

T H E

AMERICAN JOURNAL OF SCIENCE

[F O U R T H S E R I E S .]

ART. XXII.—*Block Mountains in New Zealand*; by C. A. COTTON, Victoria University College, Wellington, New Zealand.*

CONTENTS.

- Introduction.
- Part I. Block Mountains and Related Forms.
1. Structure.
 2. The Initial Surface.
 3. Possible Types of Drainage.
 - True Consequents.
 - Anteconsequent Drainage.
 - Antecedent Drainage.
 4. Sequential Forms.
 - Stripping.
 - Salients on Stripped Plateaus.
 - Mature Dissection of the Undermass.
 - Fault Scarps and Fold Scarps.
 - Composite Fault Scarps.
 - Fold Scarps.
 5. Trough Filling.
- Part II. The Block Mountains of Central Otago.
1. Historical Sketch.
 2. Structure.
 3. Major Tectonic Features.
 - The Central Otago System.
 - The Northern Highland of Otago.
 4. Drainage.
 - The Central Otago Chain of Depressions.
 - The Clutha River System.
 - The Waitaki River System.
 5. The Surfaces of Uplifted Blocks.
 - Stripped Plateau Surfaces.
 - Details of the Surface on Schist Blocks.
 - Salients on Block Surfaces.
 - Scarps of the Schist Blocks.
 - The Scarps of Greywacke Blocks.
 6. The Floors of the Central Otago Depressions.
- List of Papers to which reference is made.

* References are listed in full at the end of the article.

INTRODUCTION.

THE geologic structure of New Zealand has been described by the writer in a recent article (1916 *a*, pp. 319, 320) as "a concourse of earth blocks of varying size and shape, in places compressed; the highest blocks lying in the northeast and southwest axis of the land masses, so that the whole structure may be termed a geanticline; the blocks initially consisting of an older mass of generally complex structure much denuded and largely planed, and concealed over the greater part of the area by covering strata which had not been disturbed before the 'blocking' took place; the whole since these movements considerably modified by erosion somewhat complicated by the effects of later movements of uplift and subsidence."

In another article (1916 *b*), the block mountains and associated features in a small area in northern Nelson have been described. This paper deals with Central Otago, where the "block" features are unusually well preserved.

As an aid in presentation, the description and interpretation of selected types of New Zealand mountains is preceded by a discussion of the physiographic development of block mountains in general based on the established principles of geomorphology.

PART I. BLOCK MOUNTAINS AND RELATED FORMS.

1. *Structure.*

The structure is postulated as an undermass of rocks with varied structures which before being covered were denuded enormously and reduced to small relief. Though the final planing was accomplished in some parts of New Zealand by the sea, subaërial agencies probably prepared the large planed areas for the final marine planation.

Remnants prove the presence of a former widespread overmass or cover upon the eroded surface of the undermass. It is not necessary to assume that this overmass was laid down as a continuous sheet over the region or that it is entirely of marine origin. It may be postulated, indeed, that the covering beds are in part fluvialite, resting upon a peneplain,* and that other parts of such a surface may never have been covered.

Perhaps the most important factors to be considered in the processes of uplift and denudation are: (1) the nature of the

* It is not to be inferred from the above statements concerning covering strata in New Zealand that the writer believes submergence and the initiation of sedimentation to have been everywhere simultaneous. It is probable that overlap in the covering strata resulted from submergence of successive "blocks" of the undermass. Further, the statement of Speight (1915), based on the results of prolonged study, that in North Canterbury islands rose through the Upper Cretaceous and Tertiary sea, must not be overlooked.

FIG. 1.

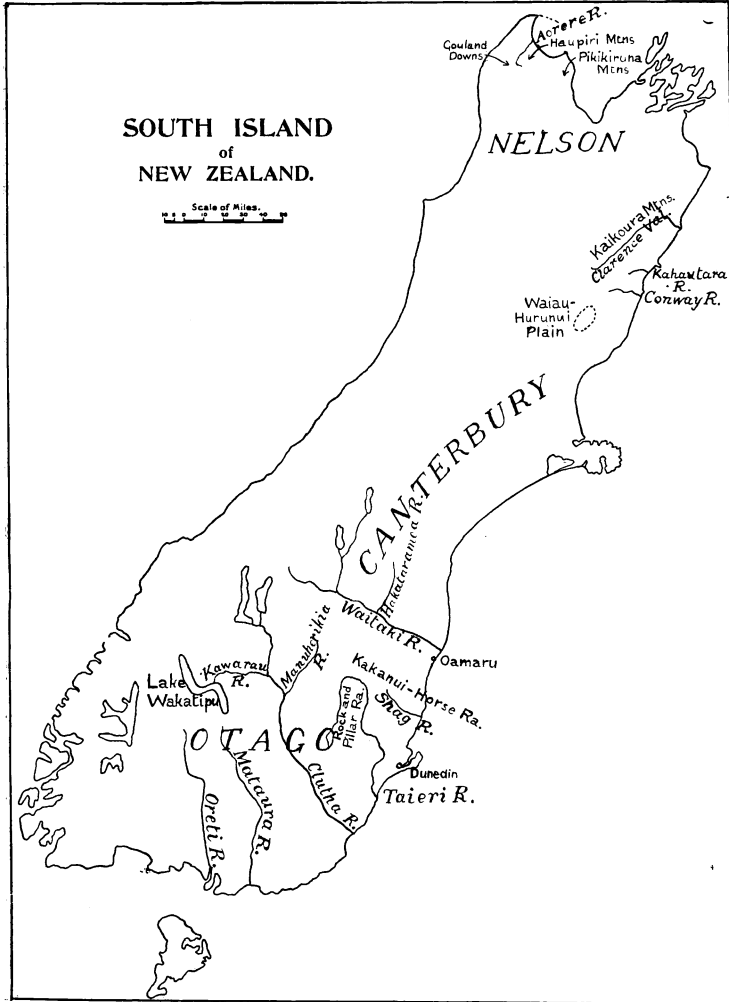


FIG. 1. Locality map of the South Island of New Zealand.
Scale 1 inch = 100 miles.

uplift, (2) the relative strength of, or resistance offered to, erosion by the undermass and the cover, and (3) the nature of the structures in the undermass where the overmass is relatively weak.

The covering strata in New Zealand are relatively weak, consisting in great part of mudstones and incompletely indurated sandstones, also of thin limestones, relatively resistant but soluble, interbedded with weak clastics. A few thick masses of indurated conglomerate which occur in places at the base of the cover offer great resistance to erosion. In some districts thin lava flows occur; but these like the limestones are weakened by interbedding with clastics.

In contrast with the overmass, the rocks of the undermass are generally highly resistant. In northern Nelson these are indurated argillite, quartzite, quartz schist, crystalline limestone, and intrusive granite. In western Otago, gneissic and plutonic rocks occur, and in Central Otago, the undermass consists entirely of schist—relatively a very resistant rock compared with the unconsolidated sands and clays largely developed in the overmass of that district.

2. *The Initial Surface.*

The form of the initial surface depends upon the nature of the uplift. Two types of uplift may be distinguished: (*a*) The blocks are differentially elevated, depressed, or tilted—the displacement being solely by faulting or by faulting replaced to a minor extent by monoclinical flexures. The initial surface must be a mosaic of plane areas at various attitudes, some perhaps horizontal and many inclined, separated by initial fault scarps facing in different directions. (*b*) Strong warping—perhaps better termed folding—attains considerable development; faults though present pass into or replace the limbs of folds, the uplifted blocks being in part anticlinal and the fault angles and trough depressions being in part synclinal. The surfaces of the structural units, which here as well as in (*a*) may be termed “blocks,” will be in part warped or flexed, though there may still be notable plane areas, and the fault-scarp boundaries between adjacent blocks will be replaced in part by monoclinical slopes. This is the type of deformation concerned in producing many of the New Zealand block mountains, and, according to Gilbert (1874), a somewhat similar type is not unknown in the North American Great Basin.

The types of initial and sequential forms for regions of uplifted and tilted blocks without cover have been deduced by Davis (1903, 1905, 1912) and matched with examples from the Basin Ranges and elsewhere. Louderback (1904) has described faulted blocks with a cover of resistant lava. In the present

paper, attention will be directed principally to forms developed in a region in which the predeformational surface is a plain of deposition, being the surface of a weak overmass lying on a planed undermass.

3. *Possible Types of Drainage.*

The early stages of the drainage of a region in which the initial forms have been produced by the faulting and folding of a weak overmass on a planed undermass must be entirely consequent if the overmass is continuous and if its surface is a plain of marine deposition. Parts, however, of the Otago district were probably emergent prior to the deformation, and some of the streams may have persisted during and after the deformation as antecedents. Such a preëxisting drainage system would be present also in any part of the area where the upper layers of the covering strata were of subaërial origin, or in any part where regional elevation antedating the deformation had brought the upper layers of marine strata above sea level. Few streams are powerful enough to persist through strong deformation, and though a few large streams may be antecedent, the greater part of the drainage, including most if not all of the minor and tributary streams, will be consequent. As movements of deformation occupy some time, erosion can accomplish much while uplift is in progress. A drainage system will be established as soon as any portion of the region is exposed as land, and this early consequent drainage tends to be perpetuated during the continuance of the movements. As movements probably will not go on continuously in all parts of the region, if the consequent drainage resulting from the deformation be alone considered, the early drainage pattern is not necessarily the same as that which would have come into existence had the final structure been instantaneously assumed. In a deformed region may be found, therefore, true antecedent streams, true consequent streams, and streams that were consequent upon the form of the surface assumed as the result of early movements but are antecedent to later movements of the same series. Such streams might perhaps be appropriately termed antecedent consequents or *antecessuents*. Spill-over courses resulting from the overtopping of divides by alluvial accumulations are also possible.

After cutting down through the covering strata, streams of any or all of these types will be superposed in places upon the structures of the undermass. Besides, all may be expected to develop insequent tributaries, and as the cycle progresses subsequent streams will form upon weaker structures in the undermass and such portions of the covering strata as have escaped complete destruction.

It is necessary to consider criteria for distinguishing the types of drainage. Subsequent streams guided by weaker strata in an inclined series are readily recognized, but when they are guided by shear-zones, ancient fault-planes, or master joints they are generally included with the insequents. Leaving these aside, we may consider the important types of drainage in the early stages of the cycle of erosion introduced by the deformation, namely, true consequents, true antecedents, and anteconsequents, all possibly superposed.

True Consequents.—On the highly improbable assumption that deformation is simultaneous and instantaneous and without contemporary erosion, it follows that consequent streams will make their way down the tilted and warped surfaces and that some consequent lakes will be formed. Under normal conditions of humidity, these lakes will spill over at the lowest gaps along consequent courses, which will be superposed later on the structure of the older mass, gorges will be cut through the higher blocks, and systems of consequent streams will be established. Exactly similar drainage patterns are to be expected if the deforming movements are simultaneous though not instantaneous. If the movements are sufficiently slow no lakes may result, as early-formed consequent courses across the lowest sags in the crest lines of the rising blocks will be continuously deepened by corrasion. Consequent lakes considerably above base-level are short-lived, so they are not likely to leave permanent records of their existence.

Anteconsequent Drainage. There is as little justification for the postulate that movements have been simultaneous throughout a period of deformation as there is for that of instantaneous deformation. Movement may be well-advanced in some parts of a region while other parts are as yet unaffected. There may even be a rhythmic passage of waves across the land surface. (In regional movements such oscillation is well attested; but the present discussion is concerned with strongly differential as distinguished from regional movements.)

In the case of a low-lying block surrounded by differentially rising blocks, the movement of which is not necessarily simultaneous, the lowest gap in the basin rim (erosion being left out of account) may not always be in the same position; and the consequent outlet of a basin established during an early stage of deformation and persisting by rapid corrasion may not at a later stage be situated at the lowest sag in the surrounding blocks.

Antecedent Drainage. Antecedent drainage channels on a surface of the kind postulated must be inherited from a simple centrifugal system of subparallel streams radiating from the old land or that portion of the undermass which escaped burial

during the period preceding the deformation. The approximate position of such a nonburied area of the undermass or the source of the material forming the covering strata furnish evidence for the direction of possible antecedent streams. Without such knowledge only streams which cannot be placed with certainty in any other category may be classed as possibly antecedent. The relation of valley directions to the trend of elongated blocks may give information. If, as in Otago, the deformation has produced longitudinal tectonic features—parallel elongated arches and troughs or long tilted blocks separated by fault angles—both true consequent and antecolsequent drainage will follow generally longitudinal courses, though perhaps breaking across here and there from one linear series of depressed areas to another. Antecedent drainage, on the other hand, may cross the longitudinal features diagonally or transversely.

