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ICE WEDGES AND INVOLUTIONS IN SCOTLAND

Abstract

Wedges and involutions found at 60 localities in Scoltland are briefly described. Some developed during an interstadial phase of the last glaciation, others during the final retreat of the glaciers up to the close of the Younger Tundra period (Zone III of the pollen sequence). A few involutions seem to have developed as late as the succeeding pre-Boreal period. The wedges occur in glacifluvial deposits, and fine to medium-sized gravel seems the most favourable material, but involutions are found not only in glacifluvial material, but also in till, glacimarine, and eolian deposits and in chemically weathered rock. Classifications of wedges on the basis of shape, disturbance of the surrounding material, and mode of formation are shown to be of little value in Scotland. Most involutions seem to have been caused by the pressures created by the growth of ice masses in the ground, rather than by the squeezing of wet unconsolidated material between the permafrost table and a surficial frozen crust. Correlation of involutions with specific types of patterned ground is regarded as premature.

INTRODUCTION

Periglacial studies in Europe north of the Alps and Carpathians have concentrated mainly on contemporary phenomena on mountains and in the Arctic, or on fossil phenomena in a belt passsing from west to east across the middle of the Continent. Between these two zones of contemporary and fossil periglaciation lies the area occupied by the Fenno-Scandian and British ice sheets during the glacial phases of the Pleistocene. Until recent years it was believed that fossil periglacial phenomena in this formerly glaciated area were insignificant, e.g. Dines et al. (1940) indicated that solifluction deposits in Yorkshire occurred only outside the terminal moraine of the last glaciation. Poser stated in 1948, on the basis of the information then available, that no ice wedges were to be found within the limits of the last glaciation in North Germany. More recent work has shown, however, that fossil periglacial phenomena associated with severe climatic conditions are to be found even in the formerly glaciated parts of Northern Europe, e.g. the work of Lembke (1954), Schultz (1956), and Pierzchałko (1956). In the British Isles too, interest in periglaciation in the northern, glaciated part of the country

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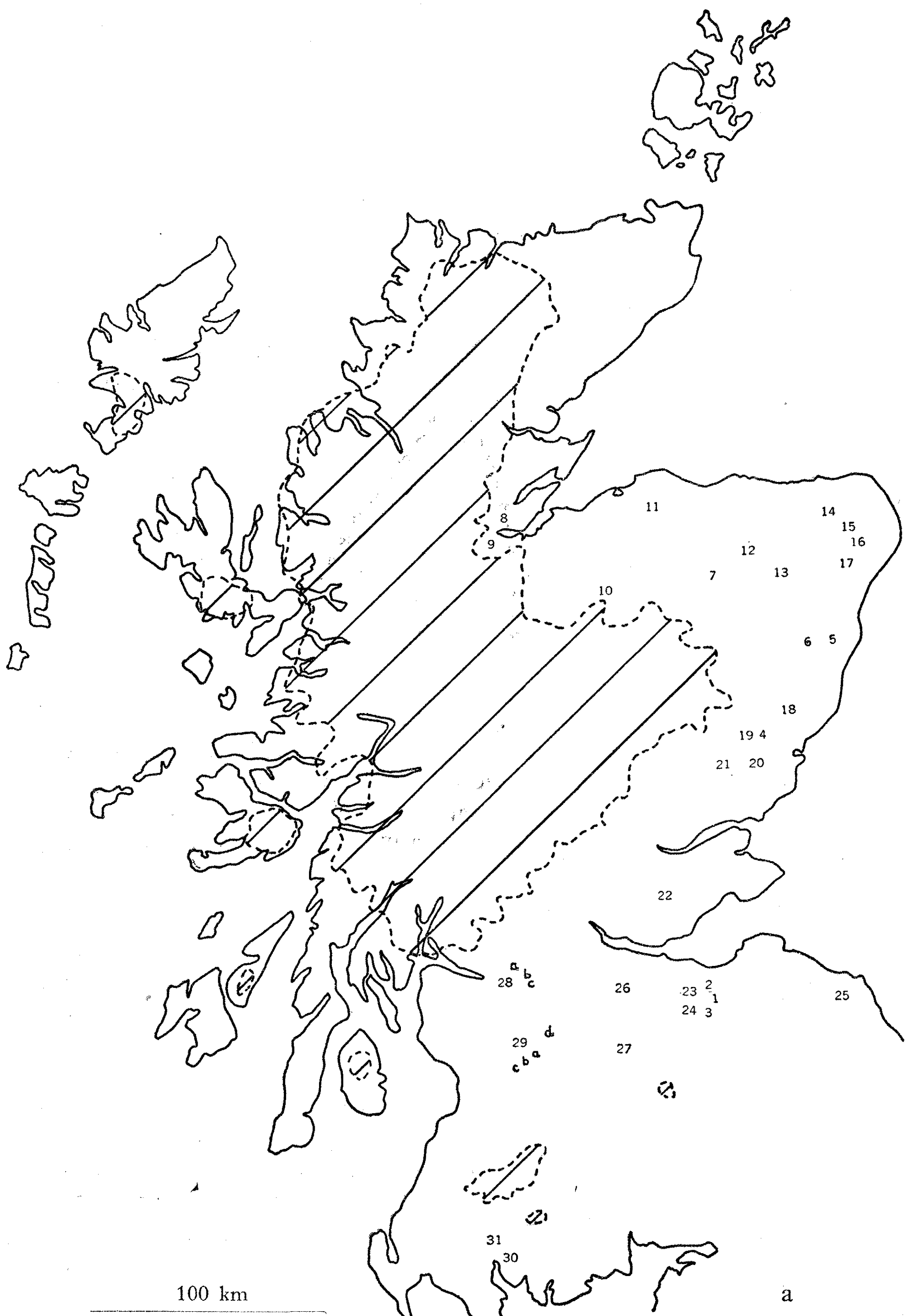
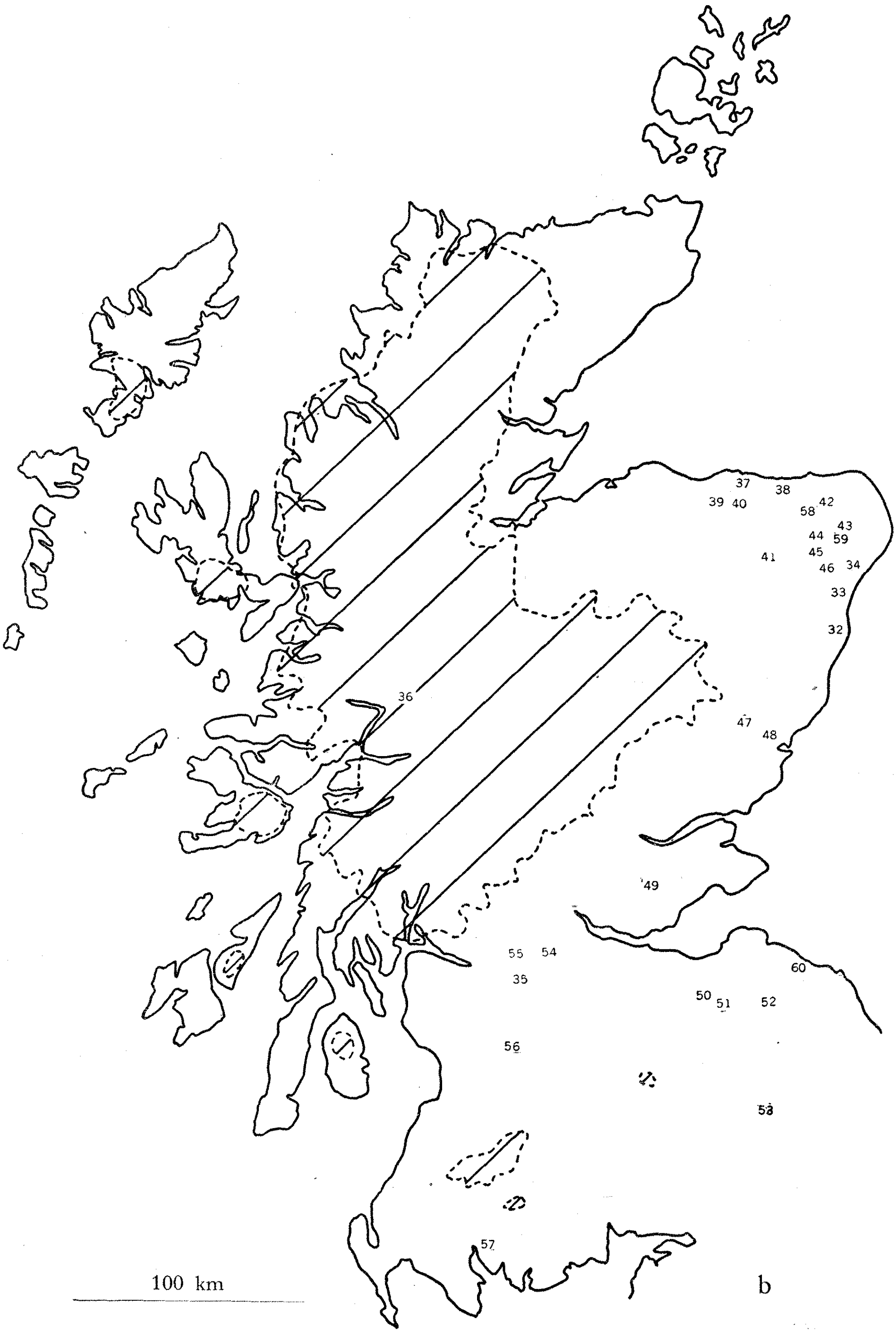


