The Rakaia Valley.

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A.—INTRODUCTION AND STATISTICS.

The Rakaia is the largest of the rivers that belong entirely to the Canterbury area; in fact, it is surpassed in importance by only two rivers, the Waitaki and the Molyneux (Clutha), belonging to the whole extent of the eastern and south-eastern slope of the Southern Alps. Its valley, too, may be considered as typical of those in the Canterbury area, and a statement of its features should bring out many interesting details as to the general physiographical characteristics of the central portion of the province. This has only been done previously by Haast in his "Geology of Canterbury and Westland," published in the year 1879—that is, fifty years ago.

General Statistics of the River:

The following are the chief features relating to the basin of the river:—

Length	87 miles.
Length of the mountain portion of its course, from the Lyell Glacier to the Gorge Bridge	49 "
Length of the course over the plains to the sea	38 "
Length from the Lyell Glacier to the junction of the Wilberforce	30 "
Length of the Wilberforce	33 "
Distance of the junction of the Wilberforce to the Gorge Bridge	19 "
Length of the main divide drained by the river and its tributaries	45 "

Area of the basin; that is, approximately the area of the mountain portion	1547 sq. miles.
General height of the main divide: Between 6000 feet and 7000 feet, with higher points and occasional passes.	
Height of the source in the Lyell Glacier ..	3568 feet.
Height of the terminal face of the Ramsay Glacier	3354 „
Height of the terminal face of the Cameron Glacier	4478 „
Height of the terminal face of the Stewart Glacier	3584 „
Height Browning Pass	4752 „
Height Whitcombe Pass	4025 „
Height Mathias Pass	4700 „
Height Mount Whitcombe	8656 „
Height Louper Peak	8165 „
Height Malcolm Peak	8236 „
Height Mount Harman	6170 „
Height Mount Arrowsmith	9171 „
Height surface of Lake Coleridge	1667 „
Height surface of Lake Heron	2276 „
Height surface of Lake Lyndon (approx.) ..	2750 „
Height Power Station	1280 „
Height Gorge Bridge (approx.)	875 „
Height Railway Bridge	331 „
Height Mount Hutt	7180 „

B.—Geographical Account of the River Basin.

1. *The Main Rakaia:*

The Rakaia rises in the Lyell Glacier at a height of 3568 ft., and flows in an easterly direction for about two miles, when it crosses the terminal face of the Ramsay Glacier, coming in from the north, and flows between it and Meins Knob (4437 ft.) at a height of 3354 ft. (Photo No. 1). These two glaciers rise in the main divide of the Southern Alps, the most important peaks in the vicinity being Malcolm Peak (8236 ft.), Blair Peak (8185 ft.), Mount Whitcombe (8656 ft.), and Louper Peak (8165 ft.), and between these the divide stretches almost unbroken by any low pass, the only one worth mentioning being the Strachan Pass (5651 ft.). To the south of this part of the course of the river is high, practically unsurveyed country, whose highest named peak is Mount Goethe, though there are probably others higher still. This lies just south of the Lyell Glacier.

After leaving the face of the Ramsay Glacier the river flows almost due east for about 18 miles in a broad, open river-bed, somewhat narrow to start with, that is less than half a mile wide, but the width soon increases till it in places exceeds a mile, over which the river finds its way in braided streams. Bordering the actual river-bed are low terraces, which vary in width from nothing up to half a mile, and which are subject to inroads of the river, so that the width across which the river swings at ordinary flow is extremely variable. Also, where spurs from the neighbouring hills reach down to the valley-floor, the bed is narrowed, and the fringe of terraces may be absent or reduced to the smallest width. In this, as in other parts of its course, the river has all the characters of an aggrading stream, the grade of the bed being approximately 260 ft. per mile for the first 6 miles and 60 ft. for the last 12 of this section.

During the section just mentioned the river receives numerous small tributaries on both banks; on the south the two Washburns and the Lake Stream. The last rises on the south-eastern face of Mount Arrowsmith (9171 ft.), first flows south-east through a glaciated valley for about 15 miles as the Cameron River, and when it reaches the vicinity of Lake Heron turns and runs N.N.W. for another 11 miles to join the main Rakaia; it receives when near Lake Heron the overflow from it. At times the Cameron has discharged into and runs through this lake, and distributary streams still do so at times of heavy flood, for the river has built a wide delta-fan which embraces nearly all the western shore of the lake, and threatens to reduce its area still more. At present the Cameron follows along the northern margin of the fan, and thus avoids the lake. It is, however, bringing down a considerable quantity of waste which it is depositing across the track of the Lake Stream, thus ponding the water back, so that the level of the lake has risen by several feet, necessitating the alteration of the grade of the road round the south-west corner.

On the north side the Rakaia receives numerous streams which rise in the main divide, the most important of these being the Louper from Whitcombe Pass, and the Mathias, the latter a stream of considerable size which rises in the Mathias Pass (4700 ft.), and runs in a south-easterly direction, the latter part of its course being over an aggraded river-bed, of considerable width, like that of the Rakaia.

Just below the junction of the Mathias, the Rakaia turns its direction, and continues south-east to the sea, with slight local variations from this general direction. It receives about nine miles down on its left bank, the Wilberforce (Photo No. 2), a tributary comparable in size with the parent stream, whose features will be dealt with separately, as they present certain important peculiarities. In this part of its course, over a stretch 18 miles in length, the main Rakaia continues to occupy a broad river-bed, nearly a mile and a-half in width, once occupied by a lake now emptied partly by infilling at its head and partly by the lowering of the bar down-stream.

The floor of this old lake is marked in places by silts, which are at times beautifully varved. Moraine covers them occasionally, excellent sections which show the relations of the two being given in the cliffs which border the river-bed below the Power House. In one or two places there are islands of solid rock projecting through the gravel floor of the river-bed, e.g., Double Hill (2240 ft.), with its twin peaks, just below the junction of the Mathias; Woolshed Hill (1723 ft.), in the angle between the Rakaia and the Wilberforce;

and the mound in the river-bed between the Power House and Redcliffe Gully (1284 ft.). The country on either side of the river-bed is downy in character, its height above the water being irregular and ranging from zero up to about 700 ft. Ice-scoured surfaces are freely exposed, and there is a general covering of moraine and fluviomorainic material irregularly disposed and of varying thickness.

The river receives on its left bank, about seven miles below the junction of the Wilberforce, a stream of some importance called the Acheron, whose low-water discharge is about 50 cusecs. It rises near Porter's Pass, at the southern end of Mount Torlesse, flows through Lake Lyndon, and continues in a south-westerly direction in a channel generally incised in the surface, joining the Rakaia after a course of some 10 miles. Lake Lyndon is about two miles in length, and is formed by the blockage of a section of a valley at one end by a fan, and at the other end by moraine. The lake was once of much greater extent, and stretched for a mile down the river valley. Lowering of the morainic barrier appears to be the reason for the shrinkage.

On the right bank the Rakaia receives numerous small streams which descend by precipitous channels from the Palmer, Black, and Mount Hutt Ranges, which bound the valley on the south. Some of these streams have developed fans in as perfect a form as any to be seen in New Zealand. Near Double Hill, examples are to be seen over five miles across their fringe, and further downstream below the Power Station they become steeper, and occasionally show a growth of one within the other. The oldest has had its fringe removed by the erosion of the main river as it crossed the fan front, and this has necessitated an adjustment of grade as the younger fans developed. In some cases the adjustment of grade has had to be renewed, and in consequence there is a nest of fans, two secondaries lying inside the primary.

At the end of this section of the course of the river it enters what is known as the Rakaia Gorge, its length being some six miles, in the upper three of which it is somewhat open, but bounded by cliffs of silts and gravels, while in the lower three the cliffs composed on volcanics and coal measures narrow in, and the river occupies the whole floor between them (Photo No. 3). It flows in well-defined meanders, deeply incised, with cliffs on either side rising to 200 ft. above water-level, and behind them flights of terraces of variable number, at most 16, but reaching a total height of 700 ft. above the river. These are capped in places by moraine, but more usually by river gravels, with moraine occasionally on top of them. In places, too, below the gorge there are lake silts such as are so typically developed in the reach above the gorge. It is uncertain whether these have been deposited in a lake or not, as it seems difficult to restore in imagination a landscape which would allow of the accumulation of water below the rock barrier lying across this part of the river course, and responsible for the ponding back of the water of the lake which occupied the reach above the gorge. It should be noted, however, that varved silts may be deposited in other places than a lake, and this may be the case here (Photo No. 4).

From the gorge onwards the river runs in a bed of the same character all the way to the sea. It varies in width from half a mile up to two miles, and the stream wanders on this bed in braided streams, between banks which get progressively lower downstream. These are 600 ft. in height near the gorge, but by the time the river has reached the railway they have diminished in height till they are at most from 12 ft. to 15 ft. high, and when they reach the sea they are lower still. In many places they fall directly to the water-level, but usually they exhibit a flight of terraces of varying width. Near the railway the main terrace is distant nearly four miles from the present position of the stream, and the base of the terrace is at a lower level than the water, indicating that it is aggrading its bed at the present time.

Some of the islands in the stream, especially in its lower part, are of considerable extent, up to five miles in length, and in favourable positions they are cultivated, but usually they have a covering of grass and scrubby bushes. These islands are specially subject to attacks by the stream when it is high, and hundreds of acres have been washed away, and again what was formerly river-bed is passing through various stages in its development into land of value for pastoral and ultimately for agricultural purposes. A noticeable feature of many of the temporary islands in the river-bed is the close covering of lupins. These obstruct the rush of water in flood time, and intercept the silt from the muddy river, building up the island, and, of course, obstructing the ready get-away of the water. Being of loose material, they are, however, readily destroyed, and there is thus a distinct loss, for the lupins by their decay tend to furnish humus for the soil, and the nitrifying nodules in their roots would greatly improve it were there any simple and economical means of conserving it.

Throughout this stretch of the river's course the banks are almost entirely of shingle, the only place where solid rock shows being at the Curiosity Shop, about three miles below the gorge, where at the foot of a high terrace there is an outcrop of Tertiary beds, consisting of sands and calcareous sandstones, the last named being a notable bed for fossils.

In the higher part of the plains near the hills the gravels are covered by moraine and fluvio-morainic material, clearly indicating that the plains had practically their present form when the ice extension was at its maximum. There is no indication of morainic matter interstratified with the gravels, but there is evidence from the increased oxidation of the lower parts exposed near the gorge, and the marked contrast in colour between this part and the upper portions, that the lower gravels belong to a much older period of deposition, perhaps pre-glacial in time. All through this stretch the river receives no tributaries, except in the immediate vicinity of the gorge, and the only addition to its volume is the rain falling directly into it or any seepage which comes from the banks.

2. *The Wilberforce* (Photos Nos. 2 and 5):

The basin of the Wilberforce presents numerous interesting geographical and geological problems. The river rises in the main divide near Pope's Pass (5290 ft.), about a mile to the east of Mount Harman (6170 ft.), and flows W.S.W. practically parallel with the range for a distance of three miles to the neighbourhood of Browning Pass (4752 ft.), where it is joined by two streams, Hall Creek and Grave Creek, then it turns and flows S.S.W. for a distance of seven miles, where it receives a large tributary on its right bank (height 2333 ft.), variously called Stewart or Unknown Stream. This has three main tributaries, all of which reach back to the main divide and rise in glaciers, the valleys being rather narrow, but easily traversed. In the reach just mentioned the Wilberforce has two other tributaries worth mentioning, viz., the Gifford on the right and the Cronin on the left bank, both of which rise in glaciers of no great size. The river-bed is here somewhat confined, but easy to traverse, and it has a grade of approximately 110 feet per mile.

Opposite the junction with Unknown Stream, the river rounds an ice-scoured bluff, called Sebastopol, and then runs S.S.E. for 13 miles in a wide river-bed, in places over a mile wide, in braided streams on a grade of 50 ft. per mile. Halfway down this reach it receives on its right bank the Moa Stream, which has considerable volume, since it drains a large area of high country between the Wilberforce and the Mathias, with peaks running up to over 7000 ft. The head of this stream forms a large basin or amphitheatre, and the sides are marked with hanging valleys. Numerous other streams of smaller size come in on either bank of the Wilberforce. The walls of the valley are steep, and the cross-section is typically that of a valley which has experienced a somewhat severe glaciation.

At the end of this section the Wilberforce receives on its left bank the Harper River, its largest tributary (Photo No. 5). This has a normal flow of about 400 cusecs. It rises in the Cass Saddle, 15 miles E.N.E., and flows in almost a straight line in a narrow valley, receives various tributaries on its north bank, and is joined about six miles from the Wilberforce by a large stream, the Avoca, which comes in on the right bank. This rises in small glaciers on the south-eastern side of Mount Greenlaw (7500 ft., approx.), some six miles east of the main divide, and well within the area which experiences heavy westerly rains. The river flows in a fine glaciated valley, and a small lake called Lillian discharging to the Harper lies near the southern end of the valley.

The Harper River flows almost due west to junction with the Wilberforce, but it has been partially diverted into Lake Coleridge in order to maintain the supply of water for power purposes. The original discharge from the lake by the Lake Stream to the Harper is utilised completely, so that below the Avoca the Harper receives no substantial addition to its volume. However, it takes the overflow from Lake Selfe, a small sheet of water, 1¼ miles in length, which lies in a picturesque and narrow valley to the south-east.

Below the junction with the Harper Valley the Wilberforce flows for 10 miles in a somewhat confined bed between Mount Algidus (4607 ft.) and Mount Oakden (5364 ft.), first of all south-west for three miles, and then south-east for seven miles, till it joins the main Rakaia at a height of 1260 ft. The grade of the river in this stretch is about 38 ft. to the mile.

Throughout the whole course of the Rakaia and its main tributaries the river is completely graded; no waterfalls and no rapids interfere with the general gradient, steep though it is. There are indications, too, that the stream has reached base level, for parts of it are actually building up the bed. This is clearly shown at the railway bridge, for this has not the clearance that it had when first erected. The conditions thus resemble those of the adjacent river, the Waimakariri, a description of which has been given by the present author in connection with the operations of the Waimakariri Trust (1928, pp. 199-229).

