at any location, and their propagational directions were inferred, wherever possible, from their orientation with respect to the water bodies (i.e. cracks which were oriented at right angles to, and propagated outward from, the body of water). Secondary frost cracks are defined as those which developed later at each location, and these cracks terminate at, and propagate towards, pre-existing primary fissures.

Of the 101 angular measurements recorded, no fewer than 79, or 80 per cent, were of the orthogonal type. As Figs. 4 and 5 indicate, most of these orthogonal intersections were formed by the junction of a primary and secondary frost crack, and only rarely were two primary frost cracks observed to intersect one another. The influence of a zone of stress relief is also manifest in the manner in which many of the secondary fissures curve to intersect the primary cracks at right angles. Where the primary cracks were sinuous, the most favoured loci for the intersection points of secondary frost cracks were located on the convex sides of the curves. This is in accordance with the distributional pattern of stress relief on a curved section of a frost crack as described by Lachenbruch (1962).

Angular intersection values of 60 degrees were by far the most common of the non-orthogonal intersection patterns. This angle was most frequently developed as a result of the bifurcation of a primary frost crack, and at points of intersection where 2 frost cracks of the same order approached one another obliquely. A great majority of the angles measured were either 90 degrees or 60 degrees, and only 2 examples were found of tri-radial intersections, forming 3 obtuse angles of about 120 degrees, suggesting that the frost cracks originated at a point (Fig. 6).

FIG. 6. Frost crack intersection pattern forming three obtuse angles of about 120 degrees, Kendall Island, Delta, N.W.T.

SUMMARY

The field evidence collected in the outer Mackenzie Delta area thus appears to substantiate the conclusions of Lachenbruch's theoretical study. Primary frost cracks were developed, essentially in a random pattern, across the ground surface, and the junctions of secondary frost cracks with these primary fissures showed a definite preferred tendency towards an orthogonal intersection pattern. According to Lachenbruch's classification scheme, the resultant crude polygonal network would therefore be classified as a 'random orthogonal system' (Lachenbruch 1962). Only in the vicinity of large bodies of water did preferred directional orientations become sufficiently pronounced to be classified as 'oriented orthogonal systems'.

The apparent dichotomy between this evidence and the fact that most tundra polygons appear to be of a non-orthogonal type has been explained by Lachenbruch to be the result of an obscuring of the intersection angles by the growth of large ice-wedges (Lachenbruch 1962). The incipient frost crack pattern, therefore, is practically the only stage in the development of a network of polygonal ground in which the angular intersection patterns can be determined with any real degree of accuracy. Moreover, these determinations can only be made in the field through ground inspection, since the frost cracks are generally too small to be identified from aerial photographs.

The transformation of an initial pattern of frost cracks into a network of tundra or ice-wedge polygons requires that recurrent fracturing takes place at the same loci. The evidence collected on Garry Island suggests that once a fracture is formed, it tends to persist as a permanent line of weakness in the mantle. Most of the larger cracks remained as open fissures throughout the summer months, possibly indicating that the ground was sufficiently elastic to absorb the strain produced by its expansion under the summer's heat and consequently no deformation took place (Leffingwell 1915). Where the ground surface was covered by a thin layer of washed peat, it is also possible that the maintenance of the open fissure may have been aided locally by a slight desiccation and shrinkage of this layer. Even where the cracks were closed, this probably did not take place before some material had infiltrated from the ground surface, and the miniature sand-wedges, produced in this manner, also assist in the preservation of the lines of weakness.

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