Fig. 1. Distribution of wedges and involutions in Scotland

a. wedges; b. involutions; shaded area shows the extent of the ice cap during the Zone III period (mainly after Charlesworth)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has grown in the last decade. This is reflected in the Progress Report prepared by FitzPatrick in 1956: almost all work on fossil periglacial phenomena published up to that year dealt with the southern part of the country, while work actually in progress, on the other hand, was mostly proceeding in the northern part, within the glaciated zone.

The present study is in line with this recent trend and contributes to the knowledge of periglaciation in a part of northern Europe that has suffered intense and prolonged glaciation. Since ice covered the country for a considerable proportion of the cold phases of the Pleistocene, periglacial phenomena could only develop during limited periods before the advent of the glaciers and after their disappearance, or during temporary withdrawals. Nevertheless, a wide range of periglacial features occurs, including the ice wedges and involutions that form the subject of this paper. In a glaciated country like Scotland especial care had to be exercised to avoid confusion of wedges and involutions with the effects of slumping, faulting, glacial overriding, and the melting of buried ice blocks.

In the discussion of fossil ice wedges the convenient abbreviation of *wedge* has been employed. The term *involution* is used here to include all disturbances of the ground, other than wedges, on more less level terrain, caused by cryoturbation. This usage is similar to that of Jahn (1956) although he restricts it to phenomena associated with the active layer. A few structures on sloping sites whose association with periglacial climatic conditions seems undoubted are also considered. To save space, wedges and involutions are described in notes only, unless specially interesting examples warrant a fuller treatment. The numbering of the descriptive notes corresponds to the numbers on the location maps (fig. 1a, 1b). Since many of the exposures are no longer visible, descriptions have been given in the past tense. Locations are given with reference to the British National Grid Reference system. Dimensions given are approximate, refer only to what was actually visible in the exposures, and do not necessarily correspond to the maximum, or the typical, dimensions of the whole structure. The widths of wedges, however, have been corrected to allow for the apparent exaggeration induced when the face of the exposure cuts the axis of the structure obliquely. In estimating the depth of wedges no allowance has been made for any hypothetical extension into the overlying active layer. Dating is given with reference to the pollen zones, where Zone I — the Older Tundra period, Zone II — the Allerod period, Zone III — the Younger Tundra period, Zone IV — the pre-Boreal period, or early post-glacial. Glacial times are considered to end with the close of Zone III.

PREVIOUS WORK

Although disturbances in the drift deposits of Scotland which would now be recognised as of periglacial origin had been reported as long ago as the opening decades of the 19th Century, the first certain identification of fossil cryoturbation was made by Anderson in 1940. He described two fossil ice wedges in sand pits near Edinburgh (locality 1 on fig. 1a). These wedges occurred in glacifluvial sands, were about 2 and 3 m deep and 75 and 30 cm wide respectively, and were filled with stony material derived from overlying till. These structures must have formed during an interstadial phase when the glaciers temporarily withdrew from the area: as the ice returned it swept away the active layer and buried the ice wedges under a layer of till, some of which slipped downwards to replace the ice bodies as they melted. Carruthers's contention that these wedges were due to post-glacial cold conditions striking down from the present landsurface does not carry conviction since there is no sign of wedge development in the till overlying the structures (Carruthers 1941). Common & Galloway (1958) have published descriptions of seven other wedges observed in this district between 1952 and 1958 (localities 2 and 3 on fig. 1 a). Five wedges have been noted in Northeast Scotland as mentioned by FitzPatrick (1956 b; localities 4, 5, 6, 7 and 12 on fig. 1 a). One of these wedges is described more fully below (locality 12). Periglacial involutions in water-laid deposits and chemically weathered rock have been noted in three localities (32, 33, 34) in Aberdeenshire by Simpson (1948) and Synge (1956). Two other instances observed by Galloway in this district and mentioned in FitzPatrick's Report (1956 b) are described in greater detail below (localities 39, 40). The Geological Survey has reported the presence of fossil periglacial ice veins and contorted strata in raised beach deposits near Glasgow and in glacilacustrine material in the West Highlands (Geological Survey photographs C4232 and C4092: localities 35 and 36 on fig. 1 b).

DESCRIPTION OF WEDGES

1—7. Wedges already described.

8. Two wedges, 1,50 and 0,80 m deep in sand and fine gravel at grid reference 28/5348.

9. Two wedges in coarse glacifluvial sand and gravel with rounded stones up to 20 cm long, at grid reference 28/5144. One wedge was 3,50 m deep, 80 cm wide at the top, tapering downwards and lined with a layer of erected pebbles enclosing an infilling of sand and stones similar to the

surrounding material, but containing a considerable proportion of reddish--brown clay and silt. This fine fraction appeared to be a weathering product washed in from above as the ice melted, or developed *in situ* by percolating groundwater after the disappearance of the ice. The second wedge was similar but not fully exposed.

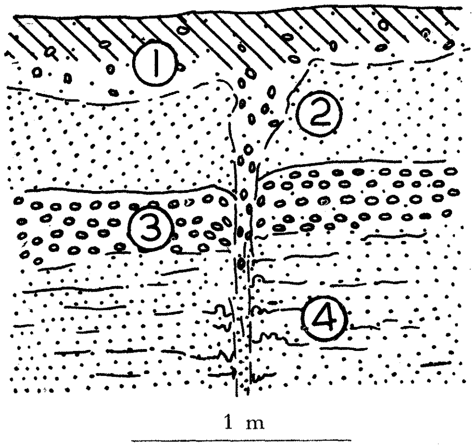

Fig. 2. Fossil ice wedge in a kame between Aviemore and Carrbridge

1. stony solufluction layer with podsol; 2. current-bedded sand; 3. fine gravel; 4. stratified sand with clay seams contorted adjacent to the wedge

10. One wedge 2,50 m deep in a sandpit beside the Perth—Inverness road between Aviemore and Carrbridge (fig. 2; grid reference not known). The material was associated with the margin of the Zone III ice cap and therefore the wedge was most probably of Zone III age.

11. One wedge about 2 m deep and 30 cm wide in a gravel pit at grid reference 38/1863. It occurred in a part of the exposure where fine gravel predominated. Some downslumping of adjacent layers of gravel had occurred at the margins.

12. One wedge 3 m deep and 40 cm wide in sand and gravel deposited at the exit of a deep glacial meltwater channel at grid reference 38/5147. Involutions also occurred in this exposure (see llocality 41 and pl. 6).

