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GLACIAL EROSION ON SOFT-ROCK OUTCROPS IN CENTRAL SCOTLAND

Sommaire

Dans l'Ecosse centrale, une partie de l'affleurement du Vieux Grès Rouge s'étend sur 100 km, depuis le lac Lomond jusqu'à Perth, et constitue le fond d'une vallée séparant deux régions d'altitude supérieure formées de roches dures. Au nord-ouest, se trouvent les Grampian Highlands (800—1000 m): au sud-est, une zone de collines formées de roches volcaniques (Kilpatrick Hills, Campsie Fells, Ochil Hills et Sidlaw Hills, 400—600 m). Dans ces deux régions, les effets de l'érosion glaciaire sont nettement sensibles, et on pouvait supposer que l'érosion eût également agi sur les roches tendres de la vallée intermédiaire. Jusqu'à présent pourtant on n'y avait jamais constaté de formes créées par l'érosion glaciaire. Au contraire, les formes du fond de la vallée sont évidemment dues à l'accumulation glaciaire et, en 1928, Ogilvie a signalé aux niveaux plus élévés deux surfaces dites „pénéplaines" d'érosion tertiaire. Des recherches récentes ont pourtant révélé trois formes de terrain bien distinctes dans la vallée, et qu'on a appelées: des pentes de moulement glaciaire (*ice-moulded valley sides*), des interfleuves triangulaires (*tapered interfluves*), des interfleuves en forme de pont (*bridge interfluves*). Les relations entre ces formes de terrain et les lignes d'écoulement de la glace (telles qu'on peut les déduire des mouvements des pierres transportées) ont démontré que ces trois formes sont des éléments résiduels du fond de la vallée préglaciaire, lesquelles ont subsisté du fait qu'elles se trouvent dans les situations les mieux abritées. Par contre, là où les principaux glaciers traversèrent le Vieux Grès Rouge, toutes les observations semblent indiquer qu'il y eut un déplacement général de 100 m de pierres sur une surface de plus de 60 km c. dans Strath Earn et de 100 km c. dans la vallée de Forth. Il est fort probable que ces quantités dépassent largement les volumes de roches dures, charriés par les mêmes glaciers à partir des affleurements de roches dures, où pourtant l'action de l'érosion glaciaire se laisse plus facilement reconnaître.

The forms of glacial erosion are often conspicuously developed on hard rocks. One thinks of numerous examples of impressive glacial troughs with lofty walls of massive naked rock, or of fields of *roches moutonnées*, similarly carved from massive igneous or metamorphic rocks. The forms to which it is here desired to direct attention are developed on much softer rocks — sandstones, flagstones and shales. Inevitably they are much less conspicuous: indeed, my first object must be to demonstrate that the forms are real and that they should properly be attributed to glacial erosion.

The forms in question are found in part of the Central Lowlands of Scotland on the extensive outcrop of the Old Red Sandstone formation between Loch Lomond and the river Tay near Perth (fig. 1). This outcrop proved in pre-glacial times to be less resistant to the forces of normal erosion than the outcrops of adjacent formations. It was reduced to the condition of a vale, generally 10 to 15 km broad and stretching from south-west to northeast for more than 100 km, with the Grampian Highlands (800—1000 m) built chiefly of mica schists and quartzites lying to the northwest, and a zone of lower hills (400—600 m — Kilpatrick Hills, Campsie Fells, Gargunnock Hills, Ochil Hills, Sidlaw Hills) built of volcanic rocks (Lower Carboniferous basalts in the hills westwards from Stirling, and Lower Old Red Sandstone andesites and tuffs in the hills eastwards of Stirling). Some of the valleys of the Grampians which open out on to the vale show signs of intense glaciation: two of them, namely the troughs that hold Loch Lomond and Loch Lubnaig, did not exist as through valleys until certain watersheds had been breached by the ice (Linton 1940; Linton & Moisley 1960). Heavy erosion by overriding ice is also conspicuous in parts of the hill belt of the volcanic zone, particularly in the Kilpatrick Hills south of Loch Lomond, the western Ochils near Stirling, and the southwestern Sidlaws and adjoining portions of the Ochils in the neighbourhood of Perth.

Since erosion by ice is conspicuous both in the hard rock areas of the Grampian Highlands to the northwest and in the zone of volcanic hills to the southeast, it should presumably have occurred also in the soft rock lowland that intervenes. This however is by no means obviously the case, and the landforms that are found there have till now been otherwise interpreted.

In any extensive view between Loch Lomond and Perth three elements are always present in the landscape:

(1) the bounding uplands, deeply dissected by interior valleys and with steep exterior slopes toward the lowland;

(2) bench-like features at the margins of the lowland, descending by moderately steep slopes to

(3) broad valley floors very close to sea-level and heavily encumbered by glacial drifts.