3. *Lake Coleridge* (Photos Nos. 6, 7, 8):

This is the largest lake in the basin of the Rakaia. It is nearly 11 miles long, with a general average width of 1½ miles, but with a maximum of just over two miles, lying in a N.N.W.-S.S.E. direction between two well-defined narrow mountain ridges, of which the highest peaks on the east are Mount Cotton (4345 ft.) and Kaka Hill (3283 ft.), and the highest on the west are Mount Oakden (5364 ft.) and Peak Hill (4083 ft.). The height of the surface was originally determined as 1667 ft., but the datum level of the Public Works Department is 1670 ft. Its water supply is maintained by small streams which discharge from the high country on either side. Through a break in the eastern ridge two miles wide, about midway along the lake, it receives its most considerable inflowing stream, the Ryton, as well as two smaller ones called the Simois and Scamander. The first drains Lakes Evelyn, Ida, and Catherine, all in the vicinity of Mount Ida (5575 ft.), and small in size, each having an approximate length of about a mile. There are a number of other small lakes and ponds draining to Coleridge, the most notable being Lake Georgina, which occasionally overflows to the Scamander, and the Red Lakes, situated in a deep, narrow gully near the Red Hill (5377 ft.), which discharge by way of Coleridge Creek into the southern end of the lake. As the area is a somewhat dry one, lying between the belt usually affected by north-westerly rains and that which experiences south-west and south-east rains, the supply of water to the lake is comparatively small, and this has presented at times serious difficulties in maintaining a high enough level for hydro-electric power purposes. This was the reason for turning the Harper River and also the Acheron into the lake.

The rainfall at the Power House is on the average 31-55 inches per year (average for 1913-31); as compared with that of 170 inches near the main divide (Arthur's Pass, 1923-31).

The lake is very deep, Haast obtaining soundings of over 700 ft. in the narrow part between the peninsula and the slopes of Mount

Oakden. The writer also got depths of over 400 ft. off the peninsula, that being the total length of line available at the time.

The shores of the lake have very few indentations, and the hills run down steeply into deep water, as can be seen when looking down on it from neighbouring heights, its pellucidity rendering it clear to great depths. Only on the eastern side is there any indentation of moment, for a projection halfway down called the Peninsula extends for some distance into the lake, and on either side of this are sheltered bays. Between this peninsula and Mount Oakden, right out in the lake, is a small islet, a few square yards in area, just projecting above lake-level, and surrounded on all sides by deep water. These are the only breaks in outline or in surface that the lake shows.

The lake shallows to both ends, towards the north owing to the fan of the Harper River, and possibly that of the Wilberforce. At the southern end it is rockbound, but with a certain quantity of detritus brought in by small streams, and also deposited by the lake itself. The north-westerly winds blow right down the lake, raise waves of tolerable size on it, sufficient at times to be dangerous to a boat, and these have swept a considerable quantity of material to the southern end, and built up a deposit on the rock bottom which slopes gradually beneath the waters of the lake. The width of this shore deposit exceeds a quarter of a mile. The rock barrier is capped on the southern end of the Peak Hill ridge on the west side of the lake by morainic and fluvio-morainic material. This is best developed between the Power House and the lake. It is only a mantle in most places, for both tunnels to tap the lake passed through a considerable length of solid rock, but north-west of the line of the tunnel it is probable that the barrier at lake-level is composed of unconsolidated debris, deposited in a channel formed by the ice which once came down the lake and overflowed towards the Rakaia past the end of Peak Hill. When the level of the lake was raised artificially by the dam near the outflow at the Harper end, springs near the Power House gave a more copious discharge, which suggests that they received additional water in consequence of raising the lake-level. The unconsolidated material is obviously glacial, for scratched stones are quite commonly contained in it, and glacially striated surfaces occur freely in its vicinity.

Around the margin of the lake there is a well-marked beach about 60 ft. above the level of the surface of the lake as it stood before it was used for power purposes. This was well developed on the east side near the point of the Peninsula, and also along the stretch of the shore formed of glacial materials. On the hard, steep sides of the hills it does not show. It is noteworthy that there is an old discharge channel, now quite dry, leading from the south-west corner of the lake to the Acheron, and followed by the present road for a couple of miles. The highest point of this channel is just 60 ft. above lake-level, so that if it were raised by this amount it would discharge in that direction again. An explanation of this will be given later.

A special feature of the lake shore is the spit on the south-western side about half a mile from the end of the lake. This has been described by the present author (1913, pp. 331-5). After the paper was written, the level of the lake was raised by the dam at the outflow end, and the shrubs and other vegetation on the spot were killed by drowning. A new spit was formed, based on the new level of the lake (Photo No. 7).

Along the western shore where it is bordered by cliffs of glacial debris (Photo No. 8) there is a marked transference of shingle along the shore, due to the waves which are raised in the lake by the strong north-westerly winds. It has accumulated in considerable quantity near the intake, due to interference with the alongshore movement by a groin. The new intake, which is placed in water 60 ft. deep well out in the lake, is threatened with interference from this cause. The transporting effect of the waves is very noticeable; pebbles can be seen to be moved along by each successive wave, and when the spoil from the intake tunnel was tipped into the lake it was rapidly carried along shore and very soon appeared on the beach at the southern end of the lake, over a mile away. This was first of all moved along shore, and then along the spit just referred to, and after that transported directly from the end of the spit to the beach, a distance of nearly half a mile across water which was 18 ft. deep. without any apparent filling effect on the lake. The pebbles forming the beach were up to one inch in length, and there is no doubt of the source of supply, for the tunnel has been driven in hard, dark-coloured slaty greywacke which can be readily identified. Its transport under the circumstances I have mentioned emphasises the carrying power of waves in a lake, in a situation which cannot be helped by tides and by currents other than those generated by the waves themselves.

Owing to the lowering of the lake by the undue drain on it for power purposes, the old spit just referred to is completely exposed. This has three hooks on its inner margin, and a channel at the end across which beach material was formerly transported. When the level of the lake was artificially raised, a new spit was built on the older one. This is composed of much coarser material, moderately well rounded, and with three hooks on the inner margin and a knob at the end. This spit forms a well-defined bank about two feet in height along the outer margin of the old spit.

When one sees the ordinary sub-surface beach exposed one is surprised at the size of the stones transported by the waves of the lake. These are up to seven inches in diameter, and judging from the accumulation at the intake, they must be transported somewhat rapidly. In some cases the movement of shingle has resulted in the formation of barrier-beaches, which are well exposed when the lake shows abnormal low level.

C.—PRE-GLACIAL GEOLOGICAL HISTORY.

The main features of the Rakaia Valley appear to be structural in origin. This idea was first of all enunciated by Edward Dobson (1865, p. 50 and map), who pointed out that the valleys of the

Canterbury rivers were oriented on lines, probably fault lines, diverging from a point about 40 miles due west of the town of Hokitika. This hypothesis was adopted with some reserve by Haast (1879, pp. 175-6). There appears to be some coincidence of the heads of the valleys with the lines drawn by Dobson, but too many divergencies occur, if the hypothesis is to be regarded as sound. There is also no direct evidence of the presence of these faults. Hutton (1884, pp. 91-2) considered the valleys to be of ancient date, and formed even before the Cretaceous and Tertiary sediments were deposited. He was of the opinion that the sea invaded the mountain portions, and that the limestones, etc., were laid down in them when they were arms of the sea, and he uses as a part of his main line of evidence the fact that a limestone mass in the bed of the Rakaia near Redcliffe Gully showed by its presence that erosion had taken place before its deposition. This mass of limestone turns out to be greywacke, so that the evidence and the conclusion deduced therefrom must be set aside.

The present author (1916, pp. 142-3) drew attention to certain features of the Rakaia region, notably to the series of parallel valleys which lie east of Lake Coleridge, and suggested that they were of structural origin. This is apparently the status of the question at present. It will be best, before considering this in detail, to give a brief statement of the geological history of the area, as far as it is known, up to the end of the Tertiary era. This is as follows:—Greywackes, slaty shales, argillites, with minor conglomerates of probable Triassic to Lower Jurassic age were folded at the end of the Jurassic or the beginning of the Cretaceous into a mountain range of modified Alpine type. The folding is characterised by overthrusts, faulting, and crushing, but this has not been of an intensity comparable with related movements in the European Alps, and it produced little metamorphism of the beds. The movement was evidently of a shallow depth, and its results are fracture and breaking rather than a recrystallisation of the materials under the stresses involved. This mountain range was reduced to a peneplain towards the end of the Cretaceous, a levelling probably finished off by marine planation, and on the surface thus produced a veneer of Senonian and Tertiary sediments was deposited.

1. *The Tertiary Veneer:*

The basal beds of this are Senonian in age, consisting of coal measures, but they pass up into Tertiary greensands, limestones, and shelly beds. Whether this veneer was continuous over the whole area is not known, but the presence of marine beds wherever the veneer is encountered suggests that the sea had a wide incidence, and the elevations above the surface of the peneplain, and standing above sea-level, were of small extent, even if they existed at all, although land certainly occurred in close proximity.

The remnants of this veneer are found in the valley of the Rakaia in the following places at the indicated heights:—

(a) Near Lake Heron, in the valley of the Cameron and in the Smite, at heights of approximately 2500 ft. Also on the high country west of Lake Heron, between the Cameron and the Rakaia, at a height of 4000 ft.

(b) In Redcliffe Gully, opposite the Power Station, to a height of 3060 ft.

(c) In the valley of the Harper River, just above the road crossing, and towards the head of the river, at heights in the latter exceeding 3000 ft. The former of these two occurrences consist of sands, with calcareous concretionary layers, striking E.-W. and dipping S. at low angles. The occurrence is obscured by wind-blown and glacial material, and can only be seen for a few chains on the left bank of the river. No fossils were seen.

(d) In the valley of the Acheron and Coleridge Creek, at heights of just over 3000 ft. There is besides the outlier in the lower Acheron, but this is only at a height of 1300 ft. to 1500 ft.

The widespread occurrence of these beds and their height above the floor of the valley can hardly be explained on Hutton's hypothesis that the valleys were eroded by Cretaceous times. There is also a general though not a precise similarity in the sequence in various places.

In addition to the localities just cited, Senonian beds occur in the gorge itself at heights of 900 ft. to 1000 ft., and Tertiaries at the Curiosity Shop, some three miles below the gorge, at a height of 650 feet above sea-level, but these occurrences are extra-montane, and have no apparent bearing on the origin of the mountain valley of the river.

The two areas in the vicinity of the Rakaia, where the Tertiaries are well developed and which are fairly well known, are the Trelissick Basin and Mount Somers. The general sequence in both places is similar, in that coal-measures occur at the base, and these pass up through sands, greensands, and marls into limestones and shelly beds with interstratified volcanics at various levels, but the age of the two series is not identical. In the Trelissick the lower coal-measures are definitely Senonian, and in the Mount Somers area the lowest marine beds lying immediately above the coal-measures are definitely Tertiary (Bortonian). This implies either a wider extension of the same beds as time progressed, that is, a diachronism existed, so that coal-measures of one part of the area may be synchronous with limestones in another part of the area, as maintained by Marshall (1911, p. 23), or that the same succession took place in separate diastrophic areas as suggested by Thomson (1917, pp. 399-401).

The succession of beds as developed in Coleridge Creek is apparently analogous to that in the Trelissick basin, from which it is now separated by the southern end of the Craigieburn Range, but the thickness is much less, suggesting the approximation of a shore line. It cannot be said definitely in the absence of fossil evidence that the relationship is proved, and it may, after all, be advisable to assign this case to the southern diastrophic province. The relation of the coal-measures in the Acheron River to this occurrence is, however, doubtful. The succession in Redcliffe Gully (1913, pp. 337-8) seems to belong to the Mount Somers province, so that its boundary appears to extend to just beyond the Rakaia. The occurrences of Tertiaries in the higher parts of the river basin are more definitely littoral in character, and do not have any development of the purer limestone facies. They seem more in accord with the higher beds of the two areas suggested for comparison, indicating a wider spread of the shallow water conditions, no doubt simultaneously, in Awamoan times, that being their probable age, and also that land existed in close proximity to the area where the main divide is now situated. It may be true, therefore, that this part of the area was not invaded by the sea when it extended over the outer fringe of what is now the mountain area. The fact that this facies of the Tertiaries is widespread over the deeper water deposits also indicates an actual shallowing of the sea, so that it seems to imply that the movements which culminated in the elevation of the mountain area in its present form were initiated when these beds were being deposited, that is, they date from Awamoan or Miocene times.

It is reasonable to think that the covering veneer persisted at a low level, probably submerged by the sea, till towards the close of the Tertiary era, when the shallowing of the Awamoan sea was accentuated, the area was raised, and land of some decided relief was formed. The evidence for this rise is furnished both by the Trelissick basin and by the Mount Somers area, for in both of these districts, and elsewhere in North and South Canterbury, the uppermost Tertiary beds consist of gravels which have experienced some warping, thus showing that distortional movements had not ceased when they were being laid down. These gravels definitely indicate changes in level, and also the proximity of a land of fairly high relief.

2.—Movements and Formation of Valleys.

These elevatory movements were in all probability attended and succeeded by faulting, and the major physical features of the area were thus determined. The fault movements continued down to quite late geological times, and it is not certain that they have entirely finished even now, for post-glacial and recent beds are involved in dislocations, and earthquakes, such as the recent one at Arthur's Pass (1929) show that all stresses have not been satisfied. The faulting which developed towards the close of the Tertiary was oriented on two main lines, one running E.N.E.-W.S.W. and the other N.W.-S.E.

The former of these is responsible first of all for the Harper Valley, for a fault line runs up this river right to the Cass Saddle. A patch of Tertiaries occurs in the upper part of this valley (Speight, 1917, pp. 356-60), whose position can be accounted for only by faulting, probably by the differential dropping down of a narrow strip. Close alongside this line, a little above the crossing of the river by the road, is an occurrence of Tertiaries whose position may be determined by this fault—it may be determined by another fault running N.N.W. and crossing the line of the former—and across the Wilberforce, in the vicinity of Mount Algidus Station, is also a small outlier of coal-measures no doubt associated with the same dislocation, and if this line be prolonged to the south-west it will follow exactly the reach of the main Rakaia Valley between the mouth of the Mathias and the Lake Stream. This agreement in position may be only a coincidence or it may have some physiographical significance.