13. One partially visible wedge in a terrace of the river Urie at grid reference 38/7226.

14. Eleven wedges in two sand and gravel pits at grid reference 38/9458. The wedges ranged from 70 cm to 3 m in depth and from 15 to 70 cm in maximum width. The wedges appeared to comprise a polygonal network with meshes 5 to 8 m across, the only locality known in Scotland where this occurs. Some of the structures could be described as ice veins rather than wedges since they were narrow and did not taper appreciably.

15. Eleven wedges from 1 to 3 m deep in three sand pits at grid reference 38/9951. Wedges in gravel were generally accompanied by down-

slumping of the adjacent bedding; wedges in sand cut cleanly across the bedding. Two wedges were twisted out of the vertical, presumably by lateral pressure during the growth of the ice body. The wedges did not form a polygonal network. Four other sand pits in this district did not have wedges.

16. One wedge, 2,40 m deep and 40 cm wide at grid reference 48/0349; also one crack-like structure about 2 m deep and 4 cm wide. A single small wedge, 60 cm deep and 10 cm wide occurred in a sand pit 1 km to the north.

17. One wedge 1,50 m deep in a late-glacial terrace of the River Ythan at grid reference 38/9731. The terrace, and therefore the wedge, was most probably of Zone III age. The wedge must have been at least 15 m long since it was exposed at two points this distance apart.

18. Four wedges in a glacifluvial delta on the northern margin of Strathmore at grid reference 37/7377. The only example fully exposed was 3,50 m deep, 60 cm wide and filled with local sand and gravel together with a little brown clay, possibly a weathering product. The bedding of the adjacent gravel was generally slumped downwards at the margins of the structure. Three other gravel pits in similar material in this district showed no cryoturbation phenomena.

19. One large wedge (fig. 3) at grid reference 37/6067. The core of the infilling consisted of stones derived from the overlying gravel layer and was flanked by sand while the true margins of the structure were indicated by thin clay layers. Clay bands in the sand adjacent to the lower part of the wedge were heavily contorted.

20. One wedge at grid reference 37/5252 (pl. 1). It was overlain by a thin layer of sand and stones suggesting some surface washing or mass movement after the replacement of the original ice body by pebbles and sand had been completed but before the advent of a vegetation cover.

21. One wedge, partially exposed, at grid reference 37/3751. A thin clay lining enclosed an infilling of gravel in which the stones were very clearly erected.

22. Two small wedges in a sand pit at grid reference 36/1299 were about 1 m deep and 5 cm wide; a third wedge had been partially destroyed during the course of extracting the sand from the pit (pl. 2). A narrow band of the sand below these wedges was stained and cemented by iron compounds in a manner that suggested ground water had been guided down the structure. Periglacial eolian silt and involutions also occurred in this exposure (see locality 49).

23. One wedge, very narrow and tapering to a point at a depth of 2 m, occurred in sand, silt and clay overlain by till at grid reference 36/2666.

24. One wedge. 1,30 m deep at grid reference 36/2963. Unlike all others described from this district (Anderson 1940; Common & Galloway 1958; locality 23) this was neither filled with, nor overlain by, till.

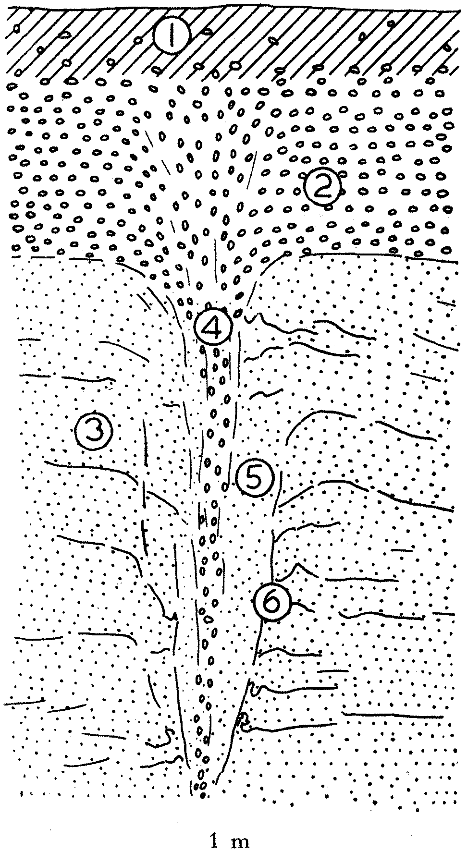

Fig. 3. Fossil ice wedge in glacifluvial outwash at Edzell golf course

1. soil; 2. gravel; 3. current-bedded sand with clay seams; 4. erected stones forming the core of the infilling; 5. sand forming the sides of the infilling; 6. thin clay lining layer

25. Two wedges in gravel overlain by till exposed in a stream bank at grid reference 36/8762 (fig. 4). The larger wedge must have been fully 3,50 m deep with a maximum width of 70 cm. The smaller was 1,20 m deep and 20 cm wide. Both were filled with gravel similar to the surrounding strata which were heavily down-slumped towards the wedges. These structures were almost unique in Scotland on account of their occurrence within, rather than at the top of the gravel deposits. Their formation must have taken place during the deposition of the gravel and been followed by a readvance of the ice which deposited the overlying till.

26. One wedge 3 m deep and 30 cm wide in sand and silt at grid reference 26/9867. The upper part was filled with stones and sand derived

from an overlying solifluction layer; the lower part was filled with sand. The stratification around the lower part of the wedge was heavily contorted.

27. One wedge, only partially visible, at grid reference 36/9446. It showed the rather unusual feature in Scotland of slight upcurling of the adjacent bedding at the margins.

28. A group of sand pits in the Kelvin valley on the northern outskirts of Glasgow. The pits are distributed over an area of several square km,

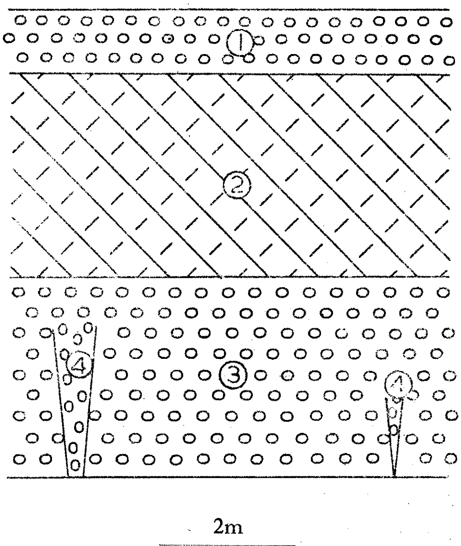

Fig. 4. Diagram to show the stratigraphic position of wedges at Reston, Berwickshire
1. gravel; 2. till; 3. coarse gravel; 4. wedges

but show many features in common and will be considered together here. The material usually consists of 50 to 100 cm of irregularly bedded earthy material and gravel, often showing signs of washing or solifluction, overlying reddish glacial till 2—6 m thick containing many erratics derived from the Highlands to the north and west. An irregular layer of poorly stratified gravel is usually present under the till and rests unconformably on well bedded sands and silts with subordinate gravel layers, as much as 7 m thick. Sometimes the intervening irregularly bedded gravel is absent and the till rests directly on the well stratified material. A rolled bone of *Tichorhinus antiquitatis* („woolly rhinoceros") which fluorished under tundra conditions has been found in the sand (Flett 1927). Disturbances have long been known in the stratified material under the till but never adequately explained; e.g. Robertson & Haldane (1937) mention a „dyke-like" structure, roughly 270 m long, 30 cm wide and filled with sand bound by manganiferous material: this may have been a wedge.