4. *Sequential Forms.*

Davis has recognized two main elements in the form of a simply tilted block mountain, the back slope and the front or scarp. These are the two main elements in the whole initial landscape of a region of tilted blocks.

In a region that has been affected by diverse movements, the elements of the initial landscape are horizontal areas (high or low-lying), back slopes (areas of surface with a more or less uniform and gentle slope), fold surfaces (areas of steeper slope, not necessarily uniform), and fault scarps. There will be transitions from fold surfaces through what may be termed fold scarps to fault scarps. The present problem is to trace the development of topographic features from an initial surface comprising these various elements, upon which a system of consequent drainage becomes established. After postulating an initial relief caused by instantaneous deformation, it is possible to consider the effects of erosion and a continuation of the deformation going on simultaneously.

In the stage of extreme youth, the block fronts (fault and fold scarps) will experience the most rapid changes of form and, as a result of slumping and the formation of consequent gullies, these will supply the largest quantity of waste. Very early, also, the perhaps closely spaced consequent streams of considerable length, which will have come into existence all over the relatively large areas of inclined block surfaces, will be actively engaged in grading their courses (see fig. 2).

From the rapidly deepened consequent valleys, insequent tributaries will be developed, and probably also subsequents. Since the spacing of the consequents alone may be close and the texture of dissection becomes finer when insequents and subsequents have also been developed, and since entrenchment of the whole system beneath the sloping surface of the weak

covering strata must rapidly take place, maturity of dissection will be rapidly attained, first in the middle parts of the steepest slopes and later over the whole area of sloping upland. On level upland surfaces, where streams may be widely spaced, on gentle slopes, where stream grade may be attained at no great depth below the initial surface, and also on low-lying blocks, where the surface is at no great height above base-level and where, consequently, deep dissection is impossible, maturity of dissection may be relatively long delayed.

FIG. 2.

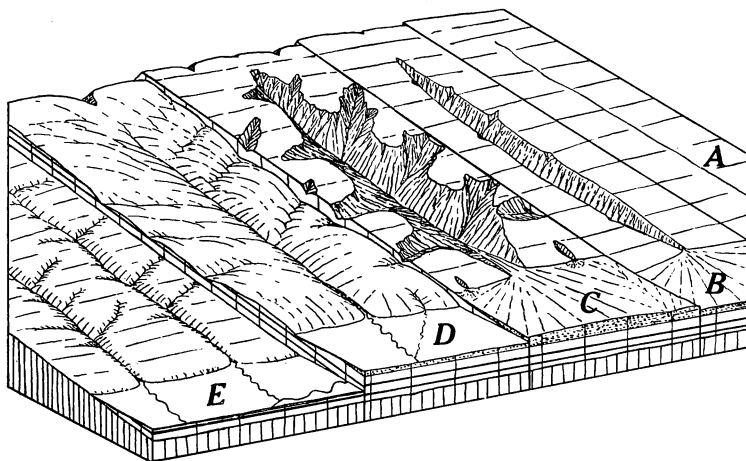


FIG. 2. Diagram of the development of the back slope of a gently tilted block with a relatively resistant undermass and weak overmass from the initial form A through sequential forms B, C, and D to a stripped floor (earlier denudation plain) with shallow dissection, E.

During this stage of the cycle, the troughs will generally be aggraded on account of an enormous quantity of waste from the upland surfaces. During the whole period of deformation, the troughs will be filled as they sink (see fig. 2, B, C, D). The waste may be laid down in part on the floors of lakes, wholly or in part conformable to the deposits of the pre-deformational period, or it may be deposited wholly subaërially as fans growing outward from the margins of the surrounding blocks, coalescing and forming an aggraded plain, the deposits of which will, in general, accumulate upon a maturely dissected surface developed as a sequel to the deforming movements.

Stripping.—When the consequent and other streams of the sloping uplands cut through the cover and become superposed

on the resistant older mass, the rate of further downward cutting will become comparatively slow. Before this stage the measure of the relief has been increasing progressively with downward cutting and may still increase slightly if maturity of dissection of the surface is still to be attained. After the attainment of maturity, reduction in height of the interfluvial areas of weak covering strata may go on more rapidly than vertical stream corrosion on the resistant underlying rocks. Even if the streams had attained grade without cutting through the cover in the early stages of dissection, after the cover has

FIG. 3.

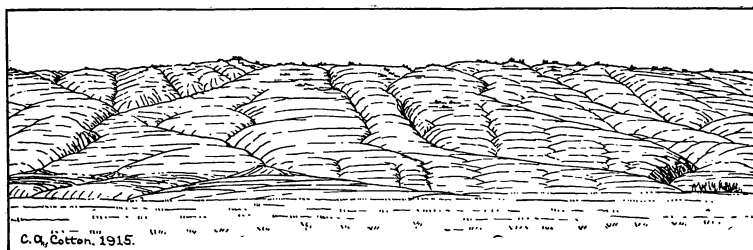


FIG. 3. A northwest-sloping stripped plateau surface forming the back slope of the Rough Ridge block in Central Otago, and descending beneath covering strata planed by the Ida Burn.

been largely removed from the higher part of the block they will be forced to cut deeper and will eventually become superposed. With the complete removal of covering strata, all the streams will be incised to some extent. Owing to the resistant nature of the undermass the ravines will long remain narrow, while inclined flat areas on the interfluves will survive. This stage will be attained earliest at the middle parts of the slopes of block surfaces. On lower slopes, undissected interfluvial areas are likely to be larger, and on slightly inclined higher slopes where there is little concentrated wash, remnants of the cover may be expected to survive for some time longer (see fig. 2, E).

These sloping plains of denudation, almost entirely stripped of their cover, and crossed by many steep-sided, generally consequent ravines, which increase rapidly in depth as followed upstream, with here and there remnants of the covering strata relieving the otherwise flat interfluvial surfaces, though common in New Zealand, have received scant attention. They have been noted by McKay, Bell (1907), the writer (1916 *b*) in the Aorere district of northern Nelson, and by Thomson (1914) in South Canterbury. The more level portions of similar sur-

faces in Otago have been termed by Park (1906, 1910) the Barewood Plateau or Central Otago Penepplain; and Speight has recognized a similar surface in the Kaimanawa Mountains in the North Island (1908).

The most perfect examples known to the writer are those forming the back slopes of some of the block mountains of Central Otago, for example, the western slope of Rough Ridge (see fig. 3); a long northeasterly slope from the broken plateaus of Central Otago to the fault-angle depression followed by the Shag River; a similar slope southeasterly to the Taieri Plain; a similar slope northeastward from the Kakanui Mountains towards the Oamaru district (see fig. 4); the westward

FIG. 4.



FIG. 4. Part of stripped plateau surface descending northeastward to Oamaru district, Otago, with a deeply incised gorge, that of the Waianakarua River, on the right, and a large residual mesa of the overmass just to the right of center.

slope of the Hunter's Hills, noted by Thomson, with which are associated similar slopes surrounding the Waihao basin; the surface of the Gouland Downs, Northwest Nelson; and the northwestward slope towards the fault-angle depression followed by the Aorere River, northern Nelson.

Salients on Stripped Plateaus.—The generally flat surface of a stripped plateau will be broken by a pattern of reëntrant ravines. Salient features may or may not be present. Such may have originated as monadnocks on the eroded surface of the undermass which has been lately reexposed, or as small isolated fault blocks in which the surface of the oldermass has been uplifted above its level in surrounding blocks; or they may be remnants of cover not yet removed, thus closely resembling monadnocks in form. Certain remnants of cover may owe their preservation to local induration or local thickening of a relatively resistant stratum and to the presence of a lava flow of small extent. Mesas or buttes of covering strata may thus be scattered sporadically over a surface. Other salients may owe their preservation to slight inequalities of uplift which have caused unusually wide interfluvial spaces between consequent streams. Salient features developed from monadnocks and from small uplifted blocks may be distinguished with great difficulty even when first laid bare, for monadnocks may

have been cliffed by wave action (Noble, 1914, p. 62), and fault-line scarps with a very similar form may be present on one or more sides of a small block. Moreover, salients of both kinds may be dissected by insequent ravines, and thus soon lose their initial form.

In New Zealand remnants of cover are common as salients projecting above stripped plateaus. In northern Nelson these are generally limestone mesas; in eastern Central Otago volcanic rocks cap many small buttes and protect large areas. On the more level plateaus are small salients of indurated quartz conglomerate. The writer has not recognized with certainty any monadnocks.

Mature Dissection of the Undermass.—Stripped plateau surfaces traversed by ravines of moderate depth will persist for a long period if the surface slope is rightly adjusted to the volumes and grade of the streams. In a region of small rainfall an initial slope of a block surface as high as 10° may have small consequent streams and a large number of subequal, graded, shallow ravines occupied by intermittent streams. Though these break up the stripped surface to some extent, unless the stream spacing is very close, the plateau remnants will be relatively stable.

Grading of the ravine sides by soil creep will cause the sharp shoulders bounding the plateau remnants to disappear and the interfluvial areas to be reduced. But still their summits will be accordant with one another and suggest the reconstruction of the tangent surface of the undermass. Such conditions exist in the stripped plateaus of South Canterbury and Otago (see figs. 3 and 4). Later, a surface tends to waste away very slowly unless destroyed by erosion working back from initially steep portions of the same block.

Under other conditions plateau remnants are relatively short-lived. If, owing to abundant rainfall, to steepness of initial slope, or to initial irregularities of surface which have resulted in concentration of consequent drainage along a few channels, the graded profile for such streams lies far below the stripped plateau surface, the plateau remnants will be cut up by consequent, insequent, and perhaps subsequent ravines. An early and complete dissection of the surface over the whole block will result, and the block will become an asymmetrical mountain ridge with strong relief throughout (see fig. 5).

Block surfaces in this stage of dissection are common in northern Nelson, examples being the surfaces sloping easterly from the Pikikiruna Mountains to Tasman Bay. Of the same kind are the northwestern slopes of the Kaikoura and Seaward Kaikoura Mountains, in Marlborough.

A special case of large stream volume leading to deep dissection of a plateau surface is that in which the descent from

the highest portion of a block to a neighboring trough takes place by a fault or flexure followed by a sloping surface (see fig. 6). Streams of large volume from the higher block will destroy the lower, gently sloping surface with its deep ravines. Such is the dissection of the northwestwardly sloping surface which descends to the Aorere fault-angle depression in north-west Nelson (Cotton, 1916, pp. 66-68).

FIG. 5.

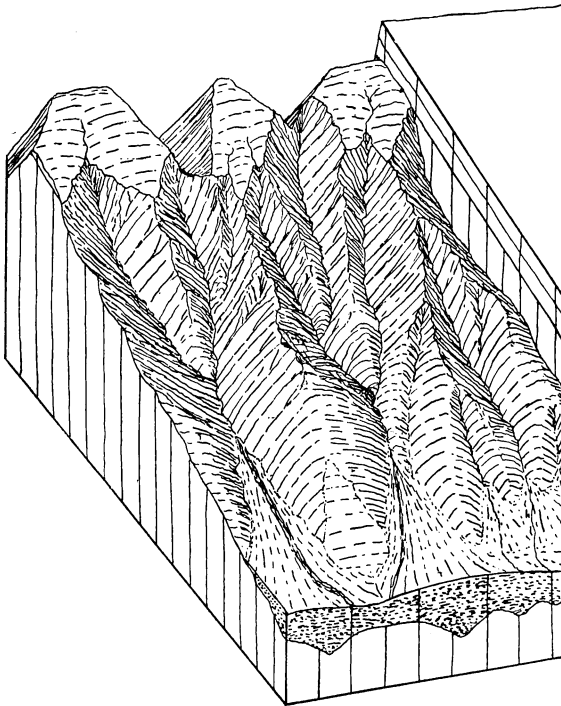


FIG. 5. Dissection of the steeply inclined back slope of a faulted block by consequent and insequent ravines. The initial form is shown on the right.

Fault Scarps and Fold Scarps.—Except for the possible case of antecedent drainage crossing an uplifted block in a direction opposite to that of the general slope of the tilted surface and emerging from gorges on the steeper side of the block, the dissection of the steeper sides of asymmetrical blocks with the structure postulated will be effected entirely by consequent streams. When they have steep fronts the blocks are bounded

by faults or steep monoclinal flexures; when the crest line is some distance back, the descent is formed either by a fold surface alone or by a fold surface broken by one or more faults.

To the former class belong the fronts of simply tilted block mountains. They are dissected by consequent ravines which in the stage of early youth divide a scarp into sections and later reduce it to a linear series of triangular facets.

FIG. 6.