The next line is one concerning which there is not much evidence from the Rakaia Valley itself, but there is no doubt that the line does extend into it. It is the fault line running up the head of the valley of the Porter River (or Coleridge Creek as it used to be called, and not to be confused with the creek of that name running to the lake) in the Trelissick Basin (1917, p. 334). This extends a distance of nearly five miles for certain, the determination being based on stratigraphical evidence, and it crosses the Craigieburn Range by the Coleridge Pass, a deep nick in that otherwise unbroken range. This line, if continued with a slight deviation, would pass through the broken eastern margin of the lake, and if continued further would fall in with a well-defined depression in the Peak Hill-Mount Oakden Ridge, which suggests, though it does not substantiate, a common origin in both cases.

The next line is that associated with the gap between the Big Ben Range and the southern end of the Craigieburn Range. The lower-lying part of this mountain region appears to be associated with fault movements, since the lower country is bounded both on the north-west and the south-east by definite faults, the former running through Lake Lyndon and Porter's Pass, its line being indicated by earthquake rents of very recent date near the pass itself, and by the presence of a Tertiary outlier at the head of Coleridge Creek, whereas the south-eastern fault passes along the north-western flank of Benmore, where there is definite evidence of the Triassic greywacke beds being thrust over coal-measures towards the north-west. Further, the position of these coal-measures relative to the accompanying greywackes can only be explained by faulting. It is possible that similar coal-measures occurring in the lower Acheron Valley, as well as the beds associated with the limestones at Redcliffe Gully, may be connected in some way with this line of fault, although it is not quite clear how the position of the latter occurrence can be accounted for on this assumption (Speight, 1924, p. 626). It is more probable that it is due to an independent dislocation, as the result of which it has been thrown down from the peneplain level into a trough by faults whose direction is practically N.-S., parallel to the sides of the depression forming the saddle. In addition, the trough of the Rakaia fronting the saddle may also be due to faulting on another line, as will be mentioned later. The height of the limestones above the floor of the valley could thus be accounted for; on the other hand, it may give some measure of the overdeepening of the main valley by glaciation.

The last of this E.N.E.-W.S.W. series of faults is that running down the High Peak Valley along the northern flank of the Rockwood Range in the direction of the Selwyn Gorge (Speight, 1924 and 1928, pp. 41-2), in which the throw is considerable to the north-west, and as a result a definite fault or fault-line scarp is formed along the range. If this line were continued to the Rakaia it would almost correspond with the upstream side of the barrier at the gorge, and thus account for the hollow in that direction. The steepness of the upstream face of this obstruction supports such a contention, and it is against the hypothesis that the hollow is due to glacial excavation, since in the latter case one would expect a gentle reverse slope, analogous to the abraded side of a roche moutonnée, and specially so since this must have been near the end of the glacier where erosive power would be declining.

This fault certainly peters out before Mount Hutt is reached, since there is no break in the face of the mountain fronting the Rakaia or any other earth lineament that could conceivably be associated with an extension in that direction.

There is also a possible line of deformation extending along the base of the mountain country, both north-east and south-west from the vicinity of the gorge. Reference to the former of these directions has been made in connection with the Memoir on the Geology of the Malvern Hills (Speight, 1928, pp. 52-3), and also in the article on the Rakaia Valley Silts (Speight, 1926, pp. 56-7), and it is possible that the same line of deformation follows south-west along the front of Mount Hutt, either parallel to an axis of folding or to a fault, the face of this mountain according to this hypothesis being a fault-line scarp or a stripped surface from which tilted beds have been removed. Definite evidence of such deformation with faulting is available further south in the Mount Somers area, for the south-eastern face of Mount Winterslow and of Mount Somers are determined in this way. The trailing spurs of Mount Hutt running down to the plain are more suggestive of folding or tilting than of faulting. This supposed movement can have little bearing, however, on the valley course of the river, and its effects on the plains are largely masked at the present time by the deposit of gravel. Of course, it may have an important effect on the grade of the river, and indirectly on the cross section of the river channel.

The evidence for the other system of dislocation is unsatisfactory and largely physiographic, resting chiefly on the striking parallelism of the valleys. There is first of all the main valley of the Rakaia stretching from the vicinity of Mount Algidus downstream as far as the gorge, and, secondly, the valley of the Wilberforce and its continuation, the trough in which Lake Coleridge lies. These are continuously parallel, whereas the other valleys on the eastern side of Lake Coleridge are broken, and their continuity is not obvious. At the south-eastern end of the lake there is the valley through which the road to the Harper River and Glenthorne passes, and in which Lake Georgina lies, which may therefore be called the Georgina Valley. This is separated from Lake Coleridge by the narrow steep-sided greywacke ridge of Kaka Hill (3283 ft.), while to the east of it lies the ridge which culminates in Mount Georgina (3100 ft.). This is a double ridge, partly cut into two, with an elevated valley dividing adjacent parallel spurs, and to the east again lies a wider valley, at a higher level than the Georgina Valley, which is oriented to run east of Mount Barker toward the Acheron River, and east of that again the deep narrow trough in which the Red Lakes lie. These are bounded on the west by a narrow steep-sided greywacke ridge, and on the east by the wall-like face of the Red Hill. All these valleys and their dividing ridges are oriented on N.N.W.-S.S.E. lines.

After a break in the country to the east of the Peninsula and the middle section of the lake, the eastern series of parallel valleys is resumed towards the north-west with (i) that in which Lakes Evelyn, Selfe, and Henrietta lie, and (ii) the Lake Catherine-Avoca Valley. The former is separated from Lake Coleridge by the Cotton Sheep Range (4345 ft.), and from the latter by the Mount Ida Ridge (5575 ft., and its continuation across the line of the Harper, first Mount Gargarus, and then the Birdwood Range, which reaches a height of nearly 7000 feet for long distances, and is practically unbroken, while to the east of this valley lie Mount Enys (7202 ft.), Mount Olympus (6866 ft.), and its extension across the Harper called the Black Range. Although it is possible to connect by low-lying ground in practical alignment this last series of valleys with that lying at the southern end of the lake, this alignment may be more or less delusive, for on their common boundary, near the middle course of the Ryton, the characteristic landscape features are isolated, round, sugar-loaf-shaped hills, located as if they were fragments of a ridge formerly crossing the line of the valleys, but now dismembered by ice erosion; such are Mount Hennah, Round Hill, Goldney Hill. The ridge which divides Lake Selfe from Lake Ida appears to have been in process of dissection, and had the ice lasted longer another of these rounded hills would have been formed. This small, picturesquely situated little lake drains south-east to the Ryton. Mount Gargarus is another similarly isolated hill, and Laing's Hill, which lies further south-east, approaches this form, although it has more the nature of a slightly elongated ridge. It is divided from the Craigieburn Range to the east by a partially developed lateral valley, whose lower portion is occupied for some distance by Moraine Creek.

One feature of the eastern side of the basin, extending from the Harper River in a south-easterly direction, is the extensive, partially dissected plateau, covered with roches moutonnées, forming a shelf at the base of the high eastern wall, whose height rises to approximately 4000 ft., with the wall rising another 2000 ft. to 3000 ft. higher. This upper portion of the valley side shows a definite and regular orientation suggesting that it is a fault-scarp in origin, or if not so, that the valley sides have been scoured absolutely free from irregularities by ice action. The north-western flanks of Mount Enys and the Craigieburn Range, as well as Mount Olympus, show this feature clearly. There is also a tendency of the streams draining this eroded plateau to run parallel with and at the base of the valley wall, which suggests that they flowed alongside the margin of the glacier as it retreated from the side of the valley, leaving a narrow strip free from ice, while the other portion of the valley floor was occupied by it. The narrow valley in which the Red Lakes lie is an illustration of this, and perhaps the lower portion of Moraine Creek behind Laing's Hill is another example. These streams, parallel to the sides of the valleys and close to them, are very deeply incised, and may therefore be associated with a narrow belt of structural weakness.

A similar shelf at a lower altitude also extends along the western face of the Big Ben Range towards the Snowdon Station, and this face has features analogous to those of the bounding walls further north-west, and in addition shows practically the same alignment. It is hard to think that this correspondence is to be entirely attributable to ice erosion.

If the valleys are initially due to diastrophic movements, then their cross section seems to demand the existence of parallel faults on the eastern side, one of which determined the upper clear-cut face of the mountains, and a second one which determined the edge of the ice-eroded plateau, the former perhaps continuous for the whole length of the valley, and the latter affecting only sections of it, and especially that between the Harper and the Ryton.

In only one case do I know of geological evidence that the valleys are structural, and this may, after all, not be the authentic, viz., the Lake Selfe Valley; for the small occurrence of Tertiaries near the road-crossing of the Harper may owe its position to a fault running across the river, but all the same it may be due to the fault which follows up the river, as mentioned previously.

Although there is no definite evidence of faulting associated with these valleys, their similarity in form and arrangement suggests that they are due to some common cause, and probably some diastrophic movement. Near the gorge, faulting does occur in the gravels in its vicinity, and there is that peculiar landscape form, known as the "Railroad," whose formation seems explicable only on the supposition that it is due to faulting (Dobson and Speight, 1924, pp. 629-30). Both of these directions have the same orientation as the valleys. However, the date of the faulting is no doubt post-Tertiary, and some of it is post-glacial, and therefore it can have little or no bearing on the form of the valley antecedent to the glaciation, except in so far as it indicates a line or lines of structural weakness oriented in a direction parallel to that of the valley.

It is possible that the height of the andesite capping of Round Top as compared with the height of similar beds in the gorge of the Rakaia just above the road, a difference of some 1000 ft., may be evidence of some differential movement, or it may be merely an indication of the irregularity of the surface over which the andesite was poured. If the former is the case it would support the contention that the valley was originally a graben, and that it was bounded by two fault lines, one running N.N.W. past the western end of the Round Top ridge somewhere in the vicinity of the Switching Station, and the other more problematical still, following along the north-eastern flank of Mount Hutt, past Redcliffe Gully. It must be admitted that the direct evidence for the existence of either fault line is weak.

The only other structural feature which needs notice in connection with the Rakaia is the Lake Heron Valley, through which a distributary ice-stream went during the height of the glaciation. This runs for a distance of some 20 miles practically in a southerly direction from the Rakaia, and it is no doubt due to a diastrophic movement, judging from its form, and the position of the Tertiaries along its margins and on the high land to the west. The difference in the height of these certainly implies some differential vertical movement. There is also definite evidence of faulting with the same orientation in parts of this valley, particularly in the vicinity of the old Clent Hills homestead, but of course this merely indicates the presence of a line of weakness, which is not antagonistic to the supposition that the whole valley is due to structural causes. Its orientation is, however, somewhat off the line of either of the other dislocation directions.

Another important geological feature which may control the course of the river is the grain of the country. The general direction of the strike of the beds taking the area as a whole is N.E.-S.W., but there are local variations from this orientation by as much as 90°, and at times such a variation may persist over a considerable area. They cannot affect the direction of the river except locally. An excellent instance of the correspondence of the strike and the direction of the stream is furnished by the Upper Wilberforce, which for several miles near Browning Pass is practically parallel with the strike, viz., N.N.E.-S.S.W.

The general direction of the stream being from N.W. to S.E., it is practically at right angles to the strike, so that inequality in hardness of the beds is only likely to affect the tributaries to any marked extent, and no doubt some of the smaller tributaries are located on beds, either lithologically weak or weak as the result of the crushing and shattering which attended the folding of the beds at the time the area was being raised to form a mountain chain. A number of smaller tributaries coming from Mount Hutt seem to be dependent on this feature for their orientation.

The beds, too, are all seriously affected with jointing, but this does not appear to be regular in direction. It does, however, aid materially in the breaking down of the rocks under the action of various erosive agents.

Some of the streams may also have their directions determined by definite belts of crushing, which may grade in either direction into faults with relative vertical displacement, but when it is remembered that the greater part of the country forming the basin of the river is composed of greywackes and argillites, in which no definite horizons have yet been determined, although they will no doubt some day, it is difficult to detect faulting unless actually visible in section or unless the overlying Tertiaries are present to give some criterion of movement. In this way faults which may control the course of tributaries may be overlooked.

The relative importance of normal erosional processes and of earth movements in determining the course of the river and its tributaries is difficult to estimate. It may be that the original direction of the main stream was dependent on the course taken on the surface of the land as it rose from the sea at the close of the Tertiary with its veneer of later sediments. This would be consequent drainage, across the strike of the covering beds, and also across the general strike of the basement beds if the former were stripped off, for in general the strike of the Tertiaries is also N.E.-S.W. The correspondence of this direction of main drainage with hypothetical structural lines, oriented similarly, increases the difficulty of assigning to each its proper role, and really the main evidence for the presence of these tectonic lines with N.W.-S.E. orientation is the arrangement of the system of parallel valleys, evidence decidedly open to suspicion. However, whether due to erosional processes, or to tectonic causes, or to a combination of both, considerable changes have taken place in the direction of drainage under the influence of subsequent faulting on E.N.E.-W.S.W. lines and of glaciation. As a result of the former, all the valleys with the exception of the main Rakaia have been cut into sections, and changes in the direction of stream flow have occurred; these changes have been accentuated by the action of glaciers, and it is hard at times to say which is the major modifying cause.

D.—Influence of Glaciation.

1. *Changes in Drainage Directions:*

I think it may be assumed that the general valley alignments before the onset of the ice-flood were much the same as those existing now, but that some modifications have resulted from the presence of the ice. The chief of these appear to be:—

(i) The Wilberforce ran down the valley now occupied by Lake Coleridge, and joined the Rakaia by the gap now blocked with moraine, etc., between Peak Hill and the intake.

(ii) The Avoca probably ran down south-east across the general direction of the Harper, following the line of the upper waters of the Ryton. This diversion may have occurred earlier as a result of the Harper fault.

(iii) The Cameron drained to the Ashburton, and only a small stream occupied the northern end of the Lake Heron Valley, and this drained to the Rakaia in a northerly direction.

(iv) It seems reasonable also that the Upper Selwyn drained to the Rakaia, and not down the High Peak Valley through the Selwyn Gorge or through the upper valley of the Hawkins past Dalethorpe towards Sheffield.