The benches were interpreted by A. G. Ogilvie in 1928 in terms of "several cycles of normal erosion which may be considered as marking successive broad uplifts that took place in the Tertiary Period". In particular he recognised a "Higher Lowland Peneplane" (150—230 m) and a "Lower Lowland Peneplane" (30—130 m) and indicated the distribution of each on a map. The low-level valley floors were moreover regarded by Ogilvie (1928, p. 426), following the views of H. M. Cadell (1912), as having been cut, during a pre-glacial episode of very low sea-level, to depths substantially below Ordnance Datum, and filled to their present level by glacial deposits. In other words the whole lowland landscape was regarded as having been shaped pre-glacially by normal erosion operating in relation to base-levels at progressively lower altitudes, and as

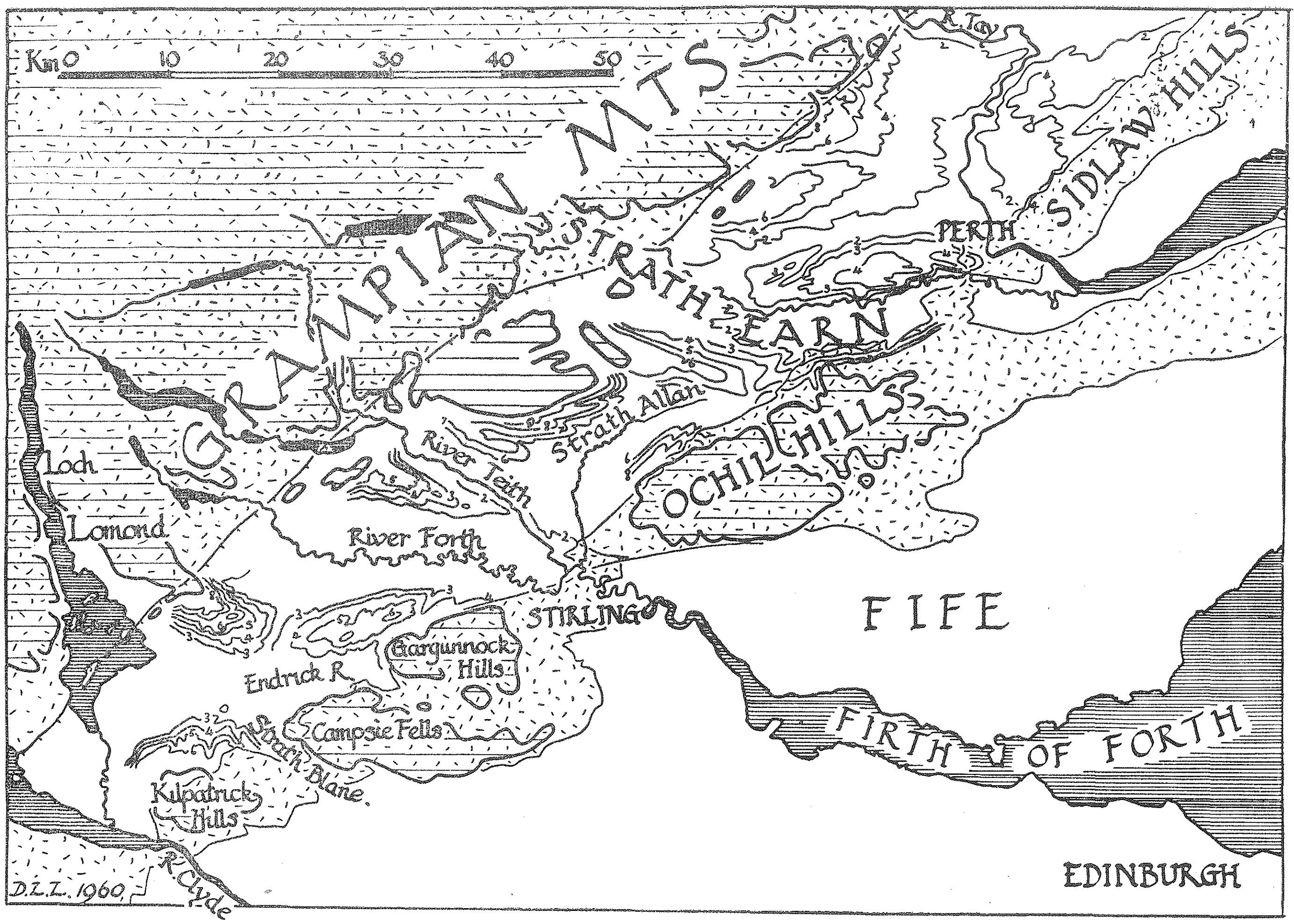

Fig. 1. Some features of the Old Sandstone outcrop between Loch Lomond and the river Tay

Form lines, numbered in hundreds of feet, depict features shown in detail in figs. 2, 3, 4, 5, 6. Ruled area bordered by heavy line is above 1000 feet. Ornamented areas cover crystalline rocks of Grampian Highlands and volcanic outcrops having been submerged in all its lower parts by glacial drifts whose surface forms constitute the present low-level topography. Between the forms of pre-glacial erosion and those of glacial deposition nothing would appear to be left to be attributed to erosion by ice. It is therefore desirable to enumerate and describe at once those landforms occurring in this area that from their form and situation seem not to be attributable either to normal erosion or to glacial deposition, but to be wholly consistent with a hypothesis of origin by glacial erosion. They may be grouped in three categories and for convenience of description are given generic names.