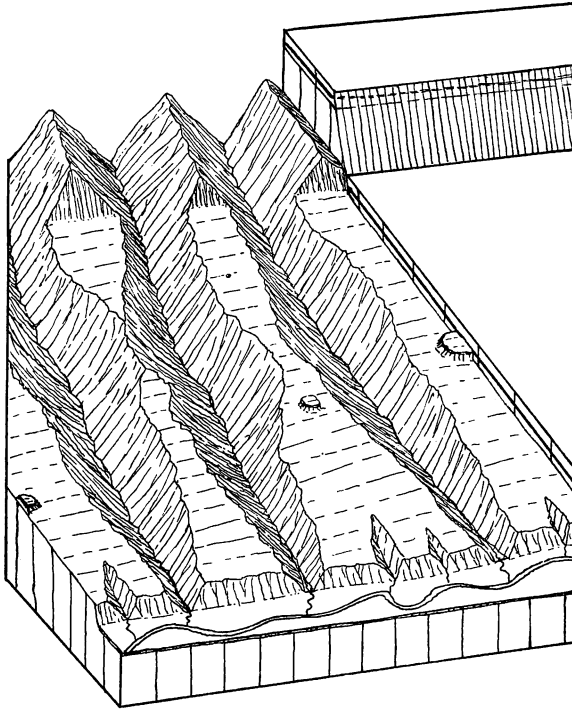


FIG. 6. Dissection of a gently sloping block surface (with a cover overlying a planed undermass) by extended consequent streams from a higher block behind it. The counterpart of this surface is formed in the Aorere fault-angle depression in northern Nelson.

Davis (1912; 1913) has distinguished fault-line scarps of generally similar form to dissected fault scarps, but originating as a result of the removal of weak rocks from one side of a fault which has brought weak and resistant rocks in contact.

Composite Fault Scarps.—In New Zealand many more or less dissected scarps occur, which agree in general form with either fault scarps or fault-line scarps, which may be in their

lower parts fault-line scarps, though where the displacement on the faults is considerable, they are true fault scarps in their upper parts.

When faulting occurs in a region where a weak cover overlies a resistant undermass, and the base of the resulting fault scarp is at a considerable height above base-level, removal of the covering strata at the base of the scarp may be going on while movement is in progress. If such removal is prevented by an abundant supply of waste spread out on the covering strata in

FIG. 7.

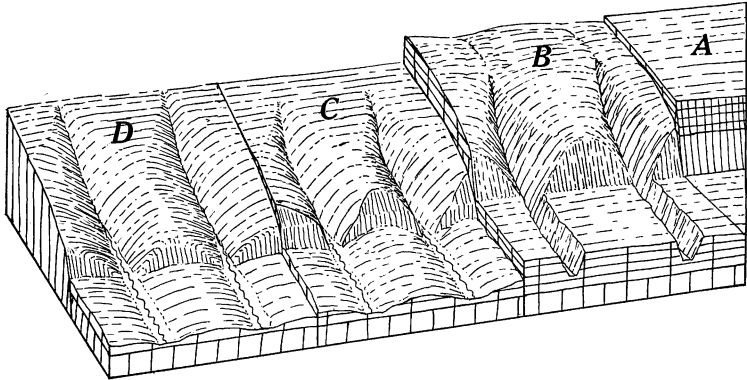


FIG. 7. Diagram of the development of a composite fault scarp, in its upper part a fault scarp and in its lower part a fault-line scarp.

the form of fans or a piedmont alluvial plain, after movement ceases degradation will soon take place. Thus a fault-line scarp will be exposed below and continuous with the already dissected fault scarp, the two constituting a single morphological feature which may be called a composite fault scarp.

During the early stages of stripping of the fault surface, the ravines by which the upper portion of the composite fault scarp is already dissected may have cut nearly to or perhaps below the surface of the undermass on the down-throw side of the fault. If so, these ravines will divide the fault-line portion of the scarp before it is exposed into sections that will be downward prolongations of the facets of the upper scarp. In some cases these lower fault-line portions of facets may be recognized by their steepness (see fig. 7 C); but the facets will soon dwindle and remnants of the fault-line portion only be left (see fig 7 D).

Where there is a continuous covering of vegetation, soil creep plays an important part in producing convexly rounded

surfaces, as has been pointed out by Davis (1892; 1912) and by Gilbert (1909). In small facets of fault scarps blunting of the edges destroys the flatness of the whole facet, though the dissection of the scarp by ravines may be incomplete. This rounding of facets is particularly well illustrated by a low scarp at Waimate, South Canterbury (see fig. 8), which was first diagnosed as a fault or fault-line scarp by Thomson (1914). Sharp-edged facets seem to occur only in the case of scarps resulting from movements that have been renewed in very recent times.

FIG. 8.

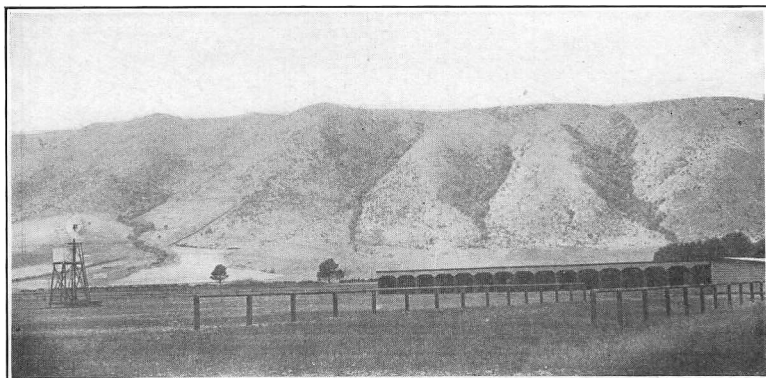


FIG. 8. An eastward-facing composite fault scarp near the southern end of the Hunter's Hills block in South Canterbury.

If the crest line—the divide between consequent drainage of the back slope and of the block front—is some distance back from the base-line, the initial descent from an arched crest to the top of a fault scarp may be gentle. Consequent streams will arise on the upper slope, and the ravines will cut deeply and rapidly into the upper slope and after removing the cover dissect the undermass. Thus, in a comparatively short time, the mountain front will be maturely dissected by steep-graded ravines which will continue to work headward and push the crest line divide down the back slope of the block. On the steep mountain-face spurs will descend between these ravines to end in a line of rapidly dwindling facets at the fault trace, and the stage of maturity will rapidly be attained. The front of the Kakanui-Horse Range facing the Shag Valley in eastern Otago appears to be a scarp of this kind (see fig. 9), also the southeastern front of the Kaikoura Mountains (Cotton, 1913).

Fold Scarps.—Simple fold surfaces and fold surfaces broken by a succession of small faults will give rise to forms very similar to those just described except in their earliest stages. Removal of a weak cover from a fold surface will be rapid and result in the exposure of some portions of the sloping floor beneath; but the graded profile of the streams may be so steep that deep cutting is not favored. Further increase in the depth of ravines will then take place only as a sequel to head-

FIG. 9.

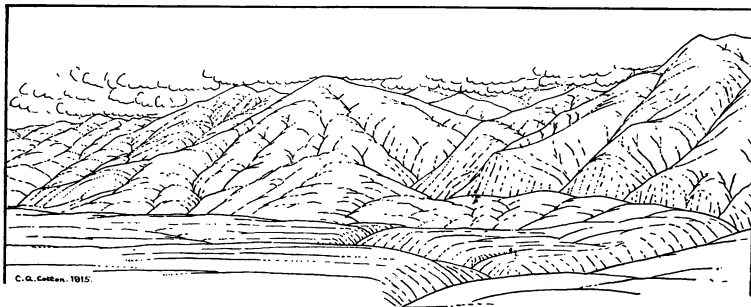


FIG. 9. Maturely dissected scarp of the Kakanui-Horse Range descending southwestward to the Shag Valley fault angle in north Otago. The stripped plateau descending in the opposite direction to meet the fault scarp is seen in the foreground, and, to the right of the center of the foreground, the gorge of the Shag River superposed on the undermass.

ward erosion, which may be so slow that flat areas will persist for a comparatively long period, though they may be steep compared with the stripped plateaus of the back slopes. With steeper initial fold surfaces, consequent graded streams may be so deeply incised as to maturely dissect the surface of the oldmass, except, perhaps, for a few facet-shaped remnants. The resulting form is indistinguishable from a maturely dissected fault scarp. Vigorous streams may be expected to push back the crest line divide, which will recede in the stage of maturity down the back slope of the block. A good example of a submaturely dissected fold scarp is the eastern face of the northern end of the Blackstone Hill block (see fig. 10). Of the same nature are the side slopes of a broad saddle of catenary form separating the stripped plateau of the Goulund Downs from the depression of the lower Aorere Valley in northern Nelson (Cotton, 1916 *b*) and probably many other scarps in the same region.

5. *Trough-filling.*

An enormous amount of waste results from the stripping of back slopes and dissection of faulted and folded fronts. Exceptionally, such waste may be all removed as it is supplied but in most places deep aggradation of troughs will take place progressively with deformation and with the degradation and dissection of the higher blocks.

FIG. 10.

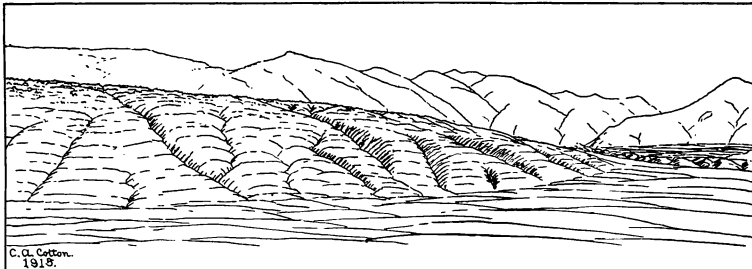


FIG. 10. Submaturely dissected fold surface towards the northern end of the Raggedy-Blackstone block in Central Otago. View looking northward.

Where initial depressions are open towards the sea and portions of low-lying blocks are submerged, or where an area unaffected by movement borders a region of uplifted blocks, the new deposits will overlie the sediments of the predeformational period without stratigraphical break but with abrupt change in the nature of the detritus. Conglomerate may overlie mudstone and pass upward into fanglomerate, as in Marlborough (Cotton, 1914). The passage of fine-grained sediments upward to conglomerate in the upper Tertiary rocks of many parts of the South Island of New Zealand is another example. In marginal areas of shallow water, however, the predeformational cover will be eroded by wave action, while unsubmerged areas will be eroded by subaërial agencies, so that when fans and deltas of waste from neighboring high blocks are built forward these will generally rest unconformably upon a denuded surface.

When the phase of maximum aggradation is reached, intermont basins will be occupied by alluvial plains through which the eroded summits of small, isolated blocks may project. At this stage, portions of the divides between basins may be buried, the waste spilling over from one basin to another in the manner described by Davis in his discussion of the arid cycle

(1905 *b*) and well illustrated in some aggraded depressions in California described by Lawson (1906, p. 455). When such spilling over occurs, the main stream draining a basin may take a spill-over course, become fixed in it during a period of degradation succeeding one of aggradation, and abandon its former outlet.

Upon the surface of the alluvium filling an intermont basin the aggrading streams will flow in braided, ever-changing channels. In the case of a trough opening to the sea the waste will form a delta or a piedmont alluvial plain. Similar forms will also result along initial fault coasts facing the open ocean.

During degradation the filling from some troughs may be removed and the underlying rock exposed. One of the largest intermont basins in New Zealand, the Upper Taieri and Maniototo plain in Central Otago, has reached the stage of dissection at which little alluvial filling remains, and there is little evidence to show whether it has ever experienced extensive aggradation. The planed surface of the covering strata of the low-lying blocks forming the floor of the basin is covered generally by a layer of flood-plain gravel. The planed surfaces form several terraces whose slope indicates that they were formed during intermittent regional uplifts by the same small streams which have since dissected them. In places, portions of the undermass project above the lowland surface. A similar stage of reduction has been reached by most of the Otago intermont basins.

In North Canterbury the large Waiau-Hurunui basin, which Speight describes as having "an origin in deformational movements either of folding or faulting" (1915, p. 348), is floored almost entirely by alluvium. A few "islands" of eroded covering strata project above the basin plain. The alluvial filling has been trenched to some extent as a result of late movements of uplift, but this affords no evidence that the period of maximum waste supply from the mountains to the northwest has been passed. The transverse course of the Waiau and Hurunui rivers across this basin and the adjacent uplifted block indicates an antecedent course (Cotton, 1913). These streams are possibly antecessors, for the Hurunui outlet is situated at a sag in the crest of the range. The basin of the Hammer Plain in North Canterbury, which is enclosed by high blocks, is completely floored with alluvium, and the covering strata that probably exist are completely buried.