28. a. A „washout" structure some 4 m deep occurred in sand overlain unconformably by a layer of gravel and by till (pl. 3, fig. 5) in a sand pit at grid reference 26/5972. The structure as a whole might be ascribed to the melting out of a small block of dead glacier ice in the sands, and the contorted bedding might have been simply the result of slumping into the resulting void. Alternatively, the structure could have been the infilling of a gully cut through the sands, although the gentle downward curl

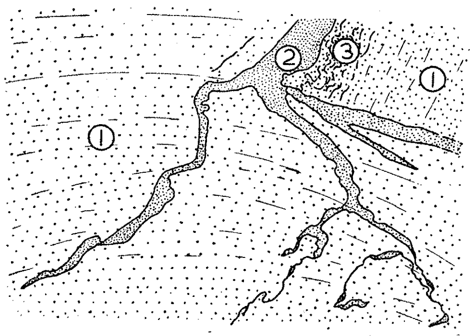

Fig. 5. Lower end of clay seam x—x shown in pl. 3
1. current-bedded sand; 2. clay and silt; 3. involutions

of a considerable thickness of sand layers in the lower right hand part of the feature (pl. 3) argues against this idea. Both these explanations fail to account for the clay-filled seam (marked x—x on pl. 3) which ran parallel to the bedding at some points and transected it sharply at others. It was an alien element to the sedimentary sequence intruded from above, and the most feasible explanation of its origin is to regard it as the replacement of a former ice vein that originally developed under periglacial conditions. The separation of the lower part of the seam into fingers (fig. 5) was in accord with this theory as was a narrow belt of involutions which margined the seam. Nearby there was independent evidence that the sands had once been frozen to a depth of at least 6 m: the bedding of the sand was abruptly cut off against the vertical side of a channel filled with gravel resembling that which capped the „washout" structure. As there was no sign of slumping at the sand—gravel contact it is reasonable to suppose that the former must have been frozen solid when the channel was cut and the gravel deposited. On the evidence available it cannot be proved if the whole „washout" structure, as distinct from the clay seam x—x was related to the presence of a former ice wedge, but if this were the case the initial ice body must have been of considerable size.

28 b. Four wedges, an ice vein and several faults were observed in stratified sand and gravel at grid reference 26/6172 together with indistinct

traces of cryoturbation in the overlying till. The largest wedge was about 30 degrees from the vertical, but appears even more oblique in pl. 4 on account of the sloping face of the exposure and the angle from which the photograph was taken. The upper part had been quarried away and the lower part was obscured: the full depth of the structure must originally have been at least 5 m. The infilling included packets of the surrounding sand, distorted, but with the original stratification still recognisable. As well as the growth of an ice mass, faulting must have played some part in the development of this structure, since there was a slight vertical displacement of the beds on either side. Another wedge, about 3 m deep, and also oblique to the vertical was clearly observed to have developed along a fault in the sand and gravel nearby. *Cf.* Šibrava & Kroutilík (1957) have noted a similar relationship between faults and wedges in Moravia. Other faults seen in this sand pit had not been subsequently modified by wedge development and the stratification of adjacent material was quite undisturbed showig that it was frozen rigid at the time the displacement occurred.

Two small wedges occurred within the stratified material in an adjacent part of this exposure, and were overlain by undisturbed sands. A vertical clay-filled ice vein 5 cm wide and at least 5 m deep traversed the sands and the overlying gravel (pl. 5) at this locality.

28 c. Four ice vein structures of unknown depth occurred in sand overlain by till at grid reference 26/6271.

29. In the Strathavon district of West Lanarkshire a belt of glacilacustrine deposits extends along the valley of the Avon Water. Several sand and gravel pits expose good sections in these deposits and in some exposures ice wedges and other cryoturbation phenomena were observed.

29 a. Nine wedges and seven ice vein or frost crack structures were noted in a sand pit at grid reference 26/6438. The wedges were all narrow, tapering to a point from a maximum width of around 15 cm. In depth they ranged from 1,4 to 2,6 m. There was no sign of a pologonal arrangement in plan. The adjacent bedding was either cleanly cut off at the margins of the wedges or slumped downwards, especially in the coarser gravel. The ice vein or crack structures were only about 50 cm deep and occurred in a horizon a few dcm below the surface. There was a slight relative displacement of the bedding of the gravel on either side of the cracks. They could best be explained as fractures caused by the pressure of water trapped between the permafrost and the refreezing upper crust in autumn (*cf.* Šibrava & Kroutilík 1957).

29 b. At grid reference 26/6337 three small wedges about 1 m deep occurred in sand. One extended downwards as a crack for a further 2 m.

29 c. Three wedges at grid reference 26/6236. The only one fully exposed was 2 m deep and filled with erected stones. Adjacent gravel layers were slumped downwards towards the wedges, while sand layers were not disturbed and cut off cleanly against the margins of the structures.

29 d. Two small wedges about 1 m deep and 6 to 10 cm wide were noted at grid reference 26/7547. Clay seams in the adjoining sand could be traced, heavily contorted, through the lower part of the wedges. Both had rounded lower ends and both were continued downwards by a narrow band of damp and discoloured sand.

30. The bedding of gravel in a denuded kame terrace at grid reference 25/4661 was heavily disturbed and many stones near the surface were frost-shattered. The disturbance seemed to have been caused by cryoturbation especially as there was some trace of involutions in the finer-grained parts of the exposure (locality 58). Nevertheless, the possibility of slumping or thrusting from an adjacent glacier cannot be ruled out in this case.

31. Two wedges were tentatively identified in an old gravel pit at grid references 25/3967.

DESCRIPTION OF INVOLUTIONS

32—36. Involutions already described elsewhere.

37. Several pocket-shaped involutions about 75 cm deep and 60—100 cm across occurred in reddish sandy till with a few wisps of included grey till overlying quartzite at grid reference 38/5265.

38. A pillar-shaped involution 40 cm high in sand with occassional silt and clay bands at grid reference 38/6663.

39. A contorted peat layer was observed in a section at grid reference 38/4555 which consisted from the surface downwards of 50 cm of peat and soil over 1 m of stony material (probably a solifluction deposit derived from till) resting on 70 cm of grey silty clay underlain in turn by 1 m of gravel and 2 m of grey till. A thin bed of peat, dated by Donner (1957) as Zone II occurred in the grey silt and was contorted into an irregular pillar about 30 cm high and 20 cm wide. This contortion was probably caused by cryoturbation during the colder succeeding Zone III period.

40. Small fold and pillar involutions formed a horizon 15 cm deep in silt and clay overlain by 1—2 m of stony solifluction material at grid reference 38/4555. The structures had been distorted in the downslope direction and it was not possible to determine the relative shares of mass movement and cryoturbation in their genesis.

41. Five columns of erected pebbles at grid reference 38/5147 corresponded to a pattern in plan of stone rings 1—2 m in diameter (pl. 6). These involutions occurred in the only part of the exposure where there was a notable proportion of sandy and silty material. In coarser material in this section occurred the wedge described at locality 12.

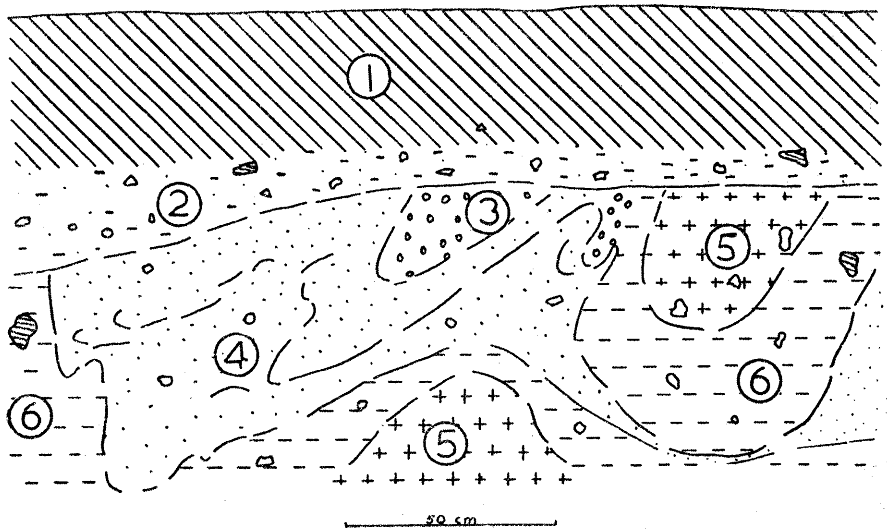

Fig. 6. Involutions at Tochineal, Banffshire

1. soil; 2. stony solifluction layer; 3. pocket of gravel; 4. sand; 5. grey till; 6. red till

42. Chemically weathered schist at grid reference 38/8654 had been cryoturbated and then overlain by post-glacial colluvium in which a podsol had developed.