2. *Extent of Ice and Distributary Streams:*

It will perhaps be best at this stage to consider the extent and thickness of ice which filled the valley.

The three main sources of supply came down from the main divide through the valleys of the Upper Rakaia, Mathias, and Wilberforce and their tributaries. A large supply was favoured by the length and height of the main divide, lying right across the path of the prevailing moisture-bearing winds, and also by the amphitheatre of high peaks which flanked the upper part of the valley on its north-eastern and south-western margins. The ice from these valleys was concentrated into a vast basin-shaped hollow occupying the middle portion of the valley, below the present junction of these three streams, and here the circumstances would be exceptionally favourable for the accumulation of great thickness of ice. The triangular shape of the collecting area above this, and also the convergence of the two valley walls towards the gorge, tended to maintain this thickness for a great length of the course of the ice-stream, since narrowing of the cross section of the valley compensated for losses by melting, ablation, etc., and thus the thickness of the ice could be measured in thousands of feet as it left the mountain tract to debouch on to the plains.

Estimates of thickness can be based only on the presence of traces of ice above the valley floor, but in this case care must be taken to eliminate such evidence as may be due to tributary ice coming from hanging valleys, basins, and hollows in the upper part of the valley wall. The height of the characteristic break in the form of the cross-section of the valley and the occurrence of a definite shelf will give an approximation to the height. This shelf shows perfectly along the southern wall of the valley from Double Hill round the northern flanks of Mount Hutt, as well as on the end of the Big Ben Range. These give a thickness of ice in this portion of the valley of at least 3000 ft. It may be urged that one is not justified in assuming that the ice extended to the top of the facet on the end of the spur, and that the upper portion of the face might be due to frost action or to slip or slump from the undercut termination of the ridge, but the uniformity of the slope and the fact that it is evidently part of one landscape feature from top to bottom, and that the form is the same in so many cases, seems to justify the assumption that the thickness of the ice may be gauged by taking the height of the top of the facet above the floor of the valley. The large masses of greywacke on the top of the rhyolite and andesite of the Rockwood Range at heights of over 1200 ft. above the floor of the valley, and also the smoothed surface of Round Top Hill (2917 ft.) in that range, give a minimum thickness of 1300 ft. to the ice in the Rakaia Valley in close proximity to that range.

There is some doubt as to how far the ice came out on to the plains owing to the difficulty in discriminating between morainic and fluvio-morainic material, especially when both occur in the same place and merge into one another. On the north side of the river the ice certainly came as far as a mile below the line of the road leading to the top of the terrace on its way to the Gorge Bridge, for morainic mounds with large angular blocks occur in irregular dumps about this spot. But below this, about a mile and a-half further down towards Glenroy, there is a wide-sweeping, semi-circular ridge, in form like a terminal moraine with surface irregular mounds, composed of angular stones. Behind this the land is low, and in places swampy, and its form stretches down to the Hororata River. About a mile above the bridge on the main road, on the banks of the Hororata and its tributary, Washpen Creek, there is a tenacious clay, containing angular, sub-angular, and rounded stones, some of the last being definitely striated, and many with suggestions of ice-wearing. The clay generally looks like a boulder clay, but in places it has a texture looser than that of a typical till. Scratched stones are also found on the downs between Washpen Creek and the Hororata River. Lying on the surface are also large angular blocks of rhyolite and occasional greywacke (Photo No. 9). The former are up to 8 ft. in diameter, and are exposed on the terraces and beds of both the main stream and its tributary. Whether these have been included in the clay or represent a surface deposit which the streams have not been able to move along with the finer material is not clear, but no block was seen to be actually embedded. Both the scratched stones and these large blocks indicate the presence of ice on the ground where they occur, and the presence of a boulder-clay indicates an extension beyond the line where the deposit occurs, since it must have been laid down under the ice and not actually at the ice front. The presence of large stranded blocks of rhyolite well out from the foot of the hills west of the Clearview Coal Mine, on the north side of the Hororata (Speight, 1928, pp. 2-3), supports the contention that the ice extended on to the plains, and if so, the fluvio-glacial deposits as distinct from the glacial, and lying on them were laid down during the retreat of the ice from this apparent maximum. Haast (1879, pp. 386-7) considered that the ice reached as far as Woolshed Hill, which forms a ridge on the top of the terrace above the Curiosity Shop, some three miles downstream from the gorge. He said that the hill was composed of angular blocks lying on sand and gravel, and marked the maximum advance of the ice along the line of the river. This conclusion appears quite reasonable, in view of the definite proof of the presence of ice near the Hororata, about the same distance from the gorge and somewhat out of the line of the direct advance of the ice.

The hill was re-examined in order to see if any fresh evidence was forthcoming. It is unfortunate that there are no good exposures either natural or artificial, and the greater part has been ploughed. As far as can be seen, the hill is chiefly composed of rounded and subangular gravel, well cemented, and without scratched stones, nor are the stones of large size. They may belong to the Kowai Gravel series, and may thus be pre-glacial in age, and the height of the ridge may be accounted for as being a remnant of a widespread preglacial covering, not destroyed by the action of ice or rivers. It is possible that they may, after all, be fluvio-glacial, though no precise evidence of ice action was observed in the limited exposures.

The summit of the hill, however, shows deposits of large angular blocks which confirm Haast's conclusions. These form low mounds which have escaped ploughing owing to their roughness, and they give the top of the ridge the characteristic topography exhibited by morainic dumps, where the roughness of the surface has been to some extent modified by a coating of soil. A specially distinctive heap lies a few chains north-west of the trig. Within a circle four yards in radius lie seven angular blocks, rhyolite and greywacke, over 4 ft. in diameter, with one 7 ft. by 5 ft. by 3 ft. These rest on other blocks partly buried in the ground. Their angularity, size, and position negative the possibility that they were deposited by water action. This is not the only accumulation of similar blocks, and masses up to 4 ft. in diameter are quite common, usually in aggregations. So that it is my opinion that while the great majority of the hill is probably of pre-glacial age, ice really came down over it, and left the thin veneer of blocks which forms its highest elevations.

On the south side of the river there is similar evidence. Just past the creamery on the road between the gorge and Methven there are heaps of angular stones, in the form of a crescent, with one horn resting on the flanks of Mount Hutt, and the other on the terrace just where the roads to Mount Somers and Methven diverge (Photo No. 10). There are also, still nearer Methven, a number of mounds which, judging by form, may be glacial in origin, and if so, it may mean that the ice extended within three or four miles of that township, which is not remarkable when one considers the position of the ice-front on the north side of the Rakaia when it reached its furthest.

The ice crossed the Rockwood Range at a height of 1300 ft. above the plain, and the fact that it had probably disappeared by the time the Hororata had been reached near Glenroy appears somewhat strange if the range had existed at its present height at the time of the glaciation, and I have suggested elsewhere (1928, pp. 52-3) that some change in height may have taken place since then, and noted that there is faulting in the gorge which affects post-glacial silts, as well as a definite earthquake rent, which must be of recent date, following along the south-eastern face of Bryant's Knob, and oriented in a N.E.-S.W. direction. There is, however, little direct evidence for this hypothesis, and when one considers the height at which there are now definite evidences of glaciation, and the magnitude of the ice stream which must have existed to produce them, then the traces which we see on the flat are not commensurate with this size, but rather indicate much weaker flows, and therefore it is possible that the ice extended for some distance on to the plains, that the clay near the Hororata is a true boulder clay laid down at the time of the great advance, and that the moraine and fluvio-morainic material, such as that between the Switching Station and the Gorge Road, belong to a period when the ice maximum had long passed, and indicate mere phases in the decline and retreat of the ice streams, or in all probability a fresh advance of less importance.

The general conditions of the mountain basin of the Rakaia at the height of the glaciation must have been as follows:—The great mountain basin was full of ice, fed chiefly by three great streams coming from the main divide down the valleys of the Rakaia, Mathias, and Wilberforce, with a subordinate flow down the Avoca. These streams coalesced and covered the whole country now occupied by the main Rakaia Valley, Lake Coleridge, and the country east of it. Perhaps the tops of such mountains as Oakden (5364 ft.) and Ida (5575 ft.) stood up as nunataks above the ice-field, but the valleys parallel with the lake were so completely flooded that they did not show in any way on the surface of the ice, except in so far as they affected the flow from depth, much as a deep river is affected by irregularities in its bed. After leaving them, the streams coalesced again, moved over the country south of Lake Coleridge, crossed the line of the Acheron, became more or less hemmed in between the end of the Big Ben Range and Mount Hutt, and, as the cross-section of the valley narrowed, passed over Snowdon and Fighting Hill (2393 ft.), over the Rockwood Hills, and reached out as a piedmont as far as the line of the Hororata near Glenroy, on the north side of the river, and in the vicinity of Methven on the south.

The basin was so filled with ice that distributary streams passed over saddles and the lower parts of its bounding ranges. These were:—

1. To Lake Heron and on towards the South Ashburton.
2. Over Redcliffe Gully to the North Ashburton, by way of its tributary, the Swift.
3. Along the northern side of the Big Ben Range, into the basin of Macfarlane's Stream and the Kowhai.
4. Down High Peak Valley and over Middle Saddle, and also into the valley of the Upper Hawkins.

These will be dealt with in turn.

(i) *The Lake Heron Overflow:*

This was perhaps the main distributary from the Rakaia. The evidence for it is to be seen in the ice-scoured slopes on either side of the Lake Heron Valley, as far down as the line of the South Ashburton, but specially near the Rakaia end of the Lake Heron Valley; the semi-detached knob called Prospect Hill and its glaciated and moraine-covered surroundings on the left side of the Lake Stream at its junction with the Rakaia; the ice-scoured basin immediately above the junction; and the large terminal moraine on the southern side of Lake Heron. This is no doubt a recessional feature, just as the moraines near the Rakaia Gorge are recessional, for the ice-smoothed slopes extend for miles beyond the moraine, and at higher and lower levels. Though the Rakaia contributed largely to the stream going through the Lake Heron Valley, it must be remembered that the Cameron and Ashburton Glaciers coming from the south-eastern slopes of Mount Arrowsmith were of great extent. They filled the valleys of the rivers now occupying them, and passed over the slopes between them, and on their own account flooded a large extent of country. The Cameron was no doubt a substantial contributor to the material of the Lake Heron moraine. The width of the valley at the spot is some six miles; it is much narrower towards the Rakaia, but the body of ice coming through it must have been of very considerable dimensions, and materially relieved the pressure in the main valley.

(ii) *Overflow by Redcliffe Gully* (Photo No. 11):

On the top of the limestone outlier of Redcliffe Hill (3060 ft.) and in the valley leading down to the Ashburton, moraine occurs freely, and the ice-scoured slopes both above and below the turn-off from the main valley indicate clearly that a distributary stream of comparatively small size entered the Ashburton River basin by way of this saddle. It is probable, too, that another small distributary crossed by Turton's Saddle (3700 ft.)—which is between Redcliffe Saddle and the Lake Stream, at the head of the Glenrock Stream—into the North Ashburton by way of Turton's Stream.

(iii) *The Benmore Distributary:*

The evidence for this is not so definite, but large greywacke blocks occur resting on coal-measures and volcanics of the Benmore outlier, whose presence can most reasonably be explained by ice transport across the rather low saddle to the south of Porter's Pass, north-west of the Big Ben Range.

(iv) *The High Peak Distributary:*

The High Peak Valley was probably filled with ice, and there was an overflow to the Hawkins, as well as over Middle Saddle (2491 ft.) to the valley of the Upper Hororata, evidenced by large blocks of greywacke resting on andesite at the top of the saddle. These blocks must have come from higher up the Rakaia Valley. This implies that an ice-sheet filled the High Peak Valley and crossed a saddle 1200 ft. above its floor. This contention is, of course, subject to the condition that the range may have risen since the ice maximum, and then such a great thickness of ice in the High Peak Valley would not be required to account for stranded blocks at such a height. However, a great thickness of ice is required to account for the height of the ice-scoured shoulder of Big Ben, on the north-west side of the entrance to the valley. The passage of ice through into the Hawkins basin is indicated by large blocks of greywacke found lying on coal-measures near Russell's Flat (Speight, 1928, p. 3).

3. *Phenomena associated more particularly with Ice Advance:*

The chief phenomena associated with ice advance are those dependent on abrasion. This has left its mark on almost all parts of the area. The most noteworthy are the production of steep lower slopes and the formation of a distinct shelf or shoulder on the valley walls near the upper level of the ice; the narrowing of ridges between adjacent parallel valleys by lateral sapping and abrasion; the triangular facetting of spurs; the formation of semi-detached knobs on the ends of spurs, such as Prospect Hill, at the junction of the Lake Stream and the Rakaia, Mein's Knob, and Jim's Knob, at the head of the Rakaia; the formation of fields of knobs or roches-moutonnées at the ends of spurs, such as occur between the Harper and Lake Catherine, on the slopes of Mount Olympus; the cutting down of divides as between the Rakaia and Lake Heron, between the Wilberforce and the Rakaia, in the vicinity of Mount Oakden and Mount Algidus, and the cutting down of the divide between Glenthorne and the Avoca behind Mount Gargarus; and the general production of roches moutonnées in the floors of valleys by abrasion or by scouring and plucking.

This leaves out the question of the efficiency of glaciers in causing valley excavation as distinct from abrasion. At first sight it might be postulated that the form of Lake Coleridge, with its deeply depressed floor, and also the hollow formed in the Rakaia behind the rock barrier at the gorge were both the result of the excavating power of thick ice. This is a matter concerning which there is room for difference of opinion. There is some reason for thinking that the hollow behind the rock barrier at the gorge is in the main structural in origin. This point has been dealt with by the present author in his paper on the Rakaia Silts (1926, pp. 56-7). In support of this it may be pointed out that the general effect of the glaciation appears to be modification of pre-existing landscape forms in this region rather than the creation of radically new ones. The fact that the tributaries of the main valleys of Canterbury which have been subjected to glaciation show no discordance in grade at their junctions with the main streams, supports the contention that the ancient glaciers of this region for some reason or other exerted little excavating power. Although this is the case here, I believe that in other instances glaciers have great powers of excavation.