With long-continued stillstand, piedmont alluvial plains, like basin plains, must be subject to dissection after the upland blocks have been reduced by erosion. The writer can not point with certainty to any example of it in New Zealand. The dissection of the Canterbury Plains by the Waimakariri, Rakaia,

and other rivers is perhaps an example (Speight, 1908).* It is equally probable that this dissection has been the result of a disturbance of the nicely balanced proportion of water to waste brought about by some climatic change.

Dissection may be caused at a much earlier stage of the cycle by coastal retrogradation or by regional uplift. A good example of deep dissection of piedmont plains occurs in an aggraded tectonic depression which extends inland in a southwesterly direction along the base of the Seaward Kaikoura Range and is followed by the coach road from Kaikoura to Waiau. It has been described by Park (1911) as the Waiau "Glacial" Valley. The streams which supplied the alluvium forming the floor of the depression descend from the mountain range, some of them uniting and reaching the sea as the Kahautara River, which leaves the depression at its northeastern end, and others uniting and flowing inland to join the Conway River. Owing to recent uplift the streams are now all deeply entrenched below the aggraded surface which is being rapidly destroyed by the headward erosion of insequent ravines.

PART II. THE BLOCK MOUNTAINS OF CENTRAL OTAGO.

1. *Historical Sketch.*

The origin of the relief of Central Otago has been studied by various writers, and various theories of origin have resulted. Hector (1862, 1869, 1881, 1890) considered the structural features as the result of normal erosion affected by later regional earth movements. One of Hector's publications (1870) includes an indefinite statement assigning a tectonic origin to the major topographic features. Beal (1871) ascribed the smooth ridges and hillsides to the work of ice and the depressions to stream erosion. Hutton (1875) also believed that the rock-bound depressions of Central Otago, "old lake basins," had been excavated by ice. McKay (1884, 1884 *b*) recognized the orogenic movements to which the present relief is due and formulated a hypothesis which agrees in some essentials with the views presented in this paper. In 1897 McKay recognized a number of great faults in this region, and called attention to the importance of these movements in determining relief. He apparently did not recognize the evidence of tectonic origin in the forms of the mountains and described the depressions as "lake basins" and the higher fluviatile gravels as "lake terraces."

Park in 1890 and Gordon in 1893 noted the high inclination of some of the beds of the covering strata and appear to have

* In a recent publication, Speight (1911) ascribes the building of the Canterbury Plains to a postglacial pluvial period and the deep incision of the rivers below the plains surface to a later period of dry climate.

been convinced that it was evidence of deformation. Gordon mentioned an interstratified leaf bed at St. Bathans "at about the same inclination as the face of the schist rock against which the quartz drift is lying" (p. 119), and appears, however, to have regarded the covering strata as local fluvial deposits, and the predeformational relief as strong.

Park in 1906, 1908, and 1910 described the ranges as block mountains and recognized that the initial forms roughed out by the deforming movements still determine the general forms of many of the mountains of Otago. He pointed out that the upland surfaces in Central and eastern Otago are portions of a dislocated plain of erosion which he termed a peneplain. This plateau had been recognized by Andrews (1905, p. 192), and mentioned also by Marshall (?1905, p. 103), both of whom regarded it as a peneplain; but neither of these authors appears to have understood the manner in which the surface had been dislocated, both regarding the relief of Central Otago as the work of erosion. With regard to the origin and filling of the so-called lake basins, Park favored an explanation involving contemporaneous deformation along lines of fault. He regarded the whole of the cover that had been affected by the deformation as lacustrine and, therefore, younger than the initiation of deformation.

Though Park (1910) has described the South Island as covered by an ice sheet in the Pleistocene glacial period, he has not specifically appealed to glacial sculpture to account for the erosional features of the Otago block mountains, merely crediting the excavation of the Dunstan gorge to the work of ice (1906), and describing some morainic accumulations in the adjacent portion of the Manuherikia depression. The Dunstan gorge was also described as guided by a fault line (1908).

The writer's hypothesis involves planation, sedimentation, and deformation followed by a period of erosion, during which large areas of the planed undermass have been reëxposed by stripping of the cover.

2. *Structure.*

For a great part of its length, the Otago-Central Railway follows a chain of broad tectonic depressions and to these the road system of Central Otago is also mainly confined. It is in connection with this chain of depressions that the salient "block" features occur that present the closest analogy with the block mountains described in other parts of the world (see figs. 11 and 13).

Throughout a great part of the area the undermass consists of metamorphic rocks irregularly but not generally closely folded, and moderately though not highly resistant. To the

northeast, folded, unaltered or but little altered, and more resistant sedimentary rocks form the undermass. The transition from typical greywacke to typical schist is in some places quite sharp. Such junctions in Otago are, perhaps without exception, fault junctions. Along the boundary between the main schist area and the main greywacke area the two types of undermass may be distinguished at a distance of several miles by the details of the relief forms developed on them, and the

FIG. 11.

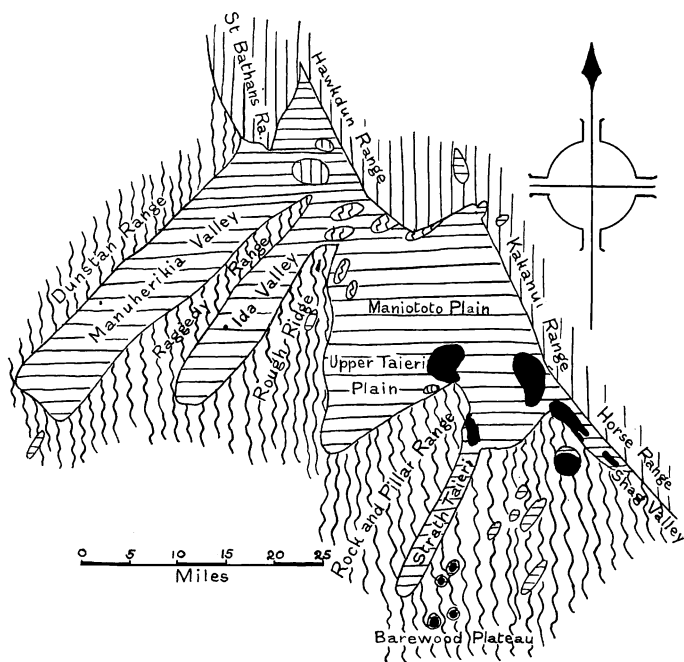


FIG. 11. Geologic sketch map of the block mountains associated with Central Otago chain of depressions. (Boundaries after McKay, with slight modifications.) The areas in which schist undermass rocks reach the surface are marked by waved north-south lines, the areas of greywacke (unaltered or little altered) by straight north-south lines, and those in which the overmass forms the surface, or is thinly covered by alluvium, by straight east-west lines. Volcanic rocks of the overmass are shown in black.

presence is thus indicated of a mosaic of blocks separated by a system or systems of relatively ancient faults to which the present relief is largely or wholly indifferent. Some of the blocks of the mosaic are too small to be shown on the small-scale maps hitherto published.

The relief due to movements on these ancient fault lines (together with that resulting from earlier folding) probably

had been almost or wholly destroyed prior to the deposition of the overmass or cover. Though the later faulting to which the existing relief is largely due appears to have followed the lines of the older faults in some places, the displacement has generally been reversed.

Upon a planed surface of the undermass rests an overmass of covering strata, which are preserved in the tectonic depressions, but are almost entirely removed from the uplands and highlands. Over a great part of the area the overmass consists of beds of fine quartz, sand, clay, brown coal, and greywacke gravel. These are generally weak and incoherent with the exception of an indurated layer—in places possibly more than one layer—several feet in thickness of quartz grit with a siliceous cement. Basalt, relatively a very resistant rock, occurs towards the east interbedded with the covering strata over a considerable area.

The overmass of Central Otago could not have been continuous unless an emergent land-mass outside this area furnished the detritus. To the northeast, east, south, and west of Central Otago, however, are remnants of a sheet of marine-covering strata, and to the north the undermass is composed almost entirely of greywacke. The lower beds of the cover throughout Otago are accumulations of detritus resulting from denudation of schist similar to that on which they rest. It is quite probable, therefore, that some portion of the eroded surface of the undermass has never been covered and so is a true peneplain (possibly with monadnocks). But the overmass was much more extensive than now. It is significant that this conclusion, at which the writer arrived independently from a study of the geomorphology, had been reached much earlier from a study of the beds themselves by McKay, and clearly stated in his later writings.

McKay writes of the so-called quartz drifts (a term applied in New Zealand to superficial and bedded auriferous deposits of fine conglomerates or grits—not glacial deposits) as follows:

“These accumulations are so disposed that they are in a large measure—what remains of them—protected from being destroyed by ordinary denuding agents, being either overlain by younger deposits or involved between older and younger strata, so that the same result is effected. That their area in past times was much greater than at present there is abundant evidence in the disjointed scattered patches that are preserved and in the great abundance of cement stones [“sarsen stones” of cemented quartz grit] over surfaces considerably distant from any deposit of loose quartz drift, and the quantities also of this particular kind of rock in the newer drifts and recent gravel deposits in interior Otago.” (1897, pp. 88-89.)

To the writer's mind conclusive evidence as to the former wide extension of an overmass is afforded by the occasional preservation of small outliers of the cover on the upland plateaus; by the wide distribution of the "sarsen stones" (fig. 12) derived from the cemented quartz grit; and by the manner in which planed surfaces of the older rocks emerge from under beveled clay and brown coal strata, as well as quartz grits, with the same inclination.

FIG. 12.

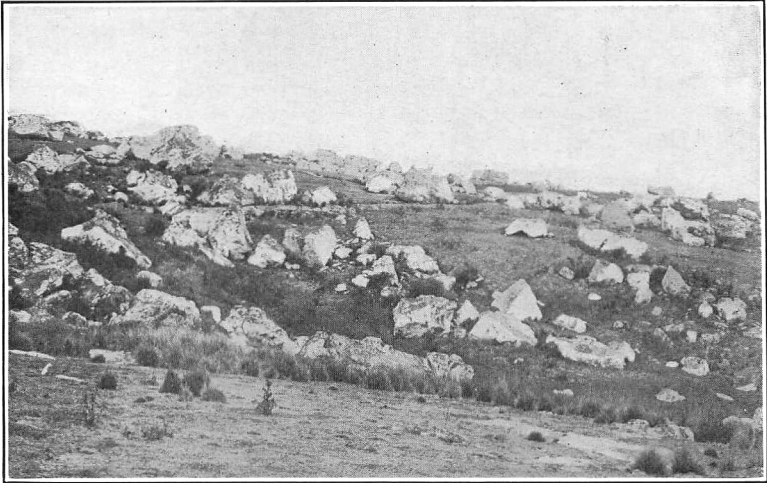


FIG. 12. "Sarsen stones" on the back slopes of the Rough Ridge block.

3. *Major Tectonic Features.*

As in most parts of New Zealand, the larger features in Otago with the exception of the volcanic massif of the Dunedin district are undoubtedly of tectonic origin. The positive forms fall under the head of block mountains of simple or moderately complex types, and in the Central and northeastern district more than one of the types of block structure recognized by Gilbert (1874) in the ranges of the Great Basin are distinguishable. These initial forms have been also sculptured in detail by erosion.

The area is characterized by uplifts of relatively simple types—uplifted masses either tilted or bounded on both sides by faults forming a set of elongated blocks with a definite southwest and northeast orientation and enclosing elongated depres-

sions. Blocks bounded on all sides by faults have not been recognized; most of the boundary faults diminish in displacement and are evidently replaced by flexures (fig. 13).

Towards the southwest, owing to diminishing displacement on the faults and flexures bounding them, the depressions are no longer distinguishable. With the mountain blocks they merge into a high, broken plateau, in which detailed investiga-

FIG. 13.