43. A few pocket and pillar-shaped involutions 40—60 cm deep occurred in a sand pit at grid reference 38/9952 at points where there was a specially high proportion of silt and clay in the sand. Wedges also occurred in this exposure (locality 15).

44. A high proportion of the pebbles in Pliocene marine gravels at grid reference 38/7939 were erected, probably as a result of cryoturbation.

45. Pillar- and pocket-shaped involutions occurred at grid reference 38/8637 in chemically weathered rock (fig. 7).

46. Pocket-shaped involutions 30 cm deep and 40 to 60 cm across existed in soft chemically weathered gneiss at grid reference 38/9936. The structures were overlain by a contemporary podsol and thus the section is a record of three successive contrasted climates: warm humid, periglacial and cool temperate.

47. Mushroom-shaped columns of sand penetrating gravel were seen at grid reference 37/5971. They appeared to be examples of the structures known as *Tropfenboden*, their base was about 1,80 m below the present surface.

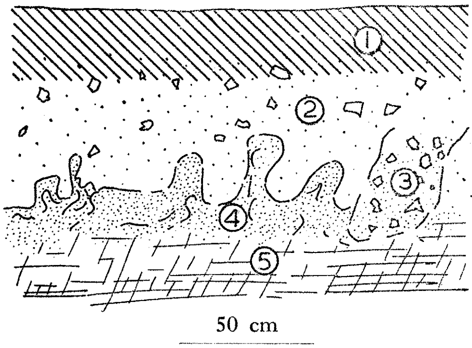

Fig. 7. Involutions near Methlick, Aberdeenshire

1. soil; 2. coarse sand and angular stones; 3. pocket of fine sand and angular stones; 4. fine sand derived from weathering of the underlying rock; 5. chemically altered basic igneous rock

48. Three different types of involution occurred in a layer of fine gravel and coarse sand of Zone I age overlain by 1 m of soil in a stream bank at grid reference 37/6665. One structure was a pocket about 50 cm deep and 40 cm in diameter lined by a layer of ferruginous and manganiferous cemented material and containing many erected pebbles in an earthy matrix. Nearby, a wisp of peat in the sand had been twisted upwards into a narrow column, sharply truncated by the present soil. Pollen analytical data for this peat is not yet available. At the west end of the exposure four columns of erected stones 30—50 cm deep and 1—2 m apart occurred. They were a shallower version of the involutions illustrated in pl. 6 and were most likely associated with fossil stone rings or stone polygons.

49. At grid reference 36/1299 1 m of gritty silt overlay gravel. In the upper 50 cm of the gravel were erected 73% of the stones: in the underlying undisturbed gravel only 16% were erected. The junction between the horizons of disturbed and undisturbed gravel possibly corresponded to the permafrost table at the period when the cryoturbation took place. The active layer would in that case have been about 1,5 m deep, unless the overlying silt, incidentally the sole known example of periglacial eolian deposits in Scotland, had accumulated after the cryoturbation had taken place.

50. Pot-shaped involutions, 40 cm deep, occupied a clay-rich horizon about 4 m below the surface in a sand pit at grid reference 36/2963 (*cf.* locality 24).

51. A single pillar-shaped involution, about 50 cm deep occurred in sand and silt overlain by till at grid reference 36/2662. It was the sole

example of cryoturbation in an exposure that extended for some 400 m, even though apparently equally suitable material occurred at many other points.

52. Involutions and erected pebbles overlain by deep peat were exposed at grid reference 36/6168 in a gully which cut into a mass of unconsolidated material partially infilling a shallow valley. The cryoturbation showed that the infilling had taken place under periglacial conditions that no longer exist.

53. Weathered Devonian sandstone and overlying till were contorted and intermingled at grid reference 36/6223. The disturbance closely resembled cryoturbation but glacier drag may have been the cause in this case.

54. Contortions such as those illustrated in pl. 7 extended to a depth of at least 8 m in glacimarine clays with silt and sand layers, probably of Zone I age, that were exposed at grid reference 26/8780. These deposits are widely distributed in low-lying areas of Central Scotland and disturbance have long been known to occur within them but until recently were ascribed to the impact of icebergs grounding on the floor of the late-glacial sea.

55. Where till rested on sand in an exposure near Glasgow (*cf.* locality 28) at grid reference 26/5972 intermixing and contortion of the two deposits was sometimes apparent. This could be the work of either cryoturbation or glacier drag, but the second explanation is excluded in the case of nearby pocket-shaped involutions lying within the stratified material and separated by undisturbed sand from the overlying till.

56. Pocket-shaped involutions about 80 cm in diameter occurred in current-bedded sand, silt and clay at grid reference 26/6438 (pl. 8). The involutions were cut across by a plane of unconformity on which 15 cm of clay and 80 cm of gravel rested (pl. 8). Nearby, a narrow wedge cut through the entire sedimentary sequence. The unconformity showed that the involutions were formed and then partly eroded during a pause in the deposition of the material, while the wedge indicated that periglacial conditions continued to prevail after deposition had finally ceased.

57. Disturbances of sand and gravel at grid reference 25/4661 have already been mentioned (locality 30).

In addition to the occurrences of cryoturbation listed above, three other structures deserve mention. Although they owe their development to mass movement rather than to the direct action of frost, it is apparent that they formed under periglacial conditions.

58. 3 m of coarse solifluction deposits consisting of a mixture of angular chunks of the underlying rock, a few glacial erratics, and a pasty

matrix of weathered material, rested on chemically altered and frost-shattered schist at grid reference 38/8658. A quartz vein, 20 cm wide, unaffected by the chemical weathering but splintered by frost, ran vertically through the weathered schist and at its junction with the overlying solifluction deposits was truncated and displaced but could be traced upwards, twisted and contorted by mass movement and/or cryoturbation, to die out in a few miniature pot-shaped involutions (pl. 9).

59. The upper part of a vertical vein of quartz in weathered granite at grid reference 38/9649 had been bent and drawn out down the slope for 15 m chiefly by solifluction, but cryoturbation had played some part, since the extended portion of the vein was disturbed by several miniature pocket and fold-shaped involutions.

60. A horizon of large stones in a stony solifluction deposit lying on a slope of 12° at grid reference 36/7867 was arranged in garlands about 30 cm across and 10 cm deep. These garlands were probably sectioned stone stripes that existed on the slope during the course of the accumulation of the solifluction material.

DISTRIBUTION AND DATING

Fig. 1 shows the distribution of wedges and involutions. The former occur in lowland areas throughout the country outside the Highlands, Islands and Southern Uplands. The distribution of the latter is broadly similar, although one occurrence (locality 36) is known in the West Highlands at Spean Bridge. This is the sole cryoturbation feature known to exist within the area occupied by the Zone III ice cap, but it must be pointed out that less field work was carried out, and fewer exposures of suitable material exist, in hill areas. The distribution shown in fig. 1 broadly corresponds to the distribution of sections examined and doubtless many more examples await discovery in the less closely examined parts of the country. The notable groups of wedges found east of Edinburgh and north of Glasgow are related to the abundant gravel and sand pits required near the main centres of population.

The distribution of involutions is broadly similar to that of wedges, but there is a more marked concentration in Northeast Scotland. This is partly because this region was ice-free during the last glaciation (Charlesworth 1955; Synge 1956), and partly because the most intensive field work was carried out in this area but is also connected with the survival of a soft mantle of chemically weathered rock. In other parts of the country this weathered mantle, the product of warm humid interglacial or preglacial climates has been largely swept away by the Pleistocene ice sheets, but glacial erosion was negligeable in the north-east and the mantle has been partially preserved to form a favourable medium for cryoturbation.