The origin of the Lake Coleridge basin should also be considered in this connection. The only phenomenon bearing on the question as far as I know that gives any indication of deformation of the basin is the occurrence of drowned valleys near the peninsula on the east side of the lake. This implies either a depression of the land in their vicinity or the raising of the water of the lake relative to the land, and the latter alternative appears to be impossible, since all the evidence points to a lowering in the level of the water, except in so far as the fan of the Harper may be responsible for some slight rise, and this would not account for the amount of drowning exhibited. It is perhaps significant that this evidence is only furnished by the middle of the lake, and also that it is near the line of one of the possible E.N.E.-W.S.W. faults which have affected the area. In other parts of the lake there is no apparent evidence of drowning, but the walls are so steep and regular that such evidence would not be forthcoming. If the drowning be restricted to the middle section of the lake, then it points to a sagging down of the middle of the valley. After all, the required deformation is not great. Assuming that the depth of the lake is 700 ft., then for 5½ miles in either direction from the middle point the grade of the bottom would only be 1 in 40, quite a gentle gradient. If, however, one does not admit the possibility of warping, then it seems impossible to restore the valley in imagination to its condition antecedent to the ice-flood without asking for considerable powers of excavation when the ice is even moderately thick. If one restored the pre-glacial grade of the valley then the thickness of the ice, before it commenced such excavation, granting that there had been no warping, could not have exceeded 3000 ft., and it may not have exceeded 2000 ft. judging from the evidence of the height to which ice reached on neighbouring mountains.

Boulder clay with scratched stones occurs on the western shores of Lake Coleridge in the vicinity of the intake, forming cliffs washed at their base by the lake, and the deposit stretches across the down country to the other end of the supply tunnel, where there are also numerous scratched stones in the deposit. Although it was maintained by Hutton that scratched stones were rare in New Zealand, it is only a matter of looking in the right place and they can nearly always be found. Thus a specially favourable situation is where a glacier climbs out of a deep bed over a rock barrier. This accounts for the occurrence of such stones on the slopes of Fighting Hill, on Sebastopol, in the Mount Cook region, on the St. Bernard Saddle, near Cass, and near the Bealey Hotel in the valley of the Waimakariri, where the Waiau Glacier climbed out of its valley towards Lake Guyon, where the Rangitata climbed the bank near the Potts River at Ross's cutting, and the occurrence here is quite analogous, for the Coleridge Glacier rose from the lake bed over the ridge of greywacke towards the Rakaia River in the direction of the Power House. Scratched stones do occur in other localities, not so placed; for example, near the mouth of the Acheron River, on the downstream side of the rock barrier at Rakaia Gorge, in the High Peak Valley just below the homestead, and the possible case near the junction of Washpen Creek and the Hororata, though in this last case greywacke in position is exposed in close proximity.

Some of the material near the end of the tunnel at the top of the pipe-line, and also that near the intake in the cliffs facing the lake, is hardly tenacious enough for a boulder-clay, being incoherent and floury in texture, and is much more suggestive of surface-till; that is, material contained in the ice and dropped as the ice melted. Some of it, too, is rudely stratified, and contains rounded pebbles, which suggest that it is fluvio-glacial in origin.

4. *Recessional Phenomena:*

Perhaps the most interesting physiographical phenomena of the area are those associated with retreat of the ice. There are first of all the Moraines, either organised into definite land forms or the sporadic blocks scattered on the land surface. The most important areas where these occur in the order of the retreat of the ice are (i) on both sides of the river in the vicinity of the gorge; (ii) on the road leading to the High Peak Valley, between Fighting Hill and the High Peak Station; (iii) on the high banks of the river lying over lake silts, below and above the junction with the Acheron, and upstream towards the Power House; (iv) on the down country on both sides of the road leading from the Acheron to Lake Coleridge and the intake of the tunnel; (v) in the Upper Acheron Valley; (vi) to the east of Lake Coleridge, opposite the peninsula; (vii) to the south of Lake Heron, between the lake and the South Ashburton; (viii) on the downs near Prospect Hill. In addition to these more or less definitely organised deposits, isolated perched blocks may occur almost anywhere. Considering the magnitude of the ice streams which issued from the area, the quantity of moraine must be considered insignificant, nor is there the organisation of the material into definite barriers such as one would be led to expect. But this is characteristic of the river valleys of Canterbury, the only dam-like forms that I am aware of being in the upper valleys of the Clyde and Havelock, tributaries of the Rangitata, and at one place in the Cameron. The whole circumstances of the thickness and distribution of moraine suggest singularly rapid retreat, so that there were few halting stages of sufficient length to allow of definite terminal accumulations, apart from those near the face of the ice at its maximum extension.

The terminal moraine stretching from the Hororata River near its junction with Washpen Creek to Woolshed Hill shows the effect of the attack by streams issuing from a retreating ice-front or a stable front further back. One channel of this river must have followed down the line of the road from the Gorge towards Hororata township, and swept away the moraine from that section. In spite of this and other attendant destruction the remnants are impressive, and indicate a fairly long period when the ice-front was practically stationary or subject to slight oscillations. All the same the size of this moraine, even if restored to what in imagination it must have been originally, is hardly commensurate with the thickness of the ice and the size of the glacier which must have existed at the outlet of the valley only three miles away.

There is a considerable space between this terminal moraine and the morainic hummocks near the road from the Point Station to the Gorge, which does not disclose evidence of the presence of ice. Although the hummocks may not be actually recessional, and indicate renewed advance after retreat, they do not postulate a long period of stability of the ice-front, but somewhat rapid recession from a temporary advance.

The inclusion of moraine among recessional phenomena may seem peculiar, but its deposition is in most cases a phase of retreat, since the material has generally been spilled from the margin of the ice or dropped where it melted. All the same moraine does indicate the presence of ice in a locality once free from it and therefore suggests advance. Even well-defined moraines, such as that just mentioned and those near Lake Heron and on the High Peak Road, indicate a maximum advance closely followed by recession. Ground moraine is more definitely a feature of advance, but it, as well as other advance phenomena, may be features of recession, and vice versa.

When the ice began to retreat from its maximum advance it would naturally evacuate that portion of its occupied territory lying on the plains and in the lower part of the High Peak Valley. Its terminal face would retreat up the valley, but it is probable that the main Rakaia Glacier would occupy ground further down the main valley than the glaciers reached in the parallel valleys to the east. While the main valley would continue to receive substantial contributions from its head near the main divide, and also from the Wilberforce, also reaching back to the divide, the valleys lying to the east not heading so far back would be only partially occupied, and conditions would resemble those now existing at the Tasman and Murchison Glaciers. It appears fairly clear that the lower ends of these valleys would become ice free progressively from the east, that the valley which is the continuation of the Avoca would be free, while the Lake Coleridge valley and to a greater extent the main Rakaia were filled with ice.

It is clear that portions of the area thus uncovered were occupied by lakes, ponded back between the ice-margin and irregularities in the floor, especially if ice invaded the lower portions of the eastern valleys from the main streams occupying the valleys to the west. The existence of lakes is proved by the presence of stratified silts near the point where the Coleridge-Lyndon road climbs the ridge after leaving the Coleridge Creek Valley at a height of some 300 ft. above the level of the lake, and near the intake of the pipe-line from the Acheron. There are also well-developed level terraces on the lower slopes of the Craigieburn Range, in the vicinity of Coleridge Pass, which can well be explained as lake terraces, if a lake formed by the valley were blocked by a solid barrier or by ice, or by a combination of both at its lower end, while the escape of water in the direction of Lake Coleridge was prevented by the side of the glacier filling the gap between the southern end of Cotton's Sheep Range and the northern end of the Kaka Hill ridge.

The following is a description of the landscape features obtaining in this locality. The main part of the area near the road lying between the courses of the Scamander and Simois consists of a level terrace about 175 ft. (aneroid measurement) above present lake level. This extends back from the road for about half a mile, with occasional sink holes and one or two small mounds composed of pebbles and finer material, and rises either directly or with intermediate discontinuous shelves at various levels to another terrace 175 ft. higher. The intermediate shelves are more definitely developed towards the Simois, though one lies on the eastern side of the Lake Georgina Valley. This will be referred to later. Behind this second terrace is a flat area, from which rises another terrace, 350 ft. high (Photo No. 12), with one or two intermediate shelves, and with its top edge bordered with moraine in irregular heaps. Behind this the terrace is horizontal as determined by aneroid and abney level, except for fairly numerous large and occasionally deep sink holes. The surface of the terrace, except for the margin, shows no evidence of moraine, but is composed of finer angular and sub-angular material. At its northern end this terrace extends across the mouth of Moraine

Creek, and is succeeded by a higher terrace, and to the east of this creek by several horizontal shelves. Then for a space it rises gradually to the fan which leads up to Coleridge Pass. Further south the surface is marked with roches moutonnées, and then it rises about 25 ft. to another terrace, edged with a levee of morainic heaps and with a flat surface behind the levee. A remnant of this terrace lies across the entrance to the valley east of Lake Georgina Valley, with roches moutonnées and morainic dumps occupying the entrance and a portion of the upper part of the valley at higher level. East of this again, behind a row of roches moutonnées lies the swampy tract which partly drains to the upper Scamander and partly to the stream running through the deep channel where lie the Red Lakes. Remnants of the main 350 ft. terrace extend along the flanks of Laing's Hill towards the north-west, with morainic heaps above them, the shelves being specially well-developed in the direction of the upper part of the course of the Simois (Photo No. 13). As far as can be determined, the surface of these terraces is as a general run practically horizontal, so they can hardly be river terraces, and they therefore represent deposits in lakes ponded in between the ice-front and the embayment bordered by solid rock to the east and south-east.

When the ice commenced to retreat from the eastern wall, then there would be a discharge along it through the Red Lake Valley and from the front of the ice which reached the upper reaches of the valley west of it. When this valley entrance was freed from ice, and the ice margin retreated from the valley wall further, then moraine would be spilled from its edge, and behind it would lie a lake in which the highest level terrace was formed. Each successive terrace would be formed as the level of the ice lowered, till the discharge would take place through the Lake Georgina Valley. Now the margin of this lake is indicated by the horizontal terrace lying to the east of Lake Georgina, which peters out as a terrace just where the level of the ground in the floor of the valley reaches its highest, the top of the terrace and the summit of the saddle exactly corresponding. Finally, when the gap between Cotton's Sheep Range and Kaka Hill was opened, the lake would drain away and leave the main lowest level terrace free.

Even if it were not occupied by lakes, it is fairly clear that streams would flow along the eastern margin, between the ice and the bounding walls of the valley, as the Murchison River does now, and in this way the gravels and terrace remnants found at fairly high levels, even above the terraces probably formed in lakes, in the more eastern valleys would be accounted for, also the narrow stream channels such as lie at the base of Red Hill, and east of the Acheron in the direction of Snowdon, Some such explanation is necessary to account for these terrace remnants, for they occur at times so high above the floor of the valley that it is unreasonable to think they could have existed while the valley was being eroded below their level had erosion been by rivers in a normal way. Also it seems unreasonable to consider them remnants of former waste-filled valley, and to have been the result of secondary excavation. The channels running parallel to the valleys would be the spillways for such lateral lakes as then existed, and the depth to which some of them are eroded indicates that the conditions favourable to their formation extended over a long period, and that new spillways were uncovered very slowly.

Although some of the smaller and higher terrace remnants were no doubt stream-formed, it appears very doubtful if the major part of the terraces at a lower level can be attributed to this cause; all the same, the evidence that they are lacustrine in origin is largely the fact that they are level, and that they lie in positions not favourable to their formation by stream action. The occurrence of kettle holes as suggested by Flint (1929, pp. 262-3) supports this contention, and it is hard to see why they should exist if the terraces had been formed by streams. Exposures, by which their intimate structure can be observed, are practically non-existent, and there is no visible occurrence in the area between the Simois and Scamander of varved silts. The material of which the main portion of the terraces appears to be constructed is angular and sub-angular gravel, like that forming the present beaches round Lake Coleridge, and it is difficult to discriminate between this and stream-borne material laid down in the deltas of the torrents which issue from the mountain region round the lake, and likewise it is impossible to separate what may have been the beach deposit of former lakes from the material carried in by streams. When the terraces are narrow and horizontal, their form appears to furnish satisfactory explanation of their origin, but when they are half a mile wide it seems difficult to imagine the circumstances which resulted in the deposit of a wide belt of material with a horizontal surface.

The lake which occupied the upper end of the Georgina Valley with the old beach on its eastern shore has a counter-part in the valley in which Lake Selfe now lies (Photo No. 14). Horizontal terraces at three definite levels mark its old shore-line, and its existence can be explained by the water being ponded between a rocky barrier in the present Lake Selfe direction, the bounding rocky walls of the valley, and an ice barrier near the line of the Harper River. The terraces left behind show the kettle holes suggested by Flint as being a characteristic of the deposit between an ice barrier and a rock slope; in fact, the illustration given by him on page 263 might have been drawn from the occurrence here referred to. The terraces at three levels indicate three definite lake levels. In places the hummocky form of the ground suggests that the heaps might be morainic dumps, but in the few exposures where the structure can be seen there is no indication of moraine, rather the stones are rounded. In a quarry alongside the road where the structure is exposed, the lower beds are composed of small angular material, with scratched stones, and the upper are of well-stratified gravels. There is no appearance of varved silts. Above the terrace the hill-sides have been well scoured by ice action.

The present remnant of this lake is called Lake Henrietta, but this is reduced from what it must have been following on the ice retreat. Lake Selfe is apparently ponded between two fans, the southern one coming down and impinging against the end of a rocky spur coming from the western slope of Little Mount Ida, whereas the northern one is aided in forming a barrier by a small fan coming from Mount Ida itself. The lake appears to be deep along the eastern rocky margin.