ICE-MOULDED VALLEY SIDES

Features of this type are well seen on both the northern and southern sides of Strath Allan. On the northern side the ground rises from the irregular glacial accumulations of the valley floor at altitudes below 150 m to hill tops at 450—500 m in slopes that exhibit striking contrasts between their upper, middle and lower sections. The upper slopes are astonishingly regular. The contour of 1000 feet runs uninflected for over 8 km (fig. 2) and higher contours up to that of 1500 feet run parallel to it. Down these slopes numerous small streams descend at right angles to the contours, flowing south or south-southeast, and without the slightest incision. These slopes are evidently just as the ice left them and their geometrical regularity, replacing a presumed pre-glacial complexity, indicates considerable ice erosion.

The topography and drainage of the middle slopes, below 300 m, are quite different. All the tiny streams of the upper slopes are gathered up by two larger ones (the Muckle Burn and the Bullie Burn) that flow nearly due east and almost parallel to the contours. They are constrained to do so by two low convex rock spurs that parallel the streams for 3 and 5 km respectively and fall gently at first from 280 to 240 metres and then more rapidly. These features bear no resemblance to the normal form of minor divides between tributary streams, but are conspicuously streamlined and drawn out in a direction parallel to the ice motion; they are here interpreted as being shaped wholly by ice erosion. They may have been carved out of a pre-glacial bench between 240 m and 280 m that could be regarded as part of Ogilvie's Higher Lowland Peneplane, but if so no portion of the bench, nor of its dissecting minor valleys, has survived the glacial onslaught. They have been replaced by the present smoothly tapered spurs and the Bullie and Muckle Burns are to be regarded as consequent streams arising on an ice-moulded surface. Below these spurs the contours of the lower slopes display something of the uniformity and parallelism of those of the ice-scoured upper slopes and doubtless for the same reason, but they become increasingly diversified downwards by smaller features attributable to glacial deposition.

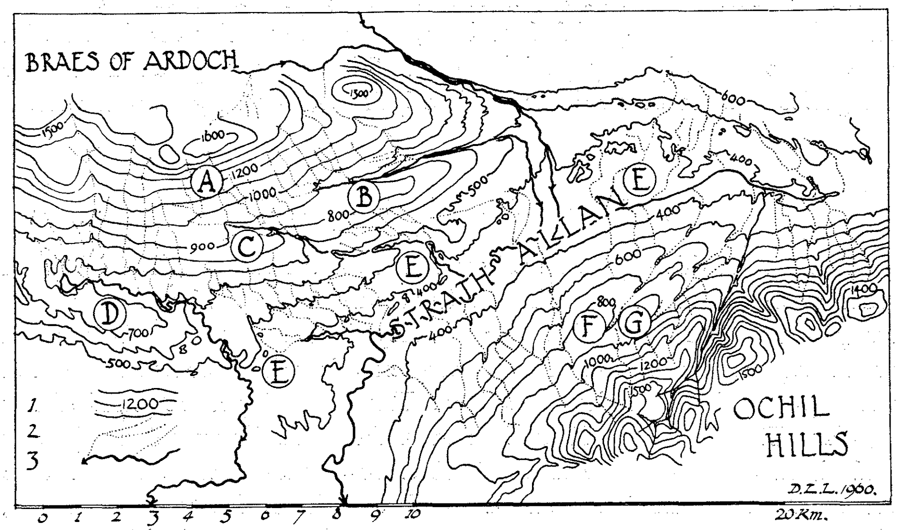

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Fig. 2. Ice-moulded valley sides bordering Strath Allan

1. contours at 100-foot intervals; 2. minor streams; 3. major streams; A — upper slopes made geometrically regular by ice erosion: hill streams without incision; B — streamlined spur tapering eastward towards valley head and created by ice moving ENE. Immediately to North is Bullie Burn consequent upon the form of the ice-moulded surface; C — similar streamlined spur with post-glacially consequent Muckle Burn to north; D — spur of similar origin with Ardoch Burn to north, but made irregular by drift accumulations; E — irregular constructional forms of drift deposits of floor of Strath Allan; F, G — streamlined spurs tapering north-eastward toward valley head and created by ice moving ENE. Immediately to east are minor streams consequent upon the form of ice-moulded surface

The south side of Strath Allan in part shows similar features. The upper slopes are broken by minor valleys inherited from pre-glacial times and lead down to the much gentler slopes of Sheriff Muir at 240—280 m. At the eastern end of Sheriff Muir two streams gather up the hill burns and deflect their waters abruptly to the northeast. These two streams are contained by low convex ice-moulded spurs tapering away to the north-east. Like those noted above they have been shaped by ice erosion: in fact, the two groups of ice-moulded features arose on opposite sides of one and the same eastward moving ice stream.