There is little significant variation in the nature or size of cryoturbation phenomena between one region or another, but examples overlain by till are confined to the Central Lowlands of the country, with a possible example in the south east in the Teviot valley (location 53). This indicates that ice temporarily vacated the lowlands during an interstadial period while a severe periglacial climate continued to prevail.

It seems that wedges are more frequent than involutions in Scotland. The former have been observed in perhaps one exposure in five of apparently suitable material (glacifluvial in every case), while the latter have been found only in about one in fifteen of the sections examined, but occur in a much wider range of materials. More observations are needed before this conclusion can be confirmed.

The palynological record shows that early Zone IV times, the pre-Boreal, was the last period at which severe climatic conditions prevailed and consequently the wedges and involutions cannot be younger than this (Donner 1957). The oldest structures are those occurring under till in Central Scotland; they must date from an interstadial period which cannot yet be correlated with the North European sequence but may correspond to the Würm I—Würm II interstadial. The youngest structures are the involutions at Spean Bridge (locality 36) which must be of Zone IV age since they lie within the area occupied by the Zone III ice cap. Wedges and involutions believed to be of Zone III age occur at localities 10, 17, 34 and 39. Some of the other structures may be of this age also, but precise dating is not possible on present evidence and most cryoturbation phenomena are best ascribed to the Zone I period since this was longer and probably colder than the Zone III period. The older structures occurring under till in Central Scotland tend to be larger than those of later origin, but it is not known if this is a consequence of more severe conditions, or of a longer period of development. There is no significant difference in size or form between cryoturbation of Zone I and Zone III age

ORIGIN OF WEDGES

The genesis of a fossil ice wedge may be divided into two stages:

1. the development of the initial ice body;

2. the phase of fossilisation when the ice body is replaced by mineral matter as the climate ameliorates.

1. Leffingwell's theory (1915) of the origin of ice wedges and tundra polygons by the freezing of water or water vapour in thermal con-

traction cracks has been widely accepted but Taber (1943) has challenged it on the grounds that these cracks are too shallow, would close before thawing commenced in spring, and rarely if ever form polygonal patterns. The last point is not significant in Scotland where it has been pointed out that wedges are rarely polygonal in plan. Taber's theory implies that ice wedges and tundra polygons were initially overlain by a horizontal ice layer underneath which the wedges developed by some process of segregation not clearly defined and which was subsequently removed to reveal the underlying patterned ground. On the whole Leffingwell's theory seems the more acceptable of the two in the case of Scotland, despite the very real difficulties pointed out by Taber. The wedges in Scotland differ from those described by Leffingwell and Taber in respect of the material in which they are found: in Alaska they occurred only in „muck" (a fine-grained mixture of organic and mineral matter) and in silt, whereas in Scotland they formed in sands and gravels.

A few wedges were noted at locality 28 b which had clearly developed along a pre-existing fault which must have provided an easty route for the penetration of groundwater which subsequently froze to form the ice body. Such wedges are readily recognised since they are usually oblique rather than vertical and since there is some vertical displacement of the strata on both sides.

Some writers when considering fossil phenomena in Europe have attempted to distinguish genetically between very narrow, untapered frost cracks, narrow untapered ice veins, and broader, tapering ice wedges. The Scottish evidence supports the conclusion that there is no significant difference between these forms. Narrow cracks or veins and broader tapering wedges are found in the same exposure in some cases (localities 14, 16, 28 b, 29 a); some wedges pass downwards into cracks (Common & Galloway 1958; locality 29 b); many wedges are so narrow and with so little taper that they could equally well be described as ice veins (localities 14, 23, 29 a).

Dylik (1956) has distinguished in Poland between deep, narrow, pointed wedges and short wedges with blunt lower ends, the former being typical of the frost tundra zone of Central Poland, the latter of the debris tundra of Northern Poland. Yet in Scotland, which lay in the debris tundra zone, it is the narrow pointed type of wedge which is the most frequent. Blunt shallow wedges are uncommon but those that do exist (locality 29 d) are essentially similar in size, location and lithology to the others and would seem to be simply a minor variation of no special significance.

Gallwitz (1949) has suggested that some wedges start as a small sheets, but glacial erosion was negligeable in the north-east and the mantle has been partially preserved to form a favourable medium for cryoturbation.

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1. Leffingwell's theory (1915) of the origin of ice wedges and tundra polygons by the freezing of water or water vapour in thermal con-

feature and grow upwards step by step with the sedimentation of the surrounding material, thus forming what he terms *syngenetic* wedges. This implies that wedges should frequently be found enclosed within sedimentary deposits as the sedimentation must have occasionally proceeded faster than the upward growth of the ice body and so overwhelmed it. Only four out of one hundred wedges in Scotland (localities 25, 28 b) are found in positions corresponding to this eventuality and they can be explained as readily by postulating development from the surface downwards during temporary pauses in the accumulation of the sediments. All other wedges have developed after the deposition of the material. The distinction between „syngenetic" and „epigenetic" wedges is unwarranted according to the evidence considered here. Gallwitz has also noted that in Central Germany fossil wedges in sand and gravel were rather narrow with little or no taper. This is not the case in Scotland where in such material wedges display a wide variety of forms.

2. The mode of fossilisation of a wedge depends on the material available to fill the void and on the manner in which the ice body melted. An infilling of material derived from distant sources, such as loess, is frequent in Central Europe but unknown in Scotland where the material is always of local origin. Flint (1957) states that ice wedges disappear by downmelting from the surface. This would favour replacement of the ice body by material derived from above. Paterson (1940) suggests that lateral melting from the sides would be important, and this would favour the development of a lining layer of fine material at the margins of the wedge. Usually in Scotland there is a lining layer derived from the margins of the wedge enclosing material from the upper sides of the structure and from the surface. Therefore the ice body seems to have melted by a combination of both down and lateral melting, with the infilling consequently derived partly from above and partly from the sides. The lining as a rule consists of a layer, a few mm or cm thick, of fine-grained material such as clay or silt, and does not form if a fine fraction is not present. The wedge at Beauly (locality 9) is an exception and has a lining layer of pebbles larger than those in the infilling.

Where a wedge cuts layers of sedimentary material with contrasted cohesiveness the greater part of the infilling is derived from the looser material. Clay, sand and silt layers are fairly coherent and consequently are usually cut off cleanly against the sides of the wedge, apart from a very minor down washing to form a lining layer, or unless they have been cryoturbated near the lower part of the structure (e.g. localities 10, 26, 29 d). Gravel layers, on the other hand, are usually slumped downwards since they become loose when the ground thaws. Only where a fine-grained stratum was near the surface and therefore especially liable to be wet and incoherent at the time when ice body melted did it contribute significantly to the infilling or show signs of marked downslumping into the wedge. The downward curl of the bedding at the sides of the majority of wedges in Scotland is thus not diagnostic of a particular mode of wedge development but is simply a consequence of the generally coarse nature of the material. This is in contrast to the opinion of many writers, such as Weinberger (1944), who seek to attach genetic significance to the downcurling or upcurling of adjacent strata. Upcurling of adjacent strata is not very common in Scotland, but where it does occur (localities 2, 27) it is probably caused by cryoturbation within the infilling of the wedge subsequent to the replacement of the initial ice body.

After the replacement of the ice body by mineral matter wedges have been subject to pedogenesis. Gołąb (1956) has pointed out how fossil wedges can provide suitable routes for the downward percolation of groundwater, and this can be seen taking place in many Scottish wedges where a narrow zone of dampness often extends below the structure (localities 22, 29 d; pl. 2). The penetration of water has been favoured by the open texture and the vertical orientation of stones in the infilling. As a consequence, the material is usually lightly cemented by iron compounds and is slightly more coherent than neighbouring uncemented material. This causes wedges to stand out a few cm from the face of gravel pits that have been left undisturbed for a few years. The greater movement of water in wedges than in the surrounding material could account for the weathered nature of the infilling noticed in some cases (localities 9, 18).