There is evidence of an overflow of ice in an easterly direction from the Wilberforce Valley behind Mount Gargarus towards the Avoca Valley, which implies a deficiency of ice in the lower end of that valley while the Wilberforce was still strongly occupied. There is also evidence of an overflow over the saddle between Mount Ida and Little Mount Ida in the direction of Lake Ida, also implying a deficiency in that direction. The peculiar feature on the southern end of the Cotton Sheep Range, called the " Carriage Drive," may also be due to a similar cause. This is a shelf formed of angular material, in places half a chain wide, which swings round the end of the range, getting lower as it is followed north away from the lake, and exhibiting a perfect grade just as a road would when passing up and round the shoulder of a hill. As it approaches the Glenthorne road it gets lower and less and less distinct, and it finally disappears. I have considered it as possibly due to the presence of an earthquake rent, but there is no sign of this on the stabilised fans to the north, or on the solid hill-side further on, so I think that possibility should be ruled out. The most reasonable explanation appears to be that it was the lateral moraine of a glacier which invaded the valley to the east when it was clear of ice while the Lake Coleridge valley was still filled, and that the material spilled over from the side of the distributary glacier, as it does when a glacier reaches the broader part of the valley, or when it debouches on to a plain or other wide area where the ice can spread. Similar landscape forms, but not so pronounced, can be seen in similar positions and due to this cause in the valley of the Upper Ashburton.

All these features point to the eastern margin of the area having been evacuated by the ice first of all, and that there was a progressive retreat allowing lakes to be ponded between the ice and any solid barriers in the topography, and to be progressively drained as new outlets were uncovered.

This method of retreat of the ice is dependent, in my opinion, on the failure of the ice supply on the eastern side of the basin, while it was maintained on the western owing to the greater length of the divide being drained by the western ice streams; but apart from that there is the possibility that the mode of retreat of the ice as a whole, and specially of the larger streams such as occupied the main Rakaia and Wilberforce valleys, was by wastage from the side, and the consequent disappearance of the ice from long sections of the valley simultaneously. This was suggested by the author in a paper on the Lake Tekapo district (1921, p. 40), and the matter has been most fully discussed by R. F. Flint in various papers, but specially in that entitled " The Stagnation and Dissipation of the Last Ice Sheet " (1929, pp. 236-289), where the features resulting from ice retreat in New England are considered in the light of the hypothesis that the retreat took place by gradual wastage from the sides, and not by the orderly retreat of a front up a valley.

It is possible that some of the silts in the lower part of the Rakaia Valley may have been formed in lakes along the margins of the glacier, though this does not appear probable, but the distribution of the moraine in the valley as a thin veneer over certain areas, and its rare organisation into well-defined barriers points to a sudden melting of the ice and the dropping of its load at the point where the debris chanced to lie on the surface of the glacier.

Another recessional feature is the 60 ft. terrace mentioned previously which follows round the shore of the lake. This may be explained by supposing that the ice located on the site of the lake acted as a barrier at the Harper end, elsewhere the lake would be rock-bound, with the possible exception of that part occupied by till deposits just north of the intake of the tunnel. No doubt the ice would retreat from the lake area towards the Harper as the intensity of the glaciation waned, and the barrier would be effective till the ice-front retreated across the line of the Harper owing to the steep, rocky sides of Mount Oakden and the Sheep Range bounding the lake on either side. The overflow of the lake would then desert the channel at the southern end leading to the Acheron and discharge by the Lake Stream to the Harper, and by that river to the Wilberforce. If perchance the glacier again advanced down the Wilberforce across the line of the Harper it would block the gap between the northern end of Mount Oakden and the Sheep Range, and restore the old direction of drainage to the Acheron.

The northern end of Lake Coleridge is now blocked by the fan of the Harper River which lies across the end of the lake, and formerly the Wilberforce may have contributed its quota to the barrier. It is possible that this may have raised the level of the lake beyond the height it reached at the time the ice barrier retreated past the line of the Harper, and this rise may account for the drowning of a portion of the shoreline near the Peninsula mentioned previously, though the rise has not been sufficient to overtake the level of the 60 ft. terrace round the lake.

As long as the ice filled the Rakaia Valley near Double Hill it is reasonable to think that the Cameron and the stream from the ice-front in the Lake Heron Valley would discharge towards the Ashburton, but when the ice retreated upstream from the junction of the Lake Stream with the Rakaia a change in direction would take place. It is possible that it took place slightly earlier, and that the stream from the Lake Heron Valley followed for some distance along the side of the Rakaia Glacier as the Murchison follows along the side of the Tasman. At one time Lake Heron was of much greater extent, and stretched from the great moraine south of it to about five miles from the Rakaia, its bed in that direction being occupied at the present time by a great swamp. The lake may at one stage have been ponded back by the distributary glacier from the Rakaia, which caused and maintained the level at that of the outlet through the moraine to the Ashburton, but when the junction of the Lake Stream with the Rakaia was uncovered, a reversal certainly took place, aided by the steep gradient of the stream channel to the main Rakaia; it falls a height of 260 ft. in five miles.

An important phase of the retreat of the ice was the existence of a lake which occupied the lower part of the mountain valley of the river. The mode of formation of the hollow occupied by the lake and the nature and characteristics of the deposits laid down in it have been fully dealt with by the present author (Speight, 1926, pp. 57-81), and as far as is known there is nothing further to record, though the circumstances of the deposition of the silts and the light they throw on any time record are worthy of much more extended examination.*

An important feature of the glacial history of the region is the evidence of at least three periods of ice advance and three of retreat. These are disclosed in the sections in Pipe-Clay Gully and elsewhere (Speight, 1926). The general order of the deposits resting on greywacke unconformably is as follows:—

1. Moraine.
2. Varved silts, usually grey in colour.
3. Boulder clay with large blocks and scratched stones in a matrix partly derived from No. 2.
4. Varved silts, passing up into coarser silts and gravels, rudely interstratified at the top.
5. Moraine.

Nos. 1, 3, and 5 indicate the presence of ice in the locality, while Nos. 2 and 4 indicate its absence. The amount of advance and retreat in each case cannot be determined, because it is impossible to assign the beds belonging to No. 3 in other occurrences of the silts to the same definite epoch. This is due to the absence of continuity in the deposits, and the possibility that a boulder clay in one occurrence may belong to a different time from that of a similar boulder clay in another occurrence, but still interstratified in the silts. This makes it possible that there are more than three periods of advance.†

However, in view of the difficulty of correlation, it may be true that changes of front indicated by these features may be due to seasonal variations or to variations of short period which imply no serious alterations in climate, and therefore no marked advance of the ice over previous deposits, rather the mere encroachment of the fringe on to deposits laid down in front of it. If this is not the case

* It is most satisfactory to note that at the present time (October-November, 1933) Dr C. C. Caldenius, of Stockholm University, is engaged on the complete examination of these silts, and specially those in Pipeclay Gully.

† Dr Caldenius suggests that Nos. 3 and 4 are part of the same phase, and that 4 represents older silts which have been disturbed and had their structure partly destroyed by the advancing ice. They therefore represent the upper less coherent portion of the till or boulder clay of No. 3. This would therefore reduce by one the number of periods of retreat and likewise the number of advances as suggested by this section.

and the advance has been considerable, then the question may be asked as to how ice can have eroded a hollow like that lying behind the rock-barrier at the gorge and yet have passed over incoherent beds for a considerable distance without seriously disturbing them. Granting that glaciers can erode as well as abrade, as has been proved by F. Matthes (1930) in his account of the history of the Yosemite Valley, then the only way to account for the discrepancy in the two cases is to postulate that the maximum glaciation was a much more serious affair than the late advances, and that while 2000 ft. or more of ice could deepen such a hollow, the thin ice of the later episode was incompetent to perform any erosive work. The general evidence elsewhere supports the contention that the last advance was a much less serious phenomenon than the first.

A final recessional feature is the suite of terraces, both fluvio-glacial and fluvial, which characterise the valley especially in the neighbourhood of the gorge. As the gorge is probably post-glacial as regards the time of cutting, the terraces which flank it on either bank are no doubt fluvial, while those at higher levels between it and Round Top on the one hand and between it and the foot of Mount Hutt on the other are dominantly fluvio-glacial. No doubt the two forms grade into one another, just as the fluvio-glacial grades into the morainic, and it is at times difficult to distinguish them. Higher up the valley, what are apparently fluvial terraces may, after all, be marginal lake beaches, and vice versa. They also are difficult to classify at times.

5. *Comparison with other Glaciated Valleys.*

A somewhat interesting comparison may be made between this exposed glaciated valley and a drowned valley or fiord. A comparison with Milford Sound or George Sound does not bring out any striking points of resemblance, but this is not the case if the Rakaia Valley be compared with Dusky Sound, and especially its upper portion. If the former were submerged till the sea was 100 fathoms deep over the general floor of the valley between Round Top and Mount Hutt, then the two would be almost exactly identical. The threshold so characteristic of the mouths of fiords would mark the entrance to the flooded area, the water would be deep inside this and carry its depth far into the mountain tract, the alignment of the islands with their cross passages so formed in the Rakaia would be analogous to those of Dusky, as well as the parallelism of the rows of islands, and there would be the drowned Lake Heron Valley to correspond with the Acheron Passage in some particulars, but not in depth. The similarity would be so remarkable that it could hardly be the result of chance.

The interpretation of the origin of the features of the Rakaia Valley as given previously in this paper is somewhat in favour of Gregory's hypothesis that fiords are determined by the fracturing of a plateau land. All I can say in this connection is that I think the Rakaia Valley and its system of parallel valleys may be structural in origin, that they were in existence before the glaciation, and that their form has been modified by glaciation, and perhaps this sequence of events could be applied to Dusky Sound by way of explaining its peculiar features. It is probable that the hollow occupied by the lower reach of the Rakaia glacier and subsequently the site of a lake is structural in origin, but has been modified, and probably deepened when the ice was thick at the peak of the ice-flood.

As far as the other valleys of Canterbury are concerned it may be pointed out that the Waimakariri and Rangitata have features analogous to those of the Rakaia, and the former is certainly, and the latter probably a structural basin. The uppermost reach of the Ashburton valley is a U-shaped hollow with a rock bar at its lower end, now notched by the stream, and the Potts Valley parallel to it and lying to the west has a similar form, and in the case of the latter its structural origin is supported by the presence of an outlier of coal-measures within the hollow, while to the east of the Ashburton is the valley of the Cameron, apparently in a similar position, but without any barrier whatsoever, the valley being open at its lower end. The Mackenzie Country, too, furnishes definite evidence that it is a great structural basin, but the lakes occupying the valleys which extend into the heart of the Mount Cook region are shallow as compared with those of the west of Otago. Solid rock is not apparent at the lower end of Lake Pukaki, the ponding being apparently chiefly by moraine, whereas in the case of Lake Tekapo the solid rock shows in close proximity to the outlet, though the upper levels of the lake are ponded back behind a barrier of moraine; this, however, is in all probability only a thin veneer. Thus in that part of the Alps where glaciation must have been most intense, and the deepest hollows due to glacial erosion should occur, if glaciers are always competent excavators as distinct from abradors, there is no clear evidence of a marked threshold and of a deep hollow behind it.

E.—Cause of the Glaciation.

In concluding this account of the glacial phenomena of the region, some allusion should be made as to the probable cause of the glaciation. Three explanations have been advanced to account for it. These are as follows:—(i) That the mountains were more plateau-like in Pleistocene times, and held more snow in consequence of their thus furnishing larger collecting grounds; (ii) the land was higher, and therefore the glaciers came down further before they melted; and (iii) there was a refrigeration of the climate without any marked change in level.

The first of these hypotheses was advanced by Haast (1879, pp. 372, et seq.), and he appears to have been the only authority who held this opinion. The evidence from the Rakaia Valley is against this, since the valley directions and also their forms were determined before the onset on the ice, and there does not appear to have been any pronounced modification of their landscape features by the ice. The ice has been merely an abrading agent, and there is no evidence that the area had any decided plateau-like form.

The second hypothesis has been most favoured, and it is supported by Hutton, Park, Marshall, and others. While admitting that there is evidence that the land was higher than at present, it is difficult to say definitely whether or not this was synchronous with the ice advance and the actual cause of it. There is evidence that other countries in the southern hemisphere experienced a similar increased glaciation; mention need only be made of Tasmania, South-eastern Australia, South America, Kerguelen Land in order to show how widespread was the glacial advance. It is unreasonable to explain all these cases in the same way, since the advance occurred in Polar regions, in temperate regions, and in the tropical regions of the Andes. It would thus demand a change in level almost hemispherical in its incidence. This, of course, could easily be explained if it were possible to attribute the apparent higher level of the land to a world-wide sinking of ocean level. According to "Daly's Theory of Glacial Control for the Formation of Coral Reefs," while a lowering of sea-level occurred in the tropics during glacial times, a rise in level of the sea occurred in latitudes higher than 45°. So the increased glaciation could not be attributed to a cause dependent on the eustatic change in level of the sea in accordance with Daly's hypothesis. It can hardly be the case that the phenomenon is in one case the cause and in the other case the result of change in level.

According to Antevs (1928, p. 81), and basing his calculations on estimates of the volumes of the ice-sheets in Pleistocene times, the lowering of the level of the sea by abstraction of the water and locking it up in the form of ice could only have been responsible for lowering the surface of the sea on both sides of the equator by 305 ft., if the glaciations in both hemispheres were simultaneous, and if the contemporaneity was only partial the sea-level may at most have been lowered 290 ft. This amount of lowering would be increased in the tropics and diminished in higher latitudes owing to the attraction of the mass of ice located near the poles, and in sub-polar latitudes there would probably be a raising of the surface of the sea, an effect which would gradually diminish in temperate latitudes. It is thus possible that little change in level from this cause could occur in New Zealand, and therefore it would be incompetent to account for the advance of the ice in that country.

The only evidence that the Rakaia furnishes in this connection is that arising from a consideration of the height of the terraces. These are highest at the base of the mountains near the gorge, and become progressively lower when traced towards the sea. It is most convenient to explain this as arising from differential elevation of the land along an axis parallel with and practically coincident with the base of the mountains. The same evidence is furnished by other Canterbury Rivers, such as the Ashley, Waimakariri, and Rangitata, but doubtfully so in the case of the Ashburton. This elevation must have been post-glacial, for the rivers as they issued from the ice-front were level with the upper surface of the plains, or practically so. Therefore this line of evidence apparently furnishes nothing conclusive. I have also urged (1908, pp. 16-43) the importance of the effect of varying load of waste on the profile of these streams.