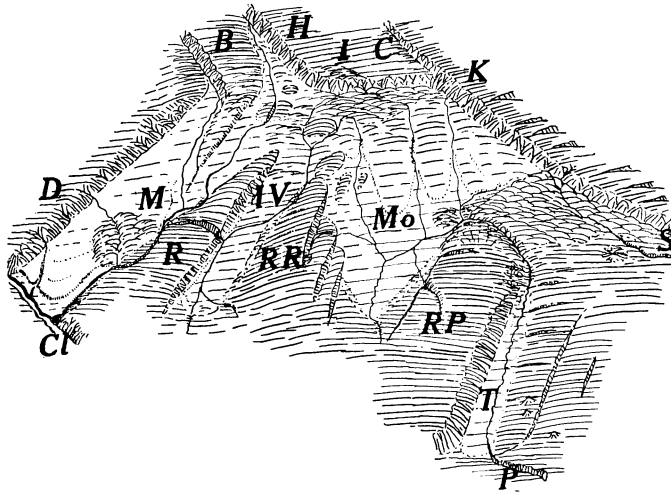


FIG. 13. Generalized diagram of the Central Otago chain of depressions and the associated block mountains. D, Dunstan block; M, Maniototo depression; R, Raggedy-Blackstone block; IV, Ida Valley depression; RR, Rough Ridge block; Mo, Maniototo depression; HP, Rock and Pillar block; T, Strath Taieri depression and Taieri River; P, Barewood Plateau; B, St. Bathans block; H, Hawkdun block; I, Mount Ida; C, Clark's Diggings fault angle; K, Kakanui block; S, Shag Valley fault angle; Cl, Clutha River.

tion doubtless will reveal the presence of a number of distinct blocks.

Towards the northeast, on the other hand, the crests of the mountain blocks slope down so as to merge more or less completely in the lowlands and form a chain of nearly continuous depressions, which is a fault angle between the northeasterly slope of the southern block-complex and a great scarp with a general northwesterly trend, or a series of scarps broken by several offsets, which forms the boundary of a northern complex of high blocks.

In the latter fault-block complex, which may be termed the northern highland of Otago, the general trend of the disloca-

tions is northwesterly; but still farther to the northeast the first-mentioned system again makes its appearance with perhaps a more northerly trend. The northeasterly trending system of late uplifts due to dislocations and folds is widespread in New Zealand, while the northwesterly system seems practically confined to Otago, making its appearance again to the southwest of the schist area of Central Otago.* The dislocations of the two systems do not, as a rule, occur together so as to define a regular rectilinear mosaic, but the blocks within the area traversed by the dislocations of each system are elongated like anticlinal and synclinal folds.

It is noticeable that while the block boundaries along the great northwest and southeast scarp that forms the boundary between the depressions and the northern highland coincide more or less exactly with the lines of junction of greywacke and schist areas of the undermass, the metamorphics, which presumably were originally the more deep-seated rocks, occupy the downthrown side. That is to say, the dislocations have followed the lines of more ancient faults of even greater throw, but have displaced the crustal blocks in the reverse direction.

The Central Otago System.—Confining our attention to the blocks somewhat directly connected with the Central Otago chain of depressions, we find that the most westerly of these—the Manuherikia depression—is bounded on the northwest by a highland block, the Dunstan Mountains, with an average height on the crest of 5,000 feet, or 4,000 feet above the floor of the Manuherikia depression. The even crest of the block indicates that its upper surface is flat, and any cover that formerly lay on the planed surface of the undermass has been stripped from it. The southeastward slope from the crest to the depression is a fault scarp, probably not of the simplest type.

The floor of the Manuherikia depression (fig. 14) has an average height of about 1,000 feet above sea-level. It is about 40 miles long and 8 miles wide. It contains a great thickness of the overmass, the beds of which are cut into terraces and dissected into residual hills, a relief that reaches a height of about 600 feet. The overmass is much obscured by a veneer of postdeformational alluvium.

The depression is bounded on the southeastern side by a narrow, elongated upland block 3 or 4 miles wide, which a transverse stream divides into two portions. The southwestern portion is called the Raggedy Range and the northeastern, Blackstone Hill. The whole may be termed the Raggedy-Blackstone block. Its somewhat undulating crest line is generally about 2,000 feet above sea-level, but rises to 3,200 feet in

* In a recent paper. Speight (1916) ascribes the courses of some of the rivers of Canterbury to dislocations with a northwesterly trend.

Blackstone Hill. The back slope has an inclination of about 10° towards the northwest, where the stripped surface of the undermass passes under the covering strata of the Manuherikia depression. The southeastern face, or front, of the block is a fault scarp (fig. 15) against which are upturned the covering strata in the next depression.

This depression, known as Ida Valley, is traversed by the Ida Burn and Pool Burn. The mean height of its floor above

FIG. 14.



FIG. 14. View looking westward across the Manuherikia depression from the back slope of the Raggedy-Blackstone block. The southern end of the Dunstan block is seen in the distance and the valley of the Manuherikia River in the foreground.

the sea is about 1,500 feet. It is about 25 miles long and 3 or 4 miles wide and has the same northeast and southwest trend as the associated blocks. It is floored largely by postdeformational alluvium, but the covering strata appear at a few points along the margins. At the southwestern end the stripped floor appears and rises to merge with the upland plateau.

To the east another upland block forms Rough Ridge. Its crest is very even for many miles with a height of about 3,200 feet above the sea. On its northwestern and northeastern sides this block is similar to the Raggedy-Blackstone block.

Farther south, however, it is complex and relatively wide, two broad splinters descending towards the northeast and forming offsets on the lowland level between the northeast-trending fault-scarp portions of the boundary line between the Rough Ridge block and the next depression to the east.

This depression, about 250 square miles in area, includes the Upper Taieri plain and the Maniototo plain—the whole being termed here the Maniototo depression. The lowest part of its floor is about 1,000 feet above the sea; the mean height of the Upper Taieri plain is about 1,200 feet and of the Mani-

FIG. 15.

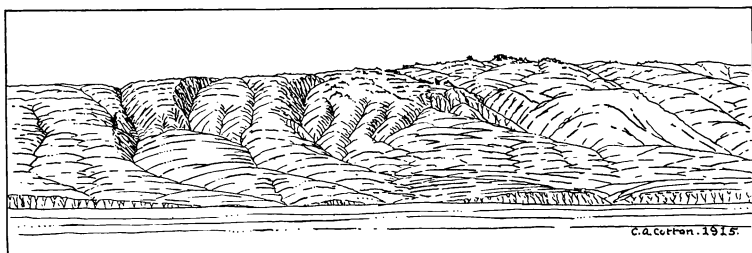


FIG. 15. The scarp or front face of the Raggedy-Blackstone block (Blackstone Hill portion).

ototo plain about 1,500 feet. Considerable portions of the surface are covered by a layer of postdeformational alluvium, but at many points the beds of the overmass appear, among which on the eastern side are sheets of basalt. At the northwestern side low islands of the undermass emerge through the cover, the largest being almost continuous with the first splinter from the Rough Ridge block. To the south, as in the neighboring Ida Valley depression, the stripped surface of the undermass emerges, and the line of division between the depression and the southern highland plateau is not simple.

A high block southeast of the Maniototo depression forms the Rock and Pillar Range, about 8 miles broad. Its western boundary is in part a fault scarp replaced towards the north by a steeply dipping "fold-surface," which passes under a sheet of cover preserved by basalt. The top of the range, presumably a stripped plateau, is gently inclined towards the northwest. The whole drainage of the highland surface is led away in that direction, and profound gorges are cut in the western scarp. In the highest portion of this block, the southeastern edge is about 4,500 feet above the sea, more than 3,000 feet above the floor of the depression on the western side and nearly 4,000 feet on the eastern side. At its north-

eastern end the block surface passes beneath the cover. A small portion, like the neighboring cover, is here maturely dissected.

On the southeastern side a very regular and apparently simple fault scarp about 20 miles in length, with an average height of 3,700 feet, descends from the even crest to a long, narrow fault-angle depression named the Strath Taieri, followed longitudinally by the Taieri River. Its planed floor, beneath which is preserved a narrow strip of the overmass,

FIG. 16.

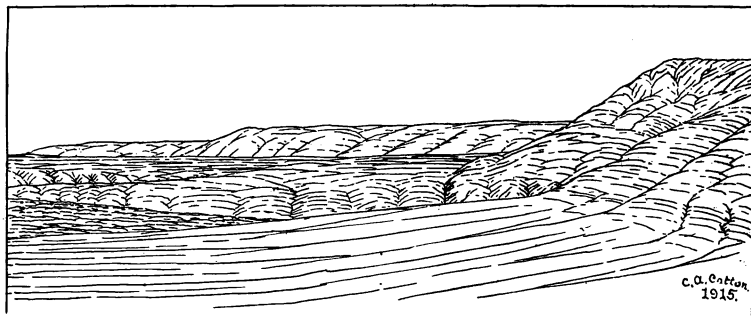


FIG. 16. View looking west across the Barewood Plateau. The Rock and Pillar Range is on the right, and the Lammermoor and Lammerlaw Ranges are seen in the distance, their fronts being the scarp of a high plateau.

descends from about 1,000 feet above the sea at the northern end to about 600 feet at the southern end.

On the southeastern side of the Strath Taieri depression the surface of the stripped undermass rises very gently to a plateau (fig. 16) varying in height from about 1,000 feet to 2,000 feet above sea-level. The plateau is traversed by a number of low, southeastward-facing fault scarps (fig. 17). In the fault angles some strips of cover are preserved and there are also lava-capped remnants on the uplands. This area with that to the southwest has been called by Park the Barewood Plateau. Its southwestern continuation is bounded on the western side by the fault-scarp margin of a higher plateau area practically continuous with the top of the Rock and Pillar block, though at a slightly lower level. This is the same broken plateau into which merge all the upland and lowland blocks enumerated. The conspicuous 2,000-foot fault scarps along the boundary between the higher plateau and Barewood plateau have caused portions to be known as the Lammermoor and Lammerlaw ranges.

The Manuherikia, Ida Valley, and Maniototo depressions are practically continuous towards the north, being separated only by gently upwarped areas in which the undermass rises sufficiently high to be stripped of its cover. The Maniototo depression is separated from the Strath Taieri, however, by a considerable area in which the covering strata, now maturely dissected, have survived as uplands owing to the presence of basalt.

The Northern Highland of Otago.—The northern boundary of the chain of depressions described above is formed by a

FIG. 17.

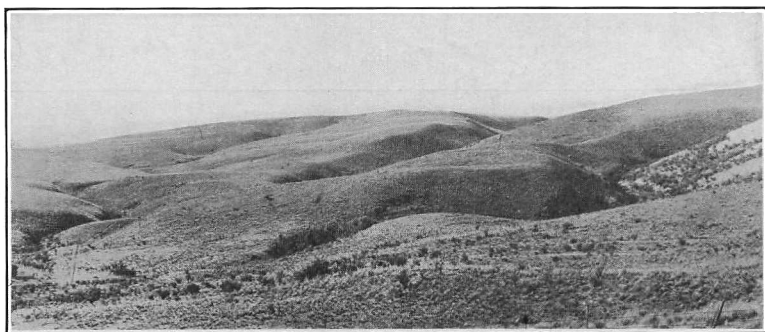


FIG. 17. Bird's-eye view of the slightly dissected stripped surface of a gently tilted, narrow fault block descending northwestward (toward the camera) and meeting a low fault scarp, the crest of which is seen in the foreground. Note that the dissection is entirely consequent and insequent. The point of view is a small lava-capped butte of rounded form, a remnant of a former more continuous cover.

series of scarps with a predominant northwesterly trend. Beginning at the western side, the northeastern end of the Dunstan block is a narrow, northwest-trending fault-angle depression occupied by Dunstan Creek separating the Dunstan block from the St. Bathans Range. The St. Bathans block merges at its southeastern end into the Manuherikia depression. It is elongated in a northwesterly direction and to the northwest merges into the highland region. It presents a fault scarp to Dunstan Creek and is strongly tilted to the northeast, the back slope descending in that direction to a fault-angle depression forming a northern prolongation of the Manuherikia depression, which is bounded on the opposite side by a long, straight, and conspicuous fault scarp, that of the

Hawkdun Range (fig. 18). This scarp forms the northern boundary of the Ida depression also.

The straight front and remarkably even crest of the Hawkdun block have been noted by McKay (1897) and by Park (1906). Professor Park informs the writer that the surface of the summit plateau is strikingly flat and horizontal.

The Hawkdun plateau descends southward from an average altitude of 6,000 feet to something over 5,000 feet in a distance of about 12 miles. At its southern end is the dissected dome of Mount Ida, rising 300 or 400 feet above the plateau (fig. 19). It is perhaps a monadnock as suggested by Park (1906, p. 6).

The boundary between the depressions and the northern highland area swings around Mount Ida and extends due east

FIG. 18.

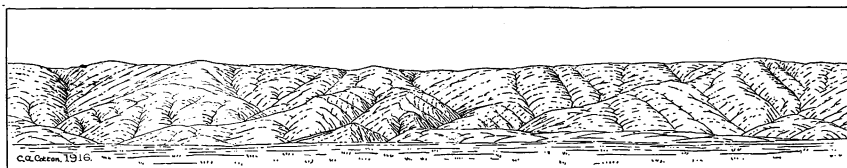


FIG. 18. Maturely dissected fault scarp of the Kakanui block. View looking north across the eastern margin of the Maniototo depression.

for 10 miles, forming a great reëntrant occupied by a portion of the Maniototo depression, though part of the relatively low-lying area along the base of the scarp is occupied by a number of low-lying, subsidiary blocks, now forming uplands of moderate height in which the undermass is exposed.