ORIGIN OF INVOLUTIONS

Since only one of the involutions described showed a flattening of its upper part which could be ascribed to contact with an overlying frozen layer, it seems unlikely that the structures developed by squeezing of wet unconsolidated material in autumn between a frozen crust and the underlying permafrost. The exception is the structure at locality 47 where mushroom-shaped columns of sand rose through gravel. This is truly „an exception which proves the rule", since it is the only structure which contained no material finer than sand, all others being associated with a proportion of silt and/or clay. The unique material and form suggest that it originated in a different way from the other involutions which seem to have been caused by the pressure differences set up by the growth and melting of segregated ice masses in the fine fraction.

Although there is little trace of an overlying frozen crust, many involutions show signs of having had a rigid frozen layer beneath them at the time of their formation. They often extend downwards as far as a definite horizon which it is believed corresponded to the upper surface of the permafrost at the time of their formation. In Scotland, the depth to this horizon, where it is recognisable, varies from 80 to 180 cm. Fitz-Patrick's pedological investigations (1956 a), on the other hand, indicate a depth of only 50—60 cm for the active layer, even in very late glacial times. Valid deductions about the depth of summer thaw cannot be made since some of the overlying material may have accumulated, or have been eroded, after the structures formed, and since all involutions did not develop at the same time and under the same climatic conditions. Furthermore, the depth of the active layer in contemporary periglacial regions varies widely form place to place and from year to year, while the upper surface of the permafrost is rarely a smooth table but more often an indeterminate zone several dcm deep.

There is a possibility that some involutions formed not in the active layer but in the permafrost. If the contortions at locality 54 are true involutions and not the work of grounding icebergs or slumping they show that cryoturbation could take place to depths at least 8 m below the surface (pl. 7). In such situations freeze—thaw cycles could not have occurred and the involutions must have developed as a consequence of the slow growth of segregated ice masses. *cf.* Edelman, Florschütz & Jeswiet (1936) have described and illustrated contortions in clays and silts extending as deep as 10 m below the surface.

It is not certain whether involutions require the presence of climatic conditions severe enough for permafrost. Denny (1951) and Dücker (1954) believe that permafrost is not necessary, while Cailleux & Taylor (1954) imply that it is. The majority of Scottish examples, including those which extend only as far down as a definite limiting horizon (e.g. localities 41, 46, 49) and the deep-lying contortions in Central Scotland (locality 54), indicate that permafrost was present. On the other hand, the involutions at locality 36 date from the post-glacial Zone IV period when the presence of permafrost is unlikely, even though the climate was still severe (Donner 1957). It can be concluded that in almost all cases the development of involutions requires climatic conditions that are severe enough to cause permafrost. This does not mean that permafrost causes involutions.

Dylik (1956) has distinguished between „constricted" and „free" types of involution, the former involving entire packets of material, the latter involving individual discrete particles. It was found that in Scotland this distinction was simply a consequence of the granulometry: ,,free" involutions occurred in stony material (with some fines), ,,constricted" involutions occurred in wholly fine material. There was no consistent contrast in form, or apparent genesis, between the two types.

It has also been suggested that ,,free" involutions are the subsurface expression of stone rings and polygons that developed in areas where vegetation was scanty while ,,constricted" involutions correspond to the vegetation tussocks or ,,thufurs" of well vegetated tundra (Dylik 1956; Jahn 1956). This idea receives only a little support from the Scottish evidence, quite apart from the doubts expressed in the previous paragraph concerning the validity of a distinction between ,,constricted" and ,,free" involutions. While the involutions at localities 41 and 48 are certainly associated with stone rings or polygons, there is no support for correlating any of the other examples with patterned ground. In the case of the erected pebbles at localities 44, 49 and 52, and the deep contortions at locality 54, the weight of evidence is definitely against any such correlation.

It must be concluded that a satisfactorary genetic classification of involutions must await greater knowledge of phenomena in contemporary periglacial regions.

SUMMARY OF CONCLUSIONS

1. Fossil ice wedges and involutions are not uncommon in Scotland: examples from 60 localities have been described. They provide unequivocal evidence that periglacial conditions have prevailed over wide areas of the country.

2. Wedge are found in areas beyond the limits of the Zone III ice cap although without further field work it cannot be stated categorically that they do not also occur within these limits. Concentrations of many wedges in a few limited areas are a consequence of the presence of suitable material and abundant exposures.

3. The wedges range in age from an interstadial period of the last glaciation down to Zone III times, but most developed during the Zone I period.

4. Most wedges occur in glacifluvial sand and gravel. Coarse gravel is unfavourable to their development.

5. Leffingwell's theory of origin of wedges seems satisfactorary, although the Scottish examples are rarely associated with tundra polygons.

6. Wedges developed after deposition of the surrounding material had ceased and not *pari passu* with its accumulation.

7. There is no noticeable difference in origin or location between narrow pointed wedges and wedges with blunt lower ends.

8. Ice wedges, ice veins and frost cracks have the same origin.

9. The frequently observed downcurling of the margins of wedges in Scotland is a consequence of the generally unconsolidated nature of the material and has no genetic significance. Upcurling of the strata is probably due to cryoturbation in the infilling after replacement of the initial ice body by mineral matter.

10. There is little or no significant variation in size or type of wedges from one part of the country to another, or between those of different ages, although some ascribed to an interstadial age near Glasgow are very large.

11. The arrangement and source of the infilling show that the initial ice bodies disappeared by a combination of melting from the sides and from above.

12. Fossil wedges have favoured the downward percolation of ground-water which has promoted weathering and cementing of the infilling in post-glacial times.

13. Involutions occur in many localities outside the limits of the Zone III ice cap, but at least one occurrence is known within these limits.

14. The involutions range in age from a Würm interstadial down to the pre-Boreal, Zone IV period.

15. Involutions exist in a wide variety of materials: stratified sands, silts and clays; till; eolian silt; chemically weathered rocks. Only one example was observed in material lacking a pronounced fine fraction: this was a *Tropfenboden* type of structure whose origin appeared to differ from that of other involutions.

16. Most involutions seem to be produced by the pressure changes set up by the growth and/or melting of ice masses in the ground. This takes place most frequently in the active layer but there is some evidence that it also occurs at depth within permafrost. Squeezing of wet mobile material between permafrost and an overlying rigid frozen crust is a satisfactory explanation for certain small crack-like features but not for involutions as a whole.

17. Most, but not all, involutions are associated with, but not caused by permafrost.

18. The distinction between „restricted" and „free" involutions is a reflection of differences in the texture of the material rather than in mode of origin.

19. Only a few involutions can be definitely associated with patterned ground.

20. Satisfactory genetic classifications of wedges and involutions must await more information from contemporary periglacial environments.

References

Anderson, J. G. C. 1940 — Glacial drifts near Roslin, Midlothian. *Geol. Mag.*, vol. 77.

Black, R. F. 1953 — Permafrost — a review. *Trans. New York Acad. Sci.*, ser. II, vol. 15.

Cailleux, A., Taylor, G. 1954 — Cryopédologie. *Expéd. Polaires Franç.*, 4, Paris.

Carruthers, R. G. 1941 — Glacial drifts. *Geol. Mag.*, vol. 78.

Charlesworth, J. K. 1955 — The late-glacial history of the Highlands and Islands of Scotland. *Trans. Roy. Soc. Edinburgh,* vol. 62, pt. III.

Common, R., Galloway, R. W. 1958 — Ice wedges in Midlothian: a note. *Scott. Geogr. Mag.*, vol. 74.

Denny, C. S. 1951 — Pleistocene frost action near the border of the Wisconsin drift in Pennsylvania. *Ohio Jour. Sci.*, vol. 51.

Dines, H. G., Hollingworth, S. E., Edwards, W., Buchan, S., Weich, F. B. A. 1940 — The mapping of head deposits. *Geol. Mag.*, vol. 77.

Donner, J. J. 1957 — The geology and vegetation of late-glacial retreat stages in Scotland. *Trans. Roy. Soc. Edinburgh,* vol. 63, pt. II.