There remains the last of these hypotheses to consider, and it presents serious difficulties. Hutton maintained from biological considerations that there was no evidence of more serious refrigeration of the climate than occurs now since the close of the Tertiary era, and it is very hard to controvert his hypothesis. It must be noted, however, that Hutton always placed the date of the glacier advance in the Lower Pliocene; that is, much earlier than suggested by any other authority, a conclusion based on a chain of arguments, and fallacious if one link proves unsound.

Botanists such as Cockayne (see " Vegetation of New Zealand, 1928 ") have accepted an increased height of the land during the Pleistocene as the most plausible explanation of the xerophytic character of the plants inhabiting the Canterbury area, for such increment in height would allow of a more pronounced steppe-like condition existing on the eastern side of the range, and also allow for the development of even more pronounced xerophytic characters than the plants at present show. This is in accordance with the opinion expressed by Diels. Also the distribution of such sub-tropical plants as the nikau *(Rhopalostylis sapida)* and the ngaio *(Myoporum laetum)* cannot easily be explained in any way except by postulating a continuation of mild climate conditions since Pleistocene times. This specially applies to the coastal vegetation. Cockayne says (loc. cit., p. 109, footnote) : " Hardly any of the coastal trees can tolerate more than a few degrees of frost, and when it is remembered that nearly all the genera are palaeotropic, while six species of the coastal forest extend to countries warmer than New Zealand, it seems highly probable that the coastal tree-florula is but a remnant of one much larger, and that the species frequent the shore-line rather on account of the mild maritime climate than through possessing special ' adaptations.' On the other hand, the almost frostless climate of the West Coast of the South Island is not unsuited for some of the coastal trees unless the colder summers and excessive rainfall are antagonistic. Perhaps the absence in the Western District of these species extending to the North-western may be ascribed to the re-populating by plants of the Westland coastal plain after the glacial period." Again, on page 425, he says: " Towards the end of the period of elevation in the Pleistocene, when the mountains were at their highest, came the extension of the glaciers. Then would the palaeotropic element be driven northwards and perhaps eastwards, especially as it is more than probable the glacial advance was, in part, the result of a colder climate. East of the Southern Alps there would be a steppe climate on the plateau." Further on he says: " Towards the close of the Pleistocene, depression of the land set in once more, the glaciers retreated into the mountains, and the re-peopling of the glaciated land as already described began." It is clear that while Cockayne contemplated elevation of the land as being the prime factor in accounting for certain peculiarities of plant distribution, he was quite aware that a change of climate might have taken place, reinforcing the effects of increased height of the land.

Alone among geologists Henderson has maintained that the advance of the ice was associated with a lower level of the land, although his statement is not quite definite. He says (1924, p. 580): "The land was at one time 1000 ft. or more higher than it is now; but later was depressed till the old strand line was submerged to 1000 ft. or more below the present level. The deposits formed prior to and during this depression are here considered as Early Pleistocene, and those of the succeeding elevation of younger Pleistocene age. The former deposits are represented by volcanic accumulations and by beds of glacial fluviatile, estuarine, and littoral origin." The sentence does not make it clear whether the glacial deposits are associated with the prior elevation or the later depression, though it is understood that it is with the latter that Dr Henderson associates the glaciation. The evidence on which these conclusions as to the changing height of the land and the time of the changes, as well as the reasons for the association of the former period with glaciation, are not given. In the paper just cited, Henderson evidently believes that the changes in level of the strand-line were due to changes in sea-level or that New Zealand has moved as a whole, whether the movement be upward or downward, and that "any differential movements between adjacent earth-blocks that may have taken place during these periods must have been small if compared to the plateau-forming movements by which New Zealand has been uplifted as a unit" (p. 591).

In his recent paper on the "Marine Terraces of the North-eastern Portion of the South Island" (1928, pp. 508-56), Jobberns describes the movements of uplift which have affected this portion of the coast-line, and would extend this movement to the coast-line of Middle Canterbury. I have attempted to show (1930, pp. 164-7) that the recent major movements of this portion of the land area have been downward, although I am entirely in agreement with Jobberns's contention as to the coast-line further north. I can therefore see no evidence of eustatic change, or that the land has been raised as a whole. It may be that both eustatic and diastrophic movements have taken place simultaneously, in which case the separation of the evidence indicating one or other may be very difficult. In any case these marine terraces indicate an uplift of the land relative to the sea for a portion of the north part of the South Island, but their precise date has not yet been determined with certainty, so that no correlation can be definitely made between them and the glaciation. Perhaps there is no relation at all, and they are all definitely posterior to the period of maximum glaciation. If they are of Pleistocene age they would tend to support Henderson's contention as regards the northern portion of the South Island, that the glaciation took place during a period when the land was lower.

However, if his contention is correct, and the glaciation was associated with a period of land depression, then the extension of the ice can only be explained by a refrigeration of the climate, and it is necessary to determine if the features of the vegetation as demonstrated by Cockayne can be explained on the assumption that there was no elevation of the land beyond what exists at present, and that the country experienced such a refrigeration that as a consequence ice filled the West Coast Sounds, and that glaciers extended from the central section of the Southern Alps over the plains of Westland beyond the present coast-line, and this at a time when the land was considerably lower in level. The former extension of the ice in that direction is clearly evidenced by the moraines in the sea near Abut Head as recorded by Haast, and if, as Henderson demands, the land was lower than at present, the ice must have extended into sea at least 100 fathoms deep, and perhaps much more.

I think it quite conceivable that the xerophylly of the plants is explicable on the assumption that the height of the land was somewhere about the same level as at present, providing that refrigeration took place, but it appears difficult to account for it were the land considerably lower. The conditions would then approach those of Stewart Island or of the Auckland Islands, or of other sub-antarctic islands whose vegetation shows no evidence of xerophylly. It must be remembered all the same that the height of the mountains has been reduced by erosion since the time of the ice maximum, so that they were probably not much different in height from what they are now even allowing for the sea to have risen as postulated by Henderson. Increased cold would bring about increasedly arid conditions on the eastern side of the Alps owing to diminished evaporation from the seas to the west. It seems possible, therefore, that cold alone would account for the xerophytic character of the vegetation on their eastern slopes. Can the distribution of the shore vegetation be explained as well?

The only way that this seems possible is that during the ice age the tender plants migrated north, and that after the climate improved a southerly migration took place, specially along the shore-line, and that on modified colder conditions obtaining again as at the present time, the warmth-loving plants only survived in sheltered spots such as on Banks Peninsula and in Southern Otago.

The following quotation from a letter to me from Dr Cockayne seems entirely apposite in this connection, and I have his permission to use it. "This brings me to the behaviour of certain indigenous plants in Wellington during this exceptionally frosty winter (1931). Thus everywhere the leaves of the Black-Tree fern have been killed, and in many places the Ngaio *(Myoporum laetum)* has been injured. This is one more hint—if such were needed—of the slight frost tolerating capacity of New Zealand plants in general. Such behaviour is certainly no new thing, and it does look as if they had never been subjected to any really strong degree of frost, and also that the winter temperature of New Zealand had been in the past warmer than colder. Of course, I am not so foolish as to base these remarks on this season's Wellington climate, but it is rather on the knowledge of how our plants have responded to several severe winters in Otago, Canterbury, and other areas; as also as to what has befallen them in countries colder in winter than New Zealand. The difficult question also arises as to how long a period a species would remain 'unacclimatised.' Could a tropical species remain frost shy for millions of years? Or, on the other hand, is the process of increasing toleration of a lower temperature comparatively rapid?

Or, again, has climate any power in regard to altering the physiological capabilities of living organisms? The truth seems to be that science is still profoundly ignorant regarding not only the causes of evolution itself, but of its more debatable side issues. All the above is, as you know, brought forward here in regard to any theories concerning glacial climates."

An opinion such as this, coming from a distinguished authority like Dr Cockayne, who knows the conditions of the New Zealand plants in field better than anyone, indicates how little reliance must be placed at present on any theory of glaciation for the Pleistocene of New Zealand, based on inferences drawn from the plant covering, and specially on any theory based on climatic change in connection therewith.

It has been suggested that a change in direction of ocean currents might have been responsible for the conditions which caused glaciation. To be a satisfactory explanation it would have to account for the glacial conditions in all lands round the South Pole, at approximately the same time, leaving out of consideration the question of the glaciation of the northern hemisphere, also probably contemporaneously, and, further, a probable world-wide glaciation affecting even the tropics. It is conceivable that a change in the currents in the Southern Ocean might cause a variation in the climate of different lands independently. For example, if the sea bottom to the south and south-west of New Zealand were raised, and the space of open sea reduced till it approximated in width to that south of South America, then the conditions obtaining in South America would exist in New Zealand, and glaciers might again come down to sea-level in the southern part of the country, as they do now in the Chilean Fiords, but such an elevation of the crust, unless it were restricted to the area south of New Zealand, would of itself cause an advance of the glaciers, apart from any effect produced by the deflection of the cold Antarctic current from its present course against our western coast. In this case the biological difficulties mentioned above would arise, so that the problem would again present serious perplexities. However, to sum up the position, in my opinion some change in climate seems necessary to account for the glaciation, and the biological difficulties will ultimately be resolved on the assumption that change in climate did really take place.

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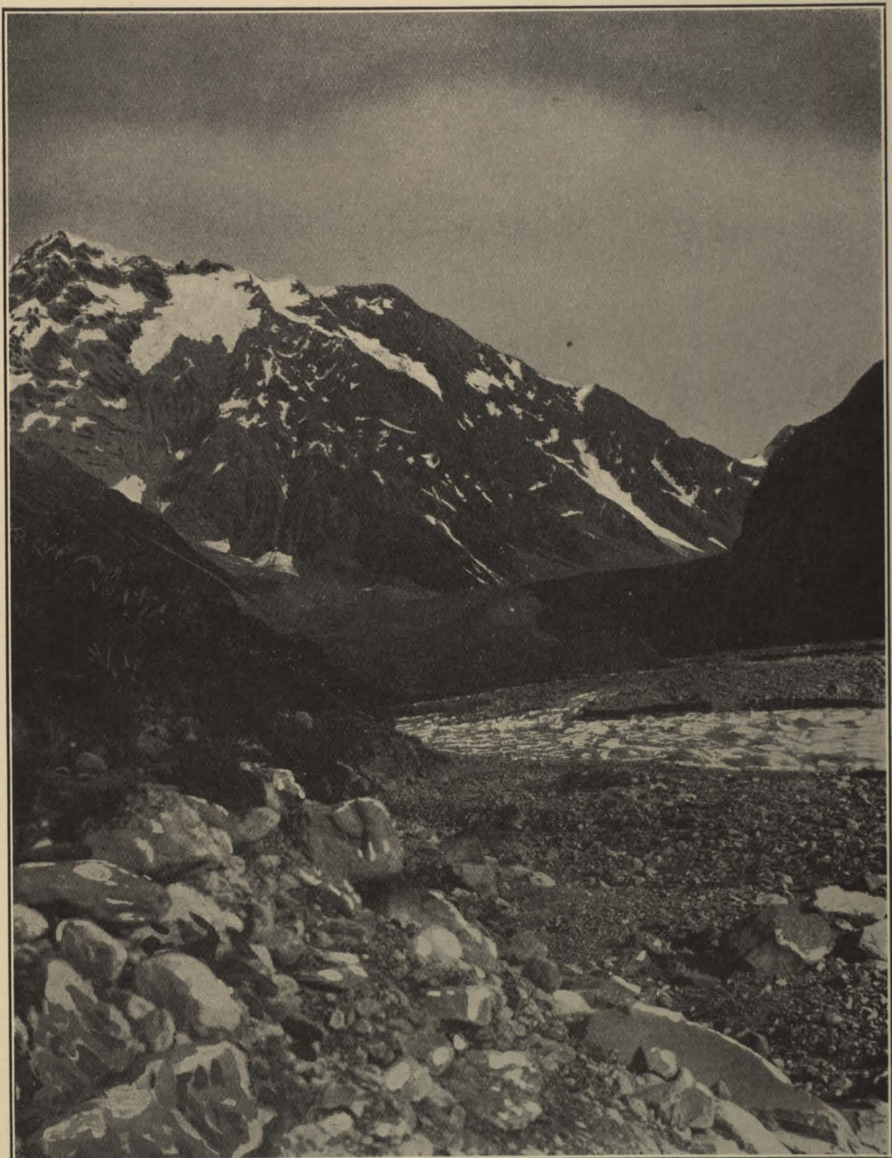


PHOTO No. 1.—Terminal face of Ramsay Glacier, with slopes of Mein's Knob on left. Mount Ramsay in background, and Jim's Knob on left.

PHOTO No. 2.—Looking up Rakaia River from slopes of Mount Oakden, Wilberforce River in foreground. Woolshed Hill and Algidus Station in right middle; the Mathias River coming in on right distance; Mount Arrowsmith in the background.

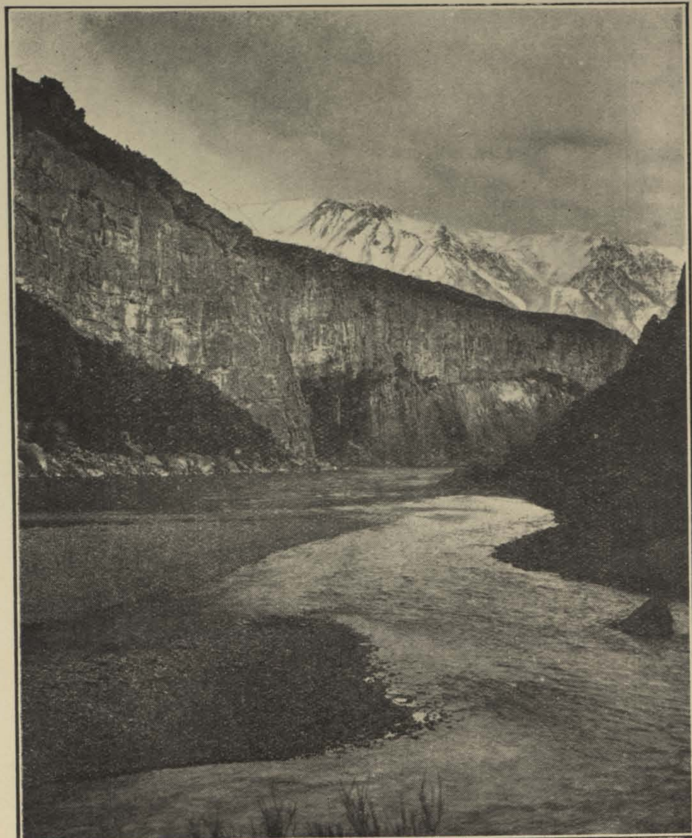


PHOTO No. 3.—Gorge of the Rakaia River; the cliffs are formed of rhyolite.