The surface of the Hawkdun block slopes gently eastward from the Hawkdun scarp and Mount Ida down to a fault angle over 4,000 feet above sea-level, bounded by the fault scarp of the Kurow and Kakanui Mountains, which faces west-south-west and rises about 2,000 feet higher. Remnants of the overmass are preserved in this fault angle on the highland surface at the locality known as the Mount Buster or Clark's Diggings (McKay, 1884, *c*).

The Kakanui fault scarp continues south-southeastward (fig. 20) and forms for 15 miles the eastern boundary of the Maniototo depression, having in this portion an average height of 5,000 feet above the sea. The great reëntrant in the highland rim occupied by a portion of the Maniototo depression is thus completed and the general southeasterly trend of the great scarp is restored. The scarp continues southeasterly to the sea,

a distance of nearly 30 miles. From the crest line of this portion of the Kakanui fault scarp, the back slope of a great tilted block descends gently to the northeast as a somewhat undulating, stripped plateau surface and dips beneath marine strata near the coast. A branch of the Maniototo depression extends towards the coast as a fault angle along the base of the Kakanui fault scarp, forming Shag Valley. Its southwestern side is a gently sloping and slightly undulating stripped

FIG. 19.

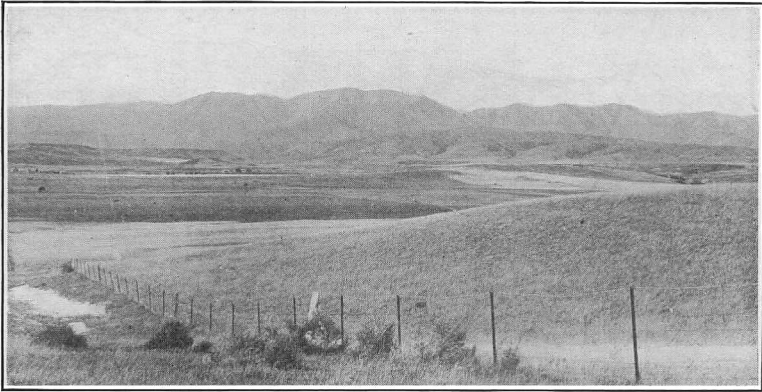


FIG. 19. The scarp of the northern highland with Mount Ida in the center, as seen from subdued hills of covering beds in the Maniototo depression, just east of the northern end of Rough Ridge.

plain descending from the Barewood Plateau. In the fault angle some remnants of marine covering strata are preserved.

4. *Drainage.*

The Central Otago Chain of Depressions.—The main lines of drainage in the chain of depressions of Central Otago appear to be entirely consequent on the deformation; but this statement does not exclude the possible occurrence of “anteconsequent” streams. The existence of true antecedent streams is not very probable.

The Manuherikia depression is traversed longitudinally by the Manuherikia River, flowing southwestward to join the Clutha (or Molyneux) River. The head of the Manuherikia occupies the fault angle at the base of the Hawkdun fault scarp, and its largest tributary, the Dunstan Creek, coming in

from the northwest emerges from the fault angle between the Dunstan and St. Bathans blocks. These streams are fed by a large number of small tributaries which with the exception of the Pool Burn are consequent on the slopes of the neighboring block mountains.

The Pool Burn, which enters the Manuherikia depression from the southeast, cuts transversely across the narrow Raggedy-Blackstone block in a deep gorge. This transverse course

FIG. 20.

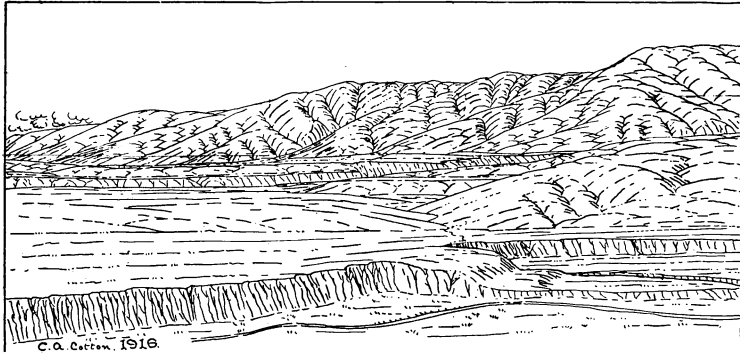


FIG. 20. Maturely dissected fault scarp of the Kakanui block. View looking north across the eastern margin of the Maniototo depression.

has been described by Park as a capture (1906, p. 13), but none of the features generally associated with recently effected captures are to be seen in the valley system. Neither of the longitudinal streams of the Ida depression—the Pool Burn and the Ida Burn—which unite to flow through the gorge, can have been reversed by capture unless the capture took place before the excavation of the covering strata.

Park says, "The Ida Valley basin, as shown by the river terraces and surface contours, at one time drained into the Maniototo Basin." He describes the Ida Burn for a distance of over 12 miles as a reversed stream; but in that distance it has a fall of 500 feet, and it flows the whole distance in a flat-floored valley opened to the full width of the Ida tectonic depression. Such terraces as survive descend in the same direction, giving no indication of reversal. There is, moreover, no stream nor abandoned valley of erosion that can be interpreted as the beheaded former course of the Pool Burn. Furthermore, it is difficult to explain why a tributary of the Manuherikia should breach the Raggedy block. The climate

is arid; other consequent streams on the back slope of the block are intermittent and feeble; and have not even begun to cut gorges through the range.

As the Pool Burn gorge (fig. 21) crosses the Raggedy-Blackstone block at a low sag in the crest line, there can be little doubt that it is consequent on the deformation. Whether the present transverse stream marks the point at which a consequent lake in the Ida Valley depression spilled over or whether

FIG. 21.

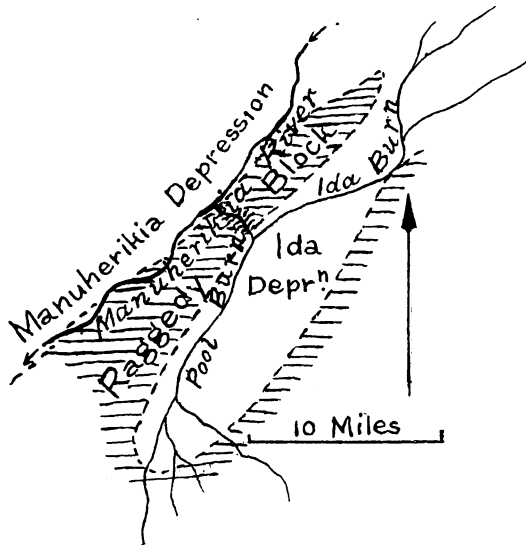


FIG. 21. The course of the Pool Burn.

the excavation of the gorge kept pace with the deformation cannot now be determined.

The centripetal consequent streams of the Ida Burn and Pool Burn systems are of insignificant size and in dry seasons practically disappear. Both the Ida Burn and the Pool Burn are fed by numerous wet-weather consequents which run down the front of the Raggedy-Blackstone block and the back slope of the Rough Ridge block; but the main volume of the Ida Burn comes from the greywacke highland to the north and of the Pool Burn from the schist plateau to the south. Their courses are thoroughly graded on the weak material of the overmass in the depression, broad valley plains have been developed, and the streams are bordering on senility. However, the gradient of the valley floor of the Ida Burn is consid-

erably steeper than that of the Pool Burn. This difference is due to the much greater load of waste which the northern stream has to transport, and which comes from the great fault scarp of the greywacke highland. The little dissected schist plateau from which the Pool Burn flows supplies a relatively small quantity of waste.

The numerous parallel, southward-flowing, consequent streams in the northern or Maniototo Plains portion of the Maniototo depression are exactly similar in their gradients and their arrangement to the streams of the northern end of the Ida Valley depression. The Ida Burn and the Wether Burn are separated by a narrow interfluvium consisting of the outcropping undermass of a northerly continuation of the Rough Ridge block. The Wether Burn and the other similar streams form the northern members of a centripetal consequent system in the Maniototo depression and are tributaries to the Taieri River.

Those streams also consequent on the deformation, which enter the depression from the schist upland plateau to the south, like the Pool Burn, flow with very gentle gradients across the wide valley plain which there forms the floor of the depression. The chief of these, the Upper Taieri, wanders freely, and oxbow lakes abound upon its flood plain. As a result of the steeper gradient of the northern streams owing to larger supply of waste, the east-and-west axis of the lowland in the Maniototo depression has been pushed far to the south.

The drainage of this depression finds an outlet by way of the Taieri River into the Strath Taieri depression, crossing the area of mature dissection around the northern end of the Rock and Pillar block in the fault angle between that block and the Kakanni fault scarp to the north. This portion of the course of the Taieri is probably consequent on the deformation, being determined either by the spilling over of a consequent lake in the Maniototo depression or cut down during slow deformation. The floor of the depression was obviously much higher in an early stage of the cycle before part of the overmass had been removed. It is unnecessary, therefore, to suppose that the present rather young gorge was cut contemporaneously with the deformation. Its cutting must, however, have gone on while the floor of the Maniototo depression was being excavated to its present depth.

The southwestwardly course of the Taieri River through the Strath Taieri depression is obviously consequent on the deformation, as also are most if not all the larger tributaries this river receives in its course across the Barewood plateau. The course of the Taieri River itself in a southeasterly direction across the plateau appears to be consequent, as it follows the lowest sag in the surface. It is graded, or almost so, with a gradient of

about 20 feet per mile, but it is still in the narrow-floored, rock-walled Taieri Gorge (fig. 22), which is incised at one place to a depth of about 1,000 feet below the plateau surface.

The Shag Valley fault angle is drained by the Shag River, which rises in the maturely dissected uplands overlooking the Maniototo Plain and follows the line of the depression in a northeasterly consequent course to the sea.

Most of the tributaries of the streams in the Central Otago depressions flowing over the rocks of the undermass might be

FIG. 22.

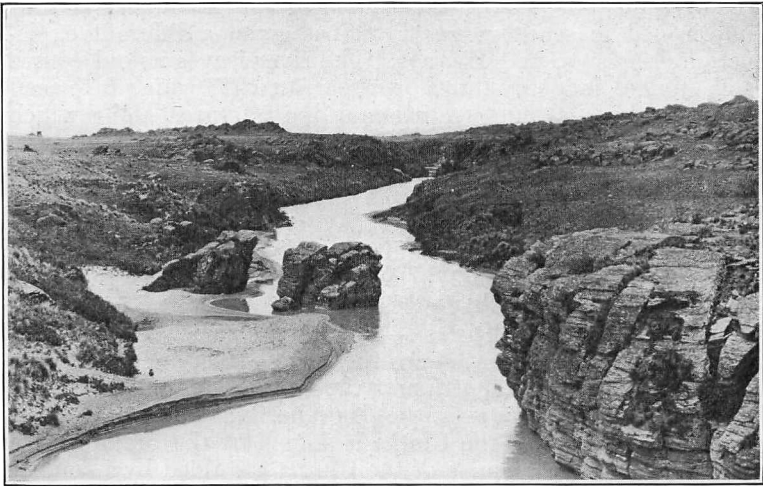


FIG. 22. View looking down the Taieri River at the upper end of the great gorge in which it traverses the Barewood Plateau.

considered superposed consequents instead of normal consequents, if it can be shown that their directions were determined by the slope of a former cover. They are indifferent to both the dip and the strike of the underlying rocks, but as they follow the slope of the surface of the undermass they may be classed as simply consequent, whether they were initially guided by the slope of the planed and tilted surface now visible or by the slope of an overmass for which that surface formed a floor.

A distinctly different kind of superposition is shown by the Manuherikia River and the Ida Burn, flowing parallel with the tilted Raggedy-Blackstone and Rough Ridge blocks, and also

by the Shag River. Portions of these streams are now superposed on the undermass of the sloping plateau as a result of shifting far over to the side of the guiding depression and failing later to slip off the gently inclined surface while cutting vigorously downward in response to rejuvenation. Each such portion is now imprisoned in a narrow rock-walled gorge, while reduction of the general level of the adjacent portions of the depressions is being carried on by minor streams. The case is closely analogous, though not strictly homologous with that of the horseshoe bend of Hoxie Creek, described by Gilbert as an exception to the general rule of monoclinical shifting (Henry Mountains, 1877, pp. 137-138).