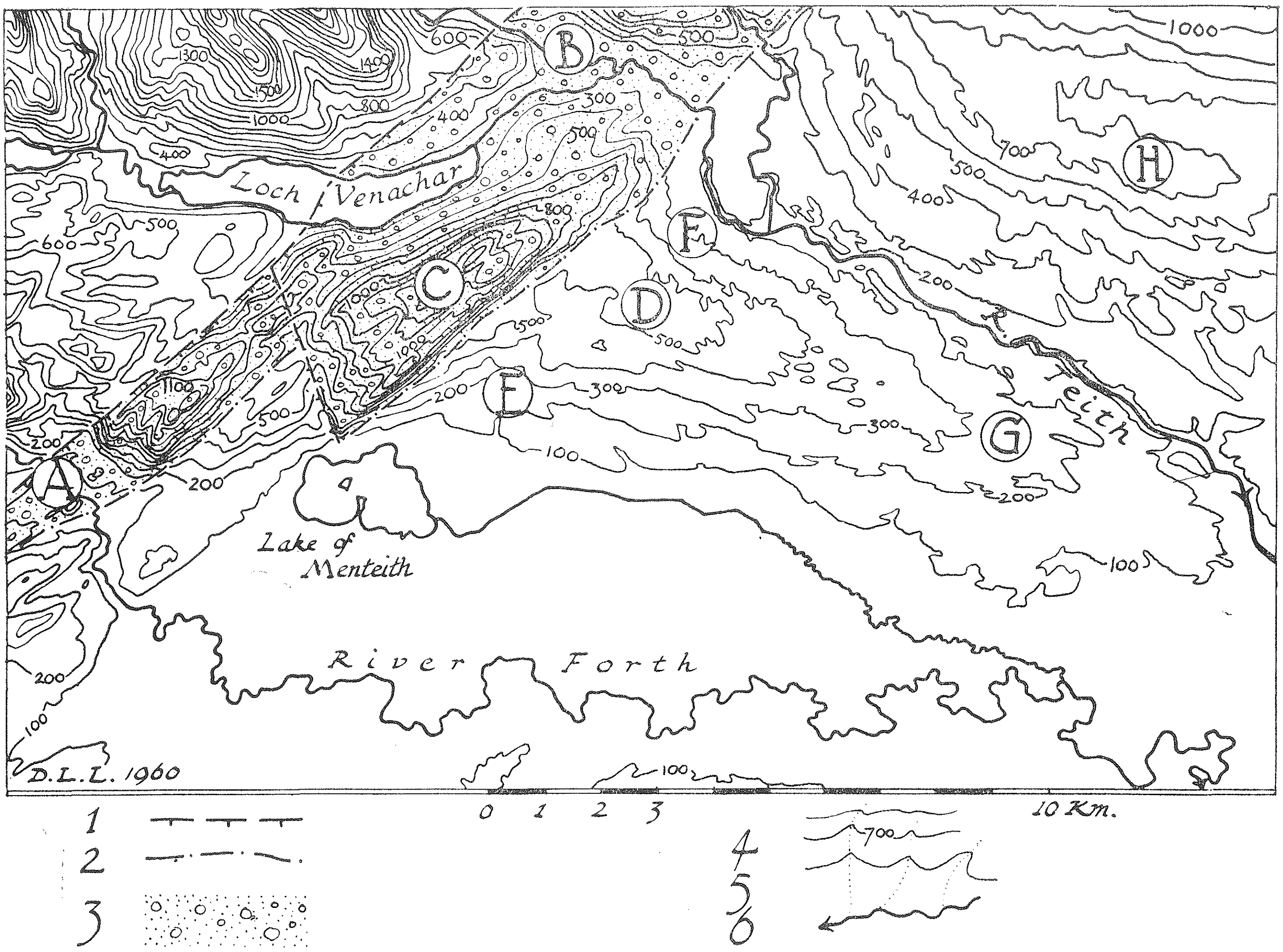

Fig. 3. Tapered interfluve between Forth and Teith valleys

1. Highland Boundary Fault forming southern limit of resistant metamorphic rocks; 2. southern limit of steeply dipping conglomerates; 3. conglomerate outcrops; 4. contours at 100-foot intervals; 5. minor streams; 6. major streams; A — point of exit of Forth glacier from Highlands; B — point of exit of Teith glacier from Highlands; C — Menteith Hills of resistant conglomerates providing sheltered situation in which tapered interfluve of Lennieston Muir (D) has survived; E — concave slope eroded by Forth ice; F — concave slope eroded by Teith ice; G — distal end of tapered spur plastered with drumlins; H — ice-moulded spur (partly obscured by drift) = D of fig. 2

TAPERED INTERFLUVES

Some 20—30 km west-northwest of Stirling two rivers emerge from the Grampian Highlands — the Forth at Aberfoyle and the Teith at Callander, and between these two places run the low but bold hogback ridges (300—400 m) of the Menteith Hills built of beds of conglomerate disposed at high angles parallel to the Highland Boundary Fault. Springing from this very solid and obdurate foundation is the more or less triangular interfluve between the two rivers (fig. 3). At its base along the Menteith Hills it is 5 or 6 km across with a smooth and level surface a little above 150 m, which because of its flatness is covered by the ill-drained peat of Lennieston Muir. Proceeding away from the base it becomes narrower and lower, falling to 50 m and tapering away to nothing at 10 km from the hills, and in this direction it becomes increasingly covered by drumlins or drumlinlike forms directed toward its apex. Taken as a whole it would be difficult to maintain that this feature has the form of a normal interfluve. The flatter and higher parts near the base may have survived from pre-glacial times and represent Ogilvie's Higher Lowland Peneplane. But the flanking slopes, concave in plan towards the Forth and Teith valleys, both appear to have been scoured by the ice streams occupying them, while the distal portions may in part have been ice-moulded from solid rock but appear chiefly to have been shaped by the ice from its own ground moraine. The impression is strongly conveyed that we see here only a remnant of the original Forth—Teith interfluve: formerly it was longer but the distal portions have been wholly destroyed, and only toward the base, beneath Lennieston Muir, does a sizeable and recognizable fragment of the pre-glacial divide remain.