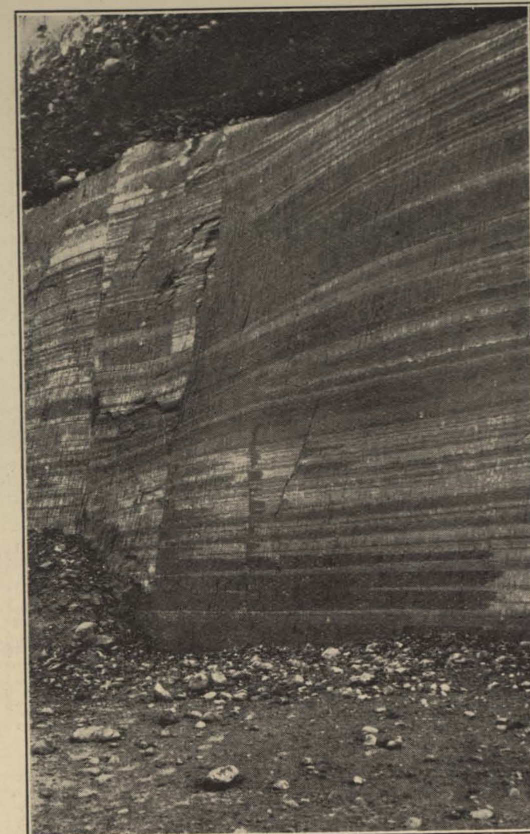


PHOTO No. 4.—Faulted varved silts on road cutting in the Rakaia Gorge, south side of river.

PHOTO No. 5.—Showing bed of Harper River with the Wilberforce beyond.

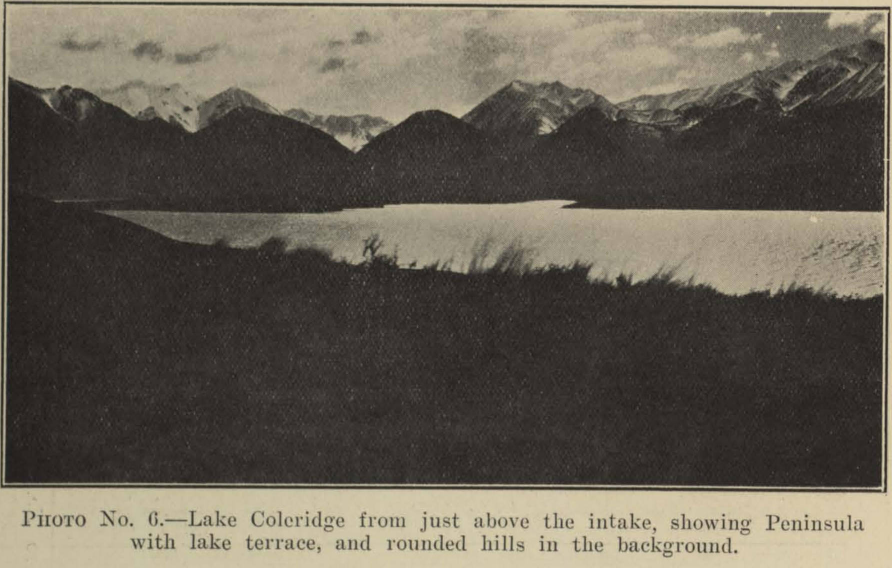


PHOTO No. 6.—Lake Coleridge from just above the intake, showing Peninsula with lake terrace, and rounded hills in the background.

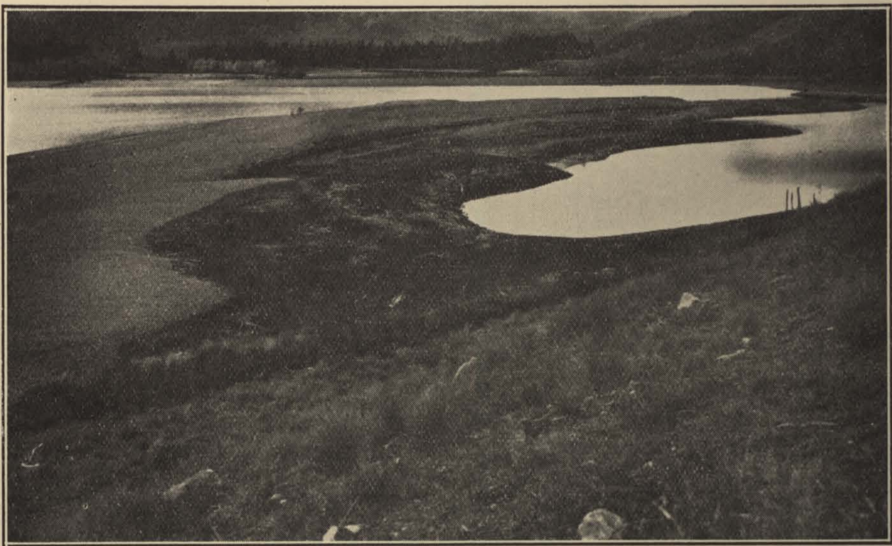


PHOTO No. 7.—Old spit on which the vegetation has been drowned, and new spit formed when the level of Lake Coleridge was artificially raised, but now exposed when the lake has been lowered in winter as the result of drawing off the water for power purposes faster than it runs in.

PHOTO No. 8.—Cliffs formed of glacial debris with scratched stones on shore of Lake Coleridge west of the intake, with pebble beach at the base, exposed during low level of the lake.

PHOTO No. 9.—Perched block lying on boulder clay with scratched stones on banks of Washpen Creek, near Glenroy.

PHOTO No. 10.—Morainic dumps between the Rakaia Gorge and the foot of Mount Hutt, south side of the River.

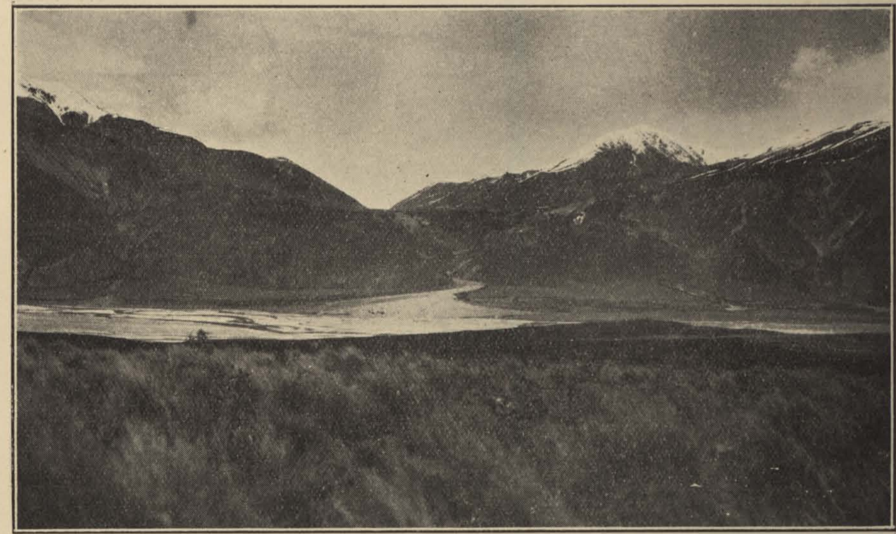


PHOTO No. 11.—Redcliffe Gully, showing channel of overflow from the Rakaia towards the North Ashburton. Limestone and other Tertiary beds are exposed on the level of the top of the pass facing the Rakaia.

PHOTO No. 12.—Horizontal terraces at head of Scamander Stream. The Red Lakes lie to the left of conical hill in middle distance; Mount Georgina on the left with open valley between them; sink-hole in foreground and roches moutonnées on the left top corner lying at base of the Red Hill. The edge of the main terrace and the heaps to the right are moraine.

PHOTO No. 13.—Suite of terraces at the foot of Laing's Hill; the Simois Stream lies on the extreme right.

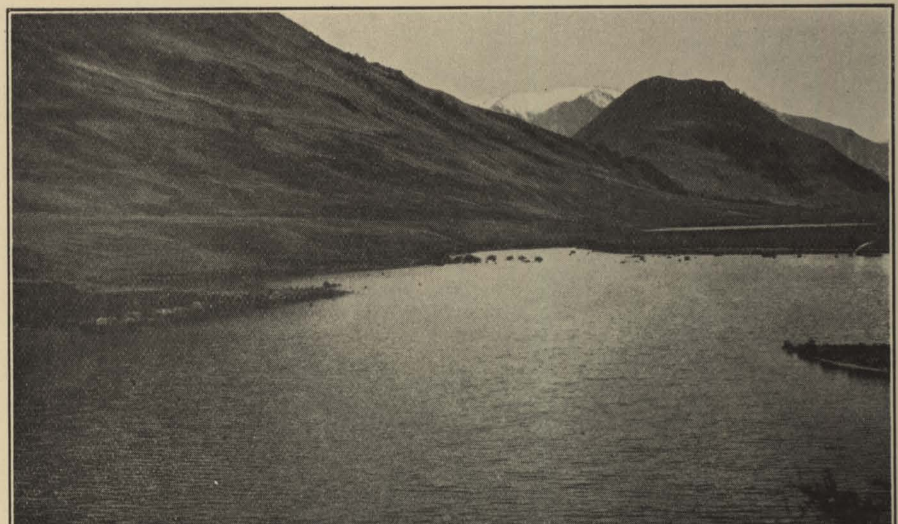
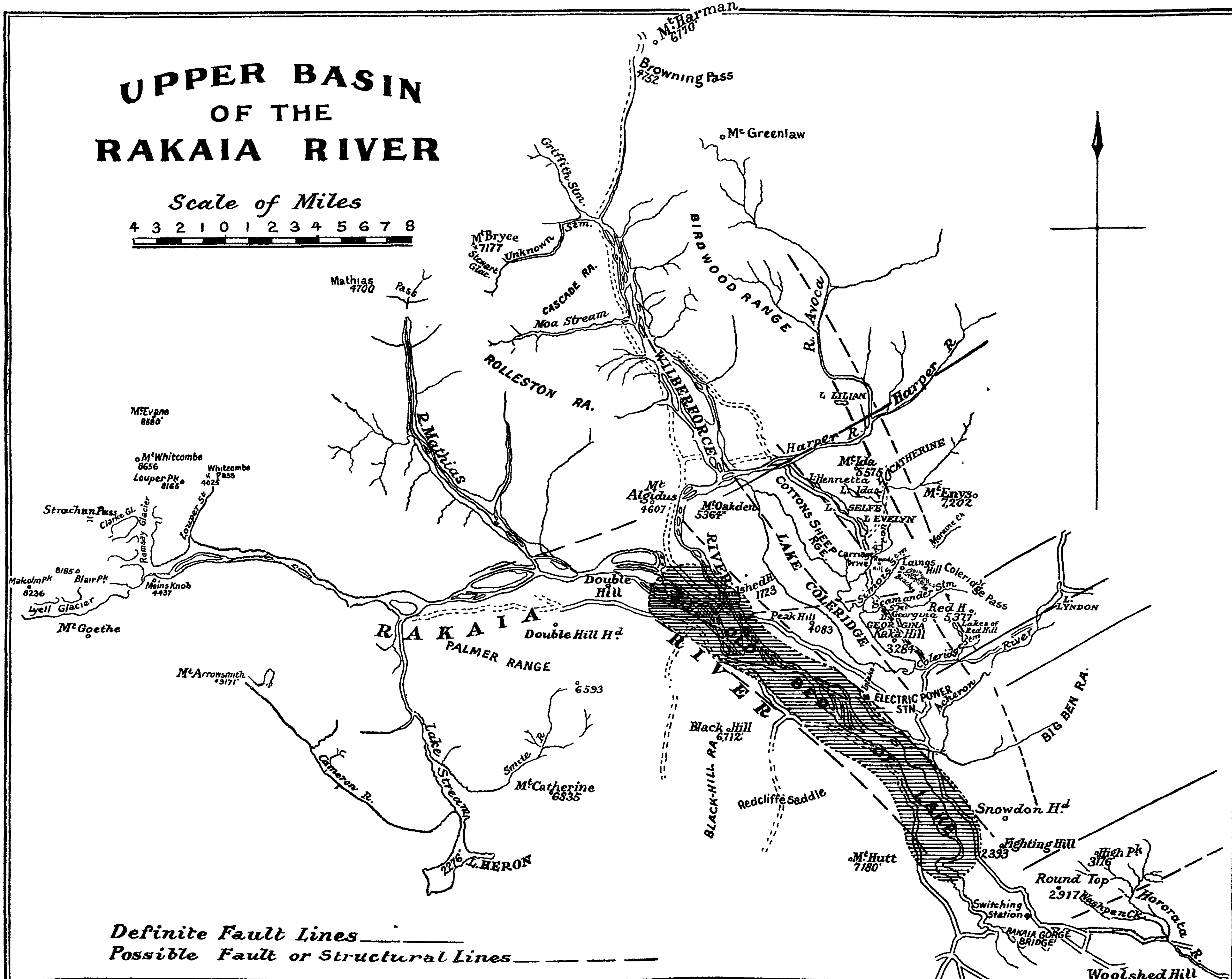


PHOTO No. 14.—Lake Henrietta, showing old lake beach, with ice-scoured slopes of Mount Ida above. Little Mount Ida in the distance. Over the saddle lies Lake Ida. An exactly analogous old lake beach lies similarly placed as regards Lake Georgina.



UPPER BASIN OF THE RAKAIA RIVER

Scale of Miles

4 3 2 1 0 1 2 3 4 5 6 7 8

Definite Fault Lines ————

Possible Fault or Structural Lines — — — —