For some portions of the course of the Manuherikia thus imprisoned in schist gorges Park has given a different explanation (1906, p. 12). He says, "The river leaves its old course and plunges suddenly into a deep, narrow rift" which is formed by "a number of intersecting faultlike fractures, along which the river runs, passing from one to the other."

Similar superposition has been described in the Clarence Valley fault-angle depression in Marlborough (Cotton, 1913, pp. 233-234). The Aorere Valley fault-angle depression in northern Nelson apparently affords another example, for which, however, Bell (1907, p. 27) has proposed a theory of capture similar to that advanced by Park for the Manuherikia.

The Clutha River System.—Beyond the area with which we are immediately concerned are the largest rivers of the region—the Waitaki to the north and the Clutha (Molyneux) to the south. The latter crosses the Manuherikia depression at its southern end, where the Clutha is joined by the Manuherikia River. The upper course of the Clutha is guided by a smaller similar chain of depressions which may be termed the Upper Clutha chain. A large tributary, the Kawarau, also receives the drainage from a number of narrow fault angles. Intermediate portions of its course may be in great part consequent on the deformation, being guided by the lower sags or fault angles in the highland plateau, considerable areas of which, as Park has shown (1908), still survive in the various flat topped ranges. The Kawarau is now the outlet for Lake Wakatipu, which formerly overflowed at its southern end by way of the air gap leading to the upper Mataura. The upper Kawarau, now deepened into a gorge throughout its length, is thus probably of recent origin and perhaps subsequent.

The combined waters of the Kawarau and the Clutha form a river of great volume and enormous energy. The portion of this stream which cut the deep Dunstan Gorge (fig. 23), leading from the tectonic depression of the Upper Clutha to the Manuherikia, seems to have been guided by a sag in the high-

land plateau between the Dunstan block and the Old Man Range to the southwest. It may, therefore, be classed provisionally as consequent. The same origin may be assigned to the gorge in which the Clutha leaves the Manuherikia depression in a southerly direction. Farther downstream the river traverses a succession of narrow tectonic depressions. The Clutha river system may, therefore, be regarded as almost entirely consequent.

The Mataura and Oreti also flow generally in broad tectonic depressions and must be classed as generally consequent.

FIG. 23.

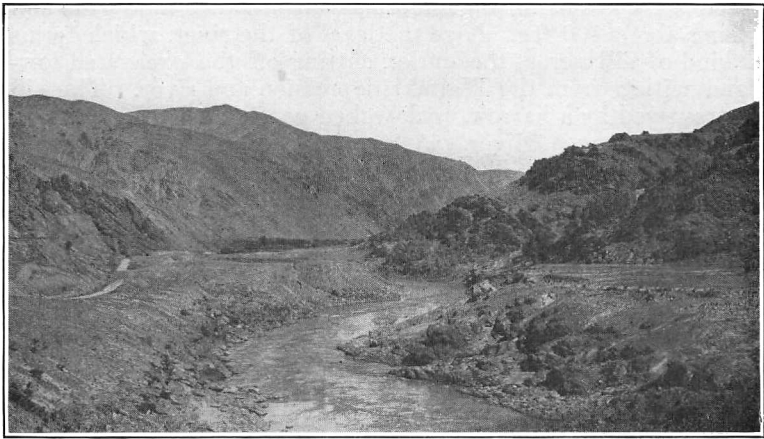


FIG. 23. View looking southeastward down the Dunstan Gorge, by way of which the Clutha River breaks into the Central Otago chain of depressions after leaving the Upper Clutha chain.

The Waitaki River System.—The great Waitaki River occupies in its upper course a broad tectonic depression, the details though not the general form of which have been modified by glacial action.* In its middle and lower course the Waitaki is guided by a linear tectonic depression irregularly bounded by the fault scarps and back slopes of a complex of blocks in the bottom of which some low-lying remnants of covering strata are preserved (Marshall, 1915).

The Waitaki River is thus probably wholly consequent on the deformation. It follows a complex graben along the north-

* Kitson and Thiele (1910) describe the Waitaki Basin as "due to pre-glacial erosion, faulting, with probably some warping, modified by glacial action" (p. 551).

ern boundary of the block-complex with predominating north-westerly trend which forms the northern highland of Otago. In the Middle Waitaki graben there are a number of small blocks in various attitudes. On the northern or Canterbury side of the graben the dislocations seem to belong to the north-easterly system, though trending somewhat irregularly, while farther north the highest blocks are elongated generally in a north-and-south direction.

One great depression, occupied by the consequent course of the Hakataramea River, a tributary of the Waitaki, is of great length and has a width on the floor of about five miles. It is bounded on the west by an imposing fault scarp of the block forming the Kirkliston Range, 6,000 feet high; but its chief peculiarity is a bar of the undermass about half a mile wide and rising about 400 feet above the level of the river, which forms a kind of sill across the outlet, cutting off the excavated lowland within from the Waitaki depression and river. The sill is traversed by a narrow, rock-walled gorge cut by the outflowing Hakataramea River. A layer of bedded fluvial gravel on the top of the sill proves that the great lowland of the Hakataramea Valley upstream from the sill has been eroded by the river during the time occupied in cutting the outlet gorge through the sill. A number of terraces in the depression mark stages in the excavation of the lowland. In the earliest postdeformational cycle, the undermass of the sill of the Hakataramea depression had probably not been revealed by erosion.

5. *The Surfaces of Uplifted Blocks.*

Stripped Plateau Surfaces.—With the exception of the lava-protected areas, the cover has been stripped from the uplifted block surfaces. The only indication of its former existence is the occurrence of “sarsen stones.” The planed surface of the undermass is thus revealed, and in a few places submaturely or maturely dissected.

The stripped plateau surface survives over large areas, even on slopes exceeding 10° . The precipitation is small and the slopes are drained by systems of numerous, intermittent, parallel consequent streams and a few unimportant insequents; but no distinctly subsequent streams or positive relief forms on the surface of the undermass have been observed. The edges of the interfluves are almost invariably rounded by soil creep.

The type of stripped sloping-plateau surface with very shallow dissection is of general occurrence in Central Otago and the neighboring area to the northeast. (See figs. 2, 3, 17.) This type of surface appears to have a close analogue in that found on the flanks of the resequent or stripped anticlinal

ridges of Table Mountain sandstone in southeastern Cape Colony (Davis, 1906, fig. 6).

Details of the Surface on Schist Blocks.—The same general type of relief is found on the schist and on the greywacke blocks. The surfaces of the latter are smooth and soil-covered (fig. 24); on the former are many residual tors—great castle-like, joint-bounded masses of bare schist (fig. 25). Tors are characteristic of a Central Otago landscape, and they have suggested the names given to many of the schist mountains—as,

FIG. 24.

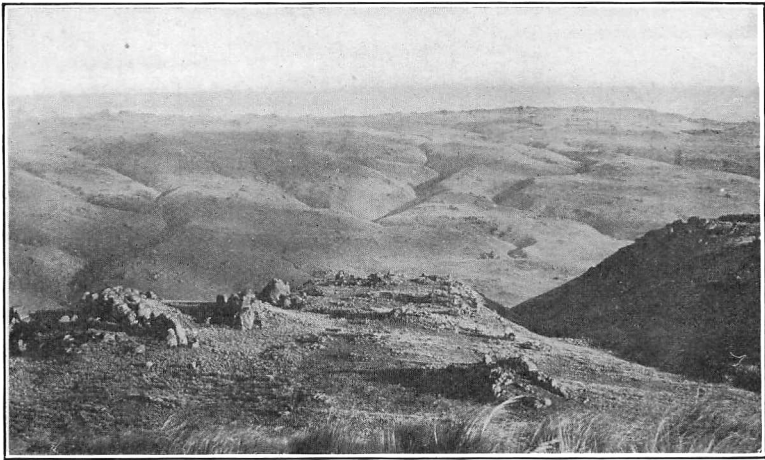


FIG. 24. Youthfully dissected stripped surface of a small greywacke block in the larger fault angle between the northern end of the Raggedy-Blackstone block and the scarp of the northern highland.

Rough Ridge and Raggedy Range. In the humid area towards the coast, tors are not found; they are largest and most abundant in the most arid districts, a gradual transition being traceable from the humid to the arid area. The development of the schist tors is, therefore, controlled by climate. They are found on both horizontal and sloping block surfaces, and their form is most characteristic and regular where the schist lies nearly horizontally.

The uneven resistance of the schist to erosion is probably not due to differences in composition, as suggested by Rickard (1893, p. 419). Finlayson (1908, p. 73) and Park (1908, p. 12) have noted that the tors are bounded by joint planes. It

would appear, therefore, that the schist is more susceptible to weathering in the interior areas on account of some peculiarity in the jointing, and it may be that the surface was deeply and irregularly weathered prior to the deposition of the covering strata. The occurrence of scattered logs of timber on the block surfaces (Park, 1908, p. 23; Speight, 1911) where the climate now borders on aridity, proves the existence of forest established in an earlier, moister period. If the forest cover-

FIG. 25.

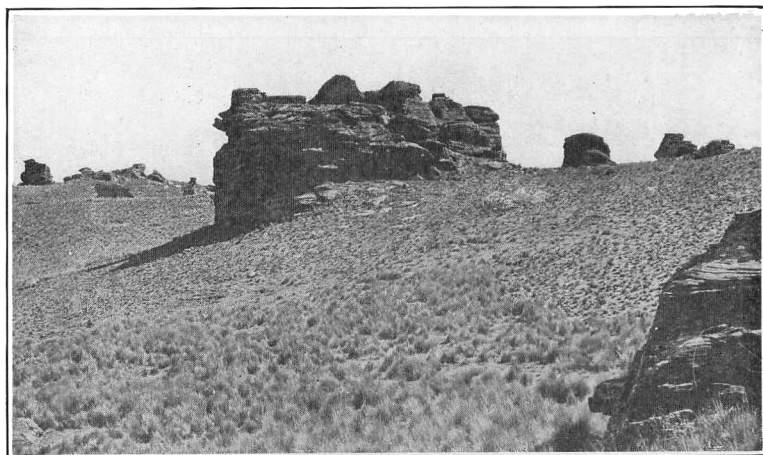


FIG. 25. Schist tors on Rough Ridge.

ing was continuous, deep and irregular weathering may have taken place even in the current cycle.

Whether differential weathering is or is not still going on, weathered material is being rapidly removed from the surface of poorly protected soil, and it is thus that the tor pattern has been etched out.

As greywacke does not occur in the most arid area, the contrast between greywacke and schist surfaces may be seen only in the vicinity of the scarp of the northern highland where the climate is semiarid. It may be that tors would form on a greywacke surface in the arid district. But as the greywacke is always thoroughly jointed, possibly no portions of the rock are sufficiently free from joints to survive as tors.

It is to be noted that the presence of tors on the plateaus and sloping uplands indicates a general lowering of the surface. Tors 20 and 30 feet high are very common, and on the higher plateaus some reach a height of 70 to 80 feet (Park,

1908, p. 12). This reduction of the block surfaces is not the result of channeling. The convexity of the edges of the interfluvial areas indicates that soil creep plays a part; but on the more nearly level interfluves, erosion is more probably of the sheet-flood kind.

Salients on Block Surfaces.—Preëxisting salients on a plain that has been strongly and in places irregularly deformed can not always be recognized with certainty even in an early stage of the postdeformational cycle (p. 257), and some may have been overlooked by the writer. On such of the Central Otago blocks as have been evenly uplifted, however, salients are absent. Mount Ida, on the edge of the northern highland, is perhaps a monadnock. Park suggests that Mount St. Bathans also is a monadnock rising above the level surface of the Dunstan Range (Park, 1906, pp. 6 and 8), but this is a distinct block (p. 278).

On the northern end of the Rock and Pillar block and on the gently tilted blocks of the eastern or Barewood Plateau are small prominent salients which are probably without exception lava-capped remnants of the overmass.

Scarps of the Schist Blocks.—The majority of the scarps following lines of dislocation in Otago are at the present stage of denudation in part fault-line scarps revealed by the removal of the covering strata. Since the fault scarps on the same lines had not been destroyed by erosion prior to the development of fault-line scarps, there is no danger of misinterpreting the geologic history in considering them entirely as simple fault scarps. Fault scarps form the boundaries of a number of blocks in Central Otago, and sufficient evidence of faulting is furnished by the attitude of the covering strata at the bases of the scarps. Along the front of the Dunstan block these beds are shown by Park (1890 *c*) and McKay (1897, figs. 20, 21, 26, 27) to be steeply inclined, vertical, and even overturned. The dip of the schist-foliation has been shown also by Park (1906) to become steep in the vicinity of the fault line, showing that the scarp is at least at its southwestern end a composite fold and reverse-fault scarp similar to that forming the southeastern slope of the Kaikoura Mountains in Marlborough (Cotton, 1913). This block boundary is the line of the Manuhēria fault of McKay (1897). The evidence of compression found here is in accord with what is known of the dislocations farther west.