A similar feature of similar size is found in a similar situation 35—40 km north-northeast of Stirling (fig. 4). Again the base of the interfluve lies for 5—6 km along the firm support provided by the O.R.S. conglomerate ridges between the openings by which the rivers Earn and Almond leave the Grampian Highlands. Near that base the surface of the interfluve is flat and peaty between 210 and 240 m and was again included by Ogilvie in his Higher Lowland Peneplane. From the base the interfluve stretches eastward for 10—12 km toward an apex near the village of Methven. On its southern side ice-moulded and fairly steep slopes form the Braes of Fowlis. Towards its eastern extremity the interfluve becomes lower and more irregular with drumlinoid forms moulded from drift.

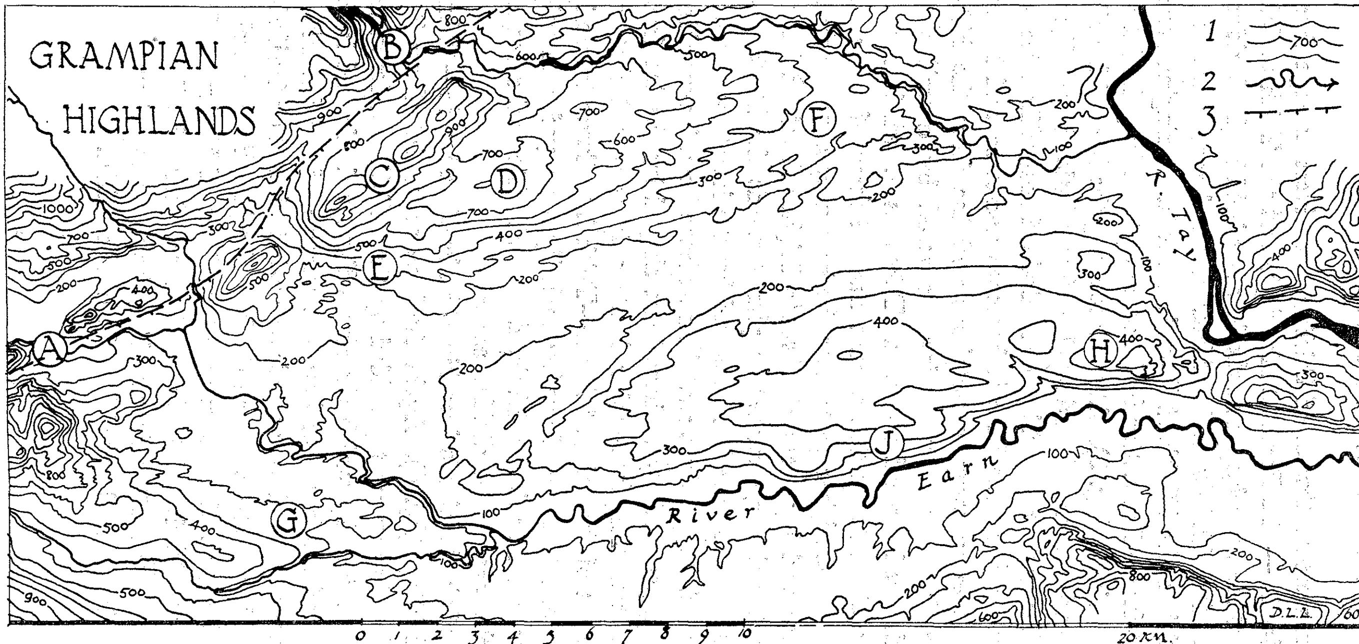

Fig. 4. Tapered interfluve between rivers Earn and Almond and bridge interfluve of Gask ridge

1. contours at 100-foot intervals; 2. major streams; 3. Highland Boundary Fault; A — point of exit of Earn glacier from Highlands; B — point of exit of Almond glacier from Highlands; C — hills of resistant conglomerates providing sheltered situation in which tapered interfluve (D) has survived; E — concave slope of Braes of Fowlis eroded by Earn ice; F — distal end of tapered spur plastered with drumlins; G—H bridge interfluve of Gask ridge: G — western abutment against conglomerate and sandstone hills, H — eastern abutment against andesitic hills (Sidlaws); J — ice-moulded southern slopes with streamlined spurs