Dücker, A. 1954 — Die Periglazial-Erscheinungen im holsteinischen Pleistozän. *Gött. Geogr. Abhandl.*, H. 16.

Dylik, J. 1956 — Coup d'oeil sur la Pologne périglaciaire. *Biuletyn Peryglacjalny,* nr 4.

Edelman, C. H., Florschütz, F., Jeswiet, J. 1936 — Über spätpleistozäne und frühholozäne kryoturbate Ablagerungen in den ostlichen Niederlanden. *Verh. Geol. Mijnb. Genoot. Nederl. en Kolon.*, Geol. Ser. II, vol. 4.

Fitz Patrick, E. A. 1956 a — An indurated soil horizon formed by permafrost. *Jour. Soil Sci.*, vol. 7.

Fitz Patrick, E. A. 1956 b — Progress report on the observation of periglacial phenomena in the British Isles. *Biuletyn Peryglacjalny*, nr 4.

Fleet, W. R. 1927 — Description of the sand deposits at Hungryside, Torrance. *Trans. Glasgow Geol. Soc.*, vol. 17.

Flint, R. F. 1957 — Glacial and Pleistocene geology. New York.

Gallwitz, H. 1949 — Eiskeile und glaziale Sedimentation. *Geologica*, Bd. 2.

Gołąb, J. 1956 — Ice-wedges as ground-water conductors. *Biuletyn Peryglacjalny*, nr 3.

Jahn, A. 1956 — Some periglacial problems in Poland. *Biuletyn Peryglacjalny*, nr 4.

Leffingwell, K. 1915 — Ground-ice wedges, the dominant form of ground-ice on the North coast of Alaska. *Jour. Geol.*, vol. 23.

Lembke, H. 1954 — Die Periglazial-Erscheinungen im Jungmoränengebiet westlich des Oder-Bruchs bei Freienwalde. *Gött. Geogr. Abhandl.*, H. 16.

Paterson, T. T. 1940 — The effects of frost action and solifluxion around Baffin Bay and in the Cambridge district. *Quart. Jour. Geol. Soc. London*, vol. 96.

Pierzchałko, Ł. 1956 — Periglacial phenomena in Northern Poland. *Biuletyn Peryglacjalny*, nr 4.

Poser, H. 1948 — Boden- und Klimaverhältnisse in Mittel- und West- Europa während der Würmeiszeit. *Erdkunde*, Bd. 2.

Robertson, T., Haldane, D. 1937 — The economic geology of the Central Coalfield. Area I, Kilsyth and Kirkintillich. *Memoirs Geol. Surv. Scotland.*

Różycki, S. Z. 1957 — Zones du modelé et phénomènes périglaciaires de la Terre de Torell (Spitsbergen). *Biuletyn Peryglacjalny*, nr 5.

Schultz, H. 1956 — Der Geschiebedecksand als spätglaziale Wanderschuttdecke im Brandenburgischen Alt- und Jungmoränengebiet. *Pet. Geogr. Mitt.*, 100 Jhg.

Šibrava, V., Kroutilík, V. 1957 — Periglacial phenomena in the region of Hlučin and Opava. *Biuletyn Peryglacjalny*, nr 5.

Simpson, S. 1948 — The glacial deposits of Tullos and the Bay of Nigg, Aberdeen. *Trans. Roy. Soc. Edinburgh*, vol. 61, pt. III.

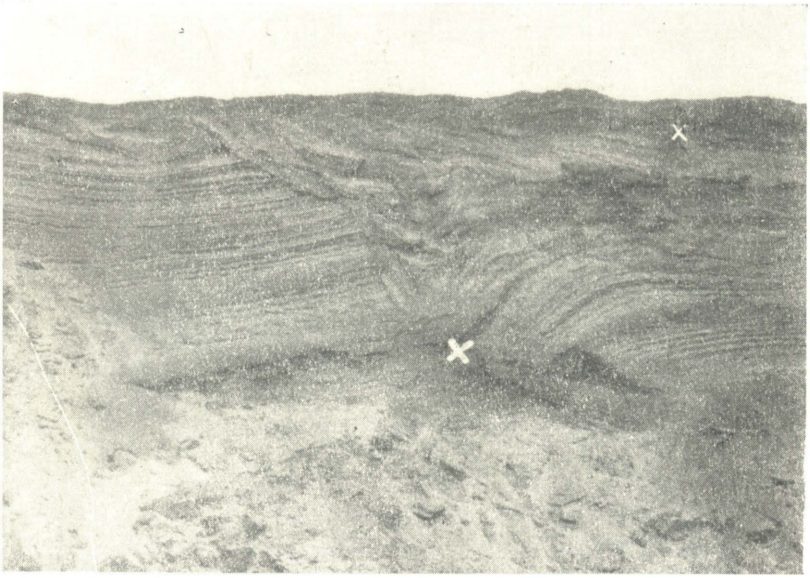
Synge, F. M. 1956 — The glaciation of North-East Scotland. *Scott. Geogr. Mag.*, vol. 72.

Taber, S. 1943 — Perennially frozen ground in Alaska: its origin and history. *Bull. Geol. Soc. America*, vol. 54.

Weinberger, L. 1944 — Frostspalten bei Leipzig. *Geol. Rundschau*, Bd. 34.

Pl. 1. Fossil ice wedge in glacifluvial gravel at Rescobie Loch, Angus

Pl. 2. Lower part of a wedge near Kinross. The sand has been consolidated by iron solutions for several dcm below the foot of the wedge



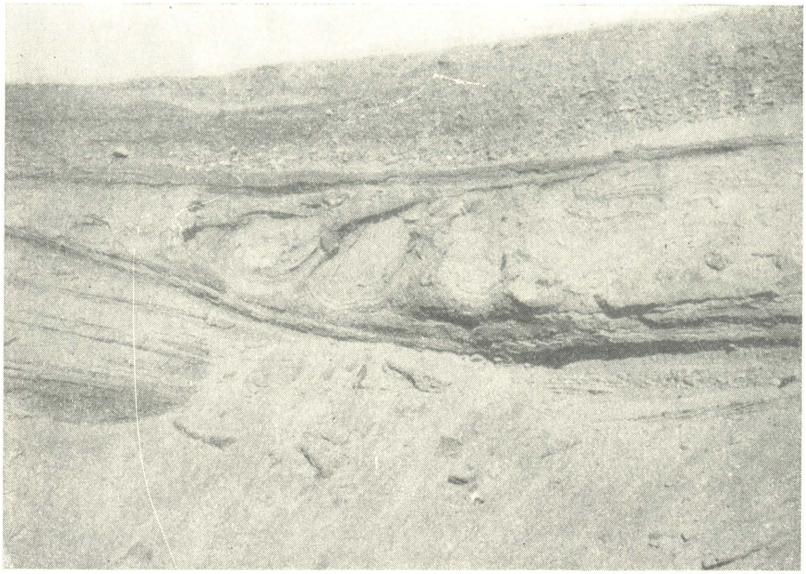
Pl. 3. „Washout" in current-bedded sand at Keir & Cawdor, no. 3 pit, Cadder, Lanarkshire. *x — x* marks the position of the clay seam whose lower end is illustrated in fig. 5

Pl. 4. Upper part of a wedge in a sand poit near Cadder, Lanarkshire

Pl. 5. Clay-filled fossil ice vein cutting bedded sand in a sand pit near Cadder, Lanarkshire. The structure does not extend into the overlying gravel

Pl. 6. Festoons of gravel near Ruthven, Aberdeenshire. Five festoons were observed, forming part of a network in plan

Pl. 7. Contortions in stratified silt and clay at Bonnybridge, Stirlingshire. Similar disturbances occur down to depths of at least 8 m. They may be caused by grounding icebergs, slumping, or cryoturbation



Pl. 8. Involutions in Drumclog sand pit, Strathavon, Lanarkshire

Pl. 9. Disturbance of frost-shattered and chemically weathered rock by solifluction and cryoturbation. The knife indicates the position of a quartz vein