Along the front of the Raggedy-Blackstone block the strata are upturned, as shown by Park (1890 *a*, p. 21), along a fault termed by McKay (1897) the Blackstone Hill fault. McKay writes: "This line runs nearly parallel to that along the southeast base of the Dunstan Mountains, and both lines have on the opposite side of the valley an outcrop of quartz drifts dipping at a lower angle in a northwest direction, or away from

the range that bounds the valley on the southeast side" (p. 112). There is no definite evidence that the fault is reversed.

In other cases the beds of the cover lie practically horizontally close to the bases of the scarps, as in the eastern scarp of the Rock and Pillar block, and in the scarp of the Hawkdun block (McKay, 1897, fig. 16), indicating probably normal faulting.

Fold scarps of small extent and not yet maturely dissected occur near the northeastern ends of the tapering Raggedy-

FIG. 26.

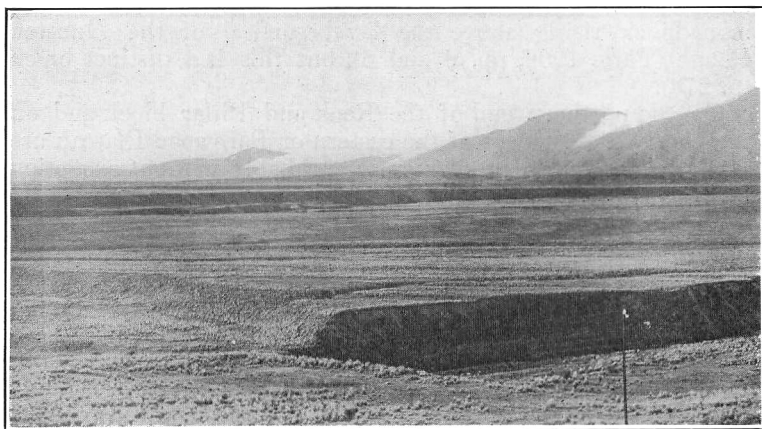


FIG. 26. The eastern portion of the Maniototo Plains and the scarp of the Kakanui Range.

Blackstone, Rough Ridge, and Rock and Pillar blocks on their eastward-facing fronts (fig. 10), and on the northwestward-facing portion of the last.

The fault scarps of the schist blocks, especially where the schist is weak, have crumbled to very gentle slopes. The great scarp, nearly 4,000 feet high, forming the long, straight southeastern face of the Rock and Pillar block, has an average slope of 20°.

The Scarps of Greywacke Blocks.—The scarps of the greywacke blocks along the margin of the northern highland of Otago are little-dissected fault scarps forming the fronts of tilted blocks, as are also the scarps of the block complex in and beyond the Waitaki Valley depression.

Among the well-preserved scarps which form the fronts of simple tilted blocks there is a decided family resemblance, and they contrast strongly with the scarps of schist blocks. The

average slope of greywacke fault scarps is nearly twice as steep as that of schist scarps. Like the schist fault scarps, though generally not deeply dissected, these may be described as sub-mature or mature with graded slopes. The difference in steepness between the schist and greywacke scarps is to be ascribed, therefore, to the much steeper gradient which in the greywacke blocks represents a condition of equilibrium after the first rush of scarp destruction by crumbling and slumping initiated by the deformation.

In low scarps (up to about 1,000 feet) the average slope of the salients (scarcely to be dignified by the term spurs) is about 40° , and that of the intervening reëntrants somewhat less. Definite sharp-edged facets are not found, the salients being generally of even slope and broadly convex as a result of grading of the slopes by soil creep. Instead of ravines the reëntrants are usually funnel-shaped shoots that merely scallop the edge of the upland surface. They are occupied by streams not of water but of angular fragments of rock. Such a scarp is found in the front of the southern end of the Hunter's Hills block in Southern Canterbury (fig. 8), and a much higher one forms the western slope of the St. Bathans block, the shallowness of the dissection of the front of which is due to the strong backward tilt of the block.

In high scarps which do not conform to this extreme type, mature dissection has been effected by steep-grade permanent streams whose heads penetrate only a short distance back into the highland plateau. Of this nature are the Hawkdun and Kakanui fault scarps (figs. 18, 20, and 26).

6. *The Floors of the Central Otago Depressions.*

In general the depressions contain no great accumulations of alluvium as a result of postdeformational aggradation. The vast quantity of waste resulting from the stripping of the overmass from the uplands and its erosion in the lowlands, as well as that derived from the erosion of portions of the undermass, has been removed in the course of ages by streams, many of which seem puny and almost powerless. In those large areas in which the covering strata extend below local base-levels and have thus escaped complete removal, planation of their surface is far advanced. This is particularly true of the southern parts of the Ida Valley and Maniototo depressions, floored by the level valley plains of the Pool Burn and the Upper Taieri River.

The northern portions of the Ida Valley and Maniototo depressions and of the Manuherikia depression, which are practically continuous, may be described as a local peneplain, the erosion of which has been lately revived several times. The upper courses of the streams of the northern part of the Manio-

toto depression are at present confined to shallow valleys, the flood-plain floors of which, though of no great width, open out downstream and become continuous. They form a plain which slopes towards the confluences of the streams with the Taieri and is accordant with the valley plain of the Upper Taieri. The recent revival of erosion along the base of the northern fault scarp is perhaps due to climatic changes affecting the supply of waste to the headwaters of the streams. The valley plains and the terraces are covered by a layer of greywacke gravel.

In the southern part of the Manuherikia depression the relief is considerable. There are broad areas of high terrace owing to the recent deepening of the valley of the Clutha, of which the Manuherikia is a tributary. The effect of this may extend into the upper Manuherikia; but it has not yet appeared to affect the streams of the Ida Valley depression; while those of the Maniototo depression do not belong to the Clutha system.

There has been a small rejuvenation in the Taieri River where it flows through the Strath Taieri depression; but the floor of this narrow fault angle is for the most part a valley plain.

LIST OF PAPERS TO WHICH REFERENCE IS MADE.

- Andrews, E. C.: Some interesting facts concerning the glaciation of southwestern New Zealand, Australasian Assoc. Adv. Sci. Rept., 10th (Dunedin) Meeting, pp. 189-205, 1905.
- Beal, L. O.: On the deposition of the alluvial deposits of the Otago gold-fields, New Zealand Inst. Trans., vol. iii, pp. 270-278, 1871.
- Bell, J. M.: The geology of the Parapara Subdivision, New Zealand Geol. Survey, Bull. 3, 1907.
- Cotton, C. A.: The physiography of the Middle Clarence Valley, New Zealand, Geogr. Jour., vol. xlii, pp. 225-246, 1913.
- On the relations of the great Marlborough conglomerate to the underlying formations in the Middle Clarence Valley, New Zealand, Jour. Geology, vol. xxii, pp. 346-363, 1914.
- The structure and later geological history of New Zealand, Geol. Mag., vol. iii, pp. 243-249 and 314-320, 1916 *a*.
- Block Mountains and a "fossil" denudation plain in Northern Nelson: New Zealand Inst. Trans., vol. xlviii, pp. 59-75, 1916 *b*.
- Davis, W. M.: The convex profile of bad-land divides, Science, vol. xx, p. 245, 1892.
- The Mountain ranges of the Great Basin: Harvard Coll. Mus. Comp. Zool. Bull., vol. xlii, pp. 142-177, 1903.
- The Wasatch, Canyon, and House ranges, Utah, Harvard Coll. Mus. Comp. Zool. Bull., vol. xlix, pp. 15-57, 1905 *a*.
- The geographical cycle in an arid climate, Jour. Geol., vol. xiii, pp. 381-407, 1905 *b*.
- Observations in South Africa, Geol. Soc. America Bull., vol. xvii, pp. 377-460, 1906.
- Die erklärende Beschreibung der Landformen, Leipzig, Teubner, 1912.
- Nomenclature of surface forms on faulted structures, Geol. Soc. America Bull., vol. xxiv, pp. 187-216, 1913.
- Finlayson, A. M.: Some observations on the schists of Central Otago, New Zealand Inst. Trans., vol. xi, pp. 72-79, 1908.
- Gilbert, G. K.: Progress report for 1872, U. S. Geog. Surveys W. 100th Mer., p. 50, 1874.

- Gilbert, G. K.: Report on the geology of the Henry Mountains: U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.
- The convexity of hilltops: Jour. Geol., vol. xvii, pp. 344-350, 1909.
- Gordon, H. A.: The goldfields of New Zealand, New Zealand Parl. Paper C.—3, Wellington, 1893.
- Hector, J.: Notes relative to the geology of the Manuherikia Valley, Otago Prov. Gov. Gazette, Sept. 3, 1862.
- Progress report, New Zealand Colonial Mus. and Geol. Survey Rept. Geol. Exploration 1868-1869, p. vi, 1869.
- On mining in New Zealand, New Zealand Inst. Trans., vol. ii, pp. 361-384, 1870.
- On the distribution of the auriferous cements in New Zealand, New Zealand Inst. Trans., vol. xiii, p. 429, 1881.
- On the deep-sinking at Naseby, New Zealand Colonial Mus. and Geol. Survey Rept. Geol. Exploration 1888-1889, p. lvi, 1890.
- Hutton, F. W.: Geology of Otago, Dunedin, 1875.
- Kitson and Thiele: The Geography of the Upper Waitaki Basin, New Zealand, Geog. Jour., vol. xxxvi, pp. 537-553, 1910.
- Lawson, A. C.: The geomorphogeny of the Tehachapi Valley system, California Univ. Dept. Geology, vol. iv, No. 19, pp. 431-462, 1906.
- Louderback, G. D.: Basin Range structure in the Humboldt region: Geol. Soc. America Bull., vol. xv, pp. 289-346, 1904.
- Marshall, P.: The geography of New Zealand, Christchurch, 1905 (?).
- Cainozoic fossils from Oamaru, New Zealand Inst. Trans., vol. xlvii, pp. 377-387, 1915.
- McKay, A.: On the northeastern district of Otago, New Zealand Colonial Mus. and Geol. Survey Rept. Geol. Exploration 1883-1884, pp. 45-81, 1884 *a*.
- On the origin of the old lake basins of Central Otago, *ibid.*, pp. 76-81, 1884 *b*.
- On the auriferous quartz drifts at Clark's Diggings, Maniototo County, *ibid.*, pp. 91-95, 1884 *c*.
- Report on the older auriferous drifts of Central Otago, 2d edition, Wellington Govt. Printer (1st ed. Parl. Paper 1896), 1897.
- Noble, L. F.: The Shinumo Quadrangle, Grand Canyon District, Arizona, U. S. Geol. Survey Bull. 549, 1914.
- Park, J.: On the Ophir district, Otago, New Zealand Colonial Mus. and Geol. Survey Rept. Geol. Exploration 1888-1889, pp. 17-22, 1890 *a*.
- On German Hills alluvial gold-diggings, *ibid.*, pp. 24-26, 1890 *b*.
- On Tinker's alluvial gold-diggings, *ibid.*, pp. 27-30, 1890 *c*.
- The geology of the area covered by the Alexandra sheet, New Zealand Geol. Survey Bull. ii, 1906.
- The geology of the Cromwell Subdivision, New Zealand Geol. Survey Bull., v, 1908.
- The Geology of New Zealand, Christchurch, 1910.
- Some notes on the Marlborough coastal moraines and the Waiau glacial valley: New Zealand Inst. Trans., vol. xliii, pp. 520-524, 1911.
- Rickard, T. A.: The goldfields of Otago; Am. Inst. Min. Eng. Trans., vol. xxi, pp. 411-442, 1893.
- Speight, R.: "Geological History" in L. Cockayne's "Report of a Botanical Survey of the Tongariro National Park," New Zealand Parl. Paper, C.—11, p. 7, 1908 *a*.
- Some aspects of the terrace-development in the valleys of the Canterbury Rivers: New Zealand Inst. Trans., vol. xi, pp. 16-43, 1908 *b*.
- The postglacial climate of Canterbury, *ibid.*, vol. xliii, pp. 408-420, 1911.
- The intermontane basins of Canterbury, *ibid.*, vol. xlvii, pp. 336-353, 1915.
- The orientation of the river-valleys of Canterbury, *ibid.*, vol. xlviii, pp. 137-144, 1916.
- Thomson, J. A.: Coal prospects of the Waimate district, South Canterbury, New Zealand Geol. Survey Eighth Ann. Rept., p. 160, 1914.