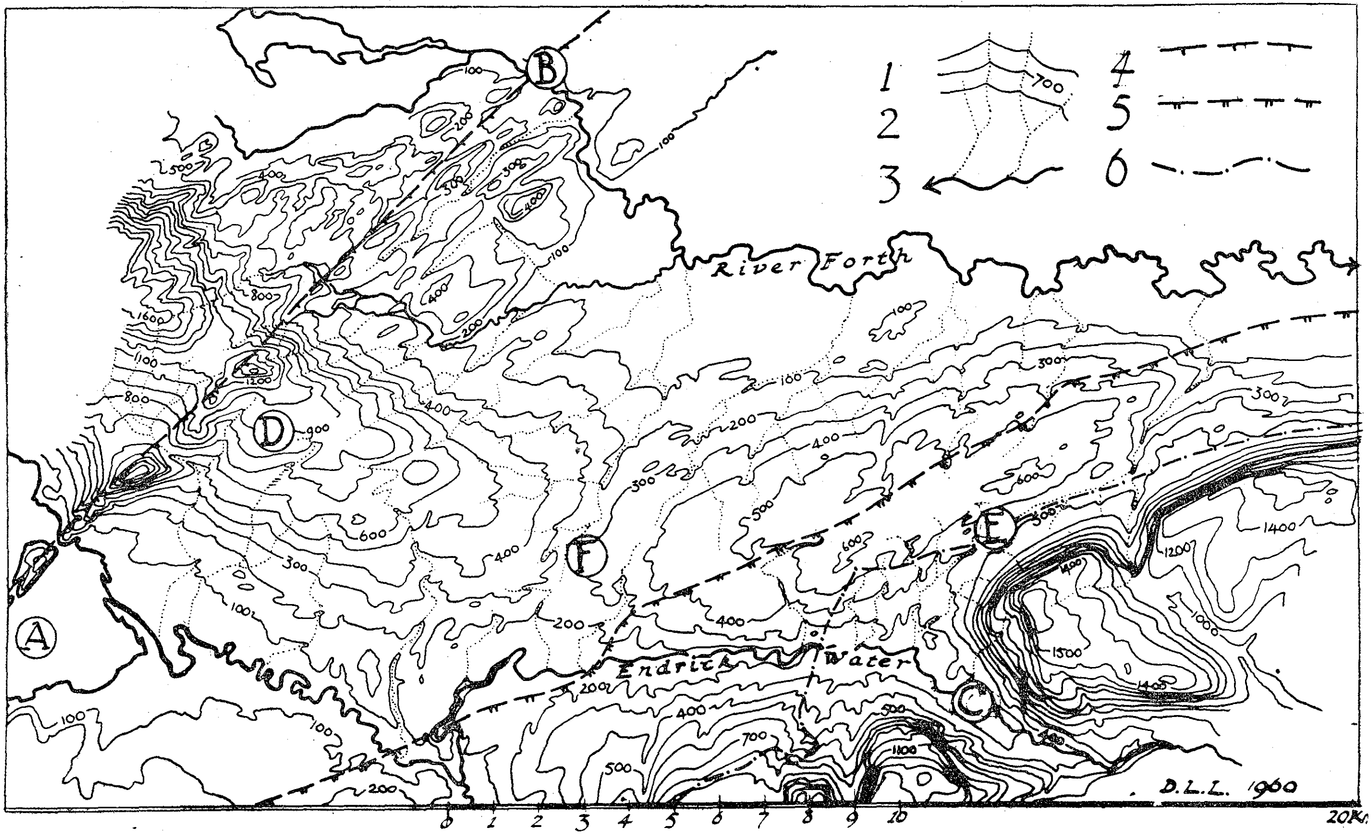

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Fig. 5. Bridge interfluve between Loch Lomond and Forth drainage

1. contours at 100-foot intervals; 2. minor streams; 3. major streams; 4. Highland Boundary Fault; 5. Ochil Fault throwing down Upper against Lower Old Red Sandstone; 6. base of Carboniferous; A — point of exit of Loch Lomond glacier from Highlands; B — point of exit of Forth glacier from Highlands; C — gap in escarpment of Lower Carboniferous basalts affording escape route eastwards for Lomond ice; D — bridge interfluve between Endrick and Forth drainages; western abutment against ridges of Old Red Sandstone conglomerates; E — bridge interfluve between Endrick and Forth drainages: eastern abutment against basalt plateau; F — gap containing glacial drifts

BRIDGE INTERFLUVES

The divides that separate Strath Allan from Strath Earn, and the drainage of Loch Lomond (the Endrick Water) from that of the River Forth, are both strikingly similar to each other and strikingly different from normal interfluves (fig. 5 and 6). Both are low and broad with very flat crests covered by extensive peat moors. In profile both are generally convex with fairly steep bounding slopes which exhibit a marked regularity and parallelism, though in detail they show abundant minor complications due to glacial deposition. The slopes toward Strath Earn are particularly regular and little encumbered by drifts; here the lack of incision by the streams and their eastward deflections make it clear that this ice-scoured slope is still very much as it was when the ice left it.

Both interfluves span the vale from side to side and thus run transversely to the geological outcrops and structures. Both, though they are plastered with drift, seem to be essentially solid rock features, and this is certainly the case for the eastern part of the Allan—Earn divide where it is cut through by the rock-walled meltwater channel known as Kincardine Glen which is up to 50 m deep. Each of these two divides is severed by a depression that contains glacial drifts and was once occupied by ice, and both these gaps afford convenient passage ways for both main roads and railways. Both these gaps have a very anomalous aspect on the map since they cut directly across their respective ridges, and that through the Allan—Earn divide does not even sever the ridge completely. They cannot therefore represent preglacial drainage lines. Both descend northwards and it seems best to ascribe both to partial overflow of the ridge by ice, at some stage of glaciation very much less than the maximum, and probably following lines initiated by overflowing meltwater.

Some 15 km north of Perth the vale is again spanned by an even broader ridge of similar character but lower altitude. This may well be a comparable feature to the two bridge interfluves just described, though much of it may be built of glacial drifts. The chief interest of this ridge, however, is that it has in late-glacial time been overflowed from north to south by the river Tay — presumably impounded by stagnant ice to the northeast in Strathmore — in a defile that is locally 50 m deep.

Finally we may group with the bridge interfluves the east-west ridge that for more than 20 km parallels the river Earn and divides Strath Earn longitudinally (fig. 4). At its eastern end it springs from the andesitic outcrops of Kirkton and Moncreiffe Hills just south of Perth; at its lower, western end it is traversed from northwest to southeast by the river Earn in another narrow defile locally superimposed on rock. This ridge —

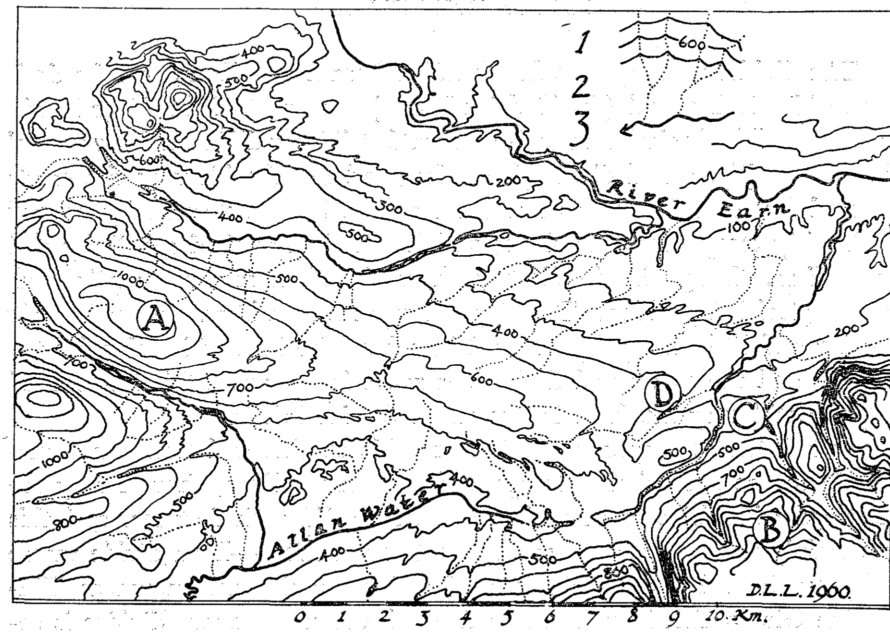

Fig. 6. Bridge interfluve between Allan and Earn

1. contours at 100-foot intervals; 2. minor streams; 3. major streams; A—B bridge interfluve: A — western abutment against Old Red Sandstone of Braes of Ardoch, B — eastern abutment against volcanic rocks of Ochil Hills; C — meltwater channel (Kincardine Glen) carrying drainage of Glen Eagles across the divide; D — wide but partial gap containing glacial drifts

which we may call the Gask ridge — thus also spans the vale, though very obliquely. In profile it is convex and flat-topped like the other bridge interfluves: in plan it is streamlined like a fish, being 5 km broad in the middle but tapering away at each end. Its southern, steeper side is markedly ice-moulded with typical valleyside streamlining south and east of Dupplin Lake, while its surface is crossed obliquely by two depressions that have certainly been modified by ice, but might just conceivably have both formed part of the pre-glacial course of the river Earn.

Viewed as a whole these features of the lowlands under review bear little relation to the topography of a lowland of normal erosion with dendritic or trellissed drainage, as a brief comparison with the detailed topographic maps of such vales as those of the Weald Clay outcrops in Kent and Sussex will make clear. They do, on the other hand, bear a striking relationship to the flowlines of the ice streams in the area as witnessed by the location of strongest incidence of glacial erosion in the adjoining hard rock uplands (fig. 7). Ice streamed out from the Grampian High-

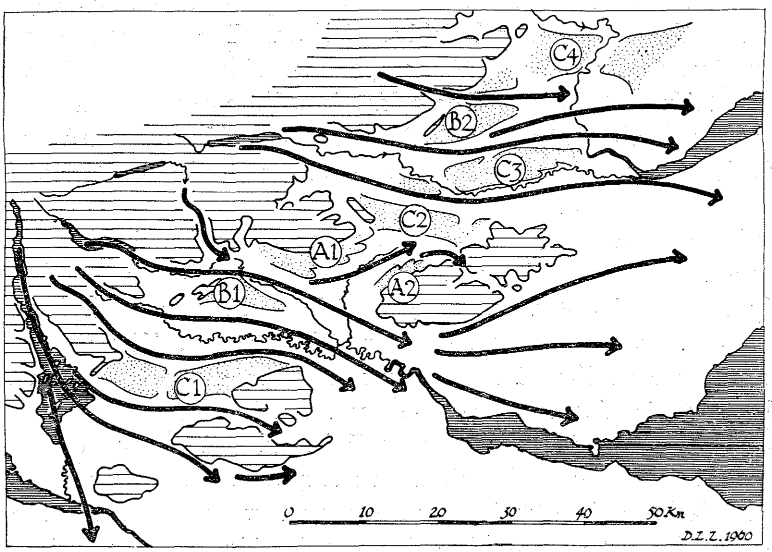

Fig. 7. Main flow lines of ice in relation to ice-moulded land forms on the O.R.S. outcrop in Central Scotland

A1 — streamlined spurs north of Strath Allan; A2 — streamlined spurs south of Strath Allan; B1 — tapered interfluve between Forth and Teith valleys; B2 — tapered interfluve between Earn and Almond valleys; C1 — bridge interfluve between Loch Lomond and Forth drainages; C2 — bridge interfluve between Strath Allan and Strath Earn; C3 — bridge interfluve of Gask ridge; C4 — bridge „interfluve" crossed by River Tay; ruled area is above 1 000 feet

lands by way of the Loch Lomond, Forth, Teith and Earn troughs, and to a lesser extent from Glen Almond and other more easterly glens. That from Loch Lomond fanned out to pass south or southeast through the hills by the Vale of Leven, Strath Blane and the Endrick valley. Between this last distributary and the main Forth glacier a bridge interfluve occupies a relatively sheltered position shielded by the spurs of Ben Lomond and the Gargunnock Hills: its slightly sinuous form graphically suggests the streamlines of ice flow. Between the confluent Forth and Teith glaciers lies the tapered interfluve of Lennieston Muir. The sides of Strath Allan are streamlined by ice that is known to have carried boulders from west to east along its length and to have intruded into Glen Eagles in the Ochil Hills (Simpson 1931—33). The bridge interfluve between this intrusive ice tongue and the much more active Strath Earn ice, reproduces exactly the bridge interfluve between the ice intruded by the Endrick valley into the Campsie-Gargunnock hill mass and the much more active Forth ice.

In Strath Earn the fish-like form of the Gask ridge clearly results from the flow of ice on either side into the two pre-glacial water gaps in the volcanic ridge at Perth and Bridge of Earn. The tapered spur beyond has survived under the lee of the conglomerate ridges between the confluent Earn and Almond glaciers. The bridge interfluve cut through by the river Tay to the north of Perth has had its northern side sharpened by the powerful ice stream emerging from the Grampians by Strath Bran and Strath Tay.

It is therefore suggested that the features here described, though they are extensively surfaced by, and in the case of the tapered interfluves partly built of glacial drifts, are essentially solid rock residuals surviving in favoured situations between powerful ice streams. The courses of the latter are today followed by valleys whose floors are at abnormally low levels for their distance from the open North Sea. Below these floors late-glacial marine deposits occur well inland and below the late-glacial and glacial deposits solid rock is in many areas far below sea-level. If the pre-glacial surface levels over the trough axes were comparable to the surface levels of the tapered interfluves and bridge interfluves that survive it follows that the troughs have been very extensively deepened. Now it is noteworthy that many valleys in the uplands bordering Strath Earn show only small modification by glacial erosion and either open out directly on to Streath Earn but well above its floor (the contour of 400 feet for example passes undeflected beneath the mouths of several), or are connected with the strath by a short rejuvenated section. In a series of fourteen small valleys in the Ochils the floor levels of the valleys above their hanging mouths or the heads of rejuvenation rise from 110 m in Glen Farg to 260 m south of Auchterarder and descend again to 180 m farther west. On the Grampian side the evidence is more scattered but wholly consonant. These indications strongly suggest that the more level tops of the tapered and bridge interfluves are surviving remnants of the floor of the pre-glacial lowland. Doubtless that floor descended to lower levels along what are now the main valley axes but my own observation leads me to the belief that only near Perth in Strath Earn and near Stirling on the Forth would the altitude have been as low as 100 m.

This reconstruction permits us to perceive the magnitude of glacial erosion in this area. The pre-glacial main streams as they crossed the sandstone belt between the Highland Boundary and the volcanic hills probably descended from about 150 m to about 100 m above (present day) sea-level. The modern valleys of the Forth and Earn are wide and flat and below 30 m and 50 m respectively almost to the Highland Boundary. The removal of thicknesses of rock of the order of 100 or 120 m over 100 sq. km of the Forth valley and 60 sq. km in Strath Earn must be postulated to account for the difference. This, however, is still an underestimate since the ice-scoured floor of the glacial troughs is hidden beneath an unknown thickness of glacial deposits and marine clays: over considerable areas it may well be below sea-level as it is known to be in the area bordering the lower Forth below Stirling.

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