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The Alpine Fault*

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Abstract

INFORMATION on the Alpine Fault, scattered through a great deal of literature, is reviewed. The fault, which is steeply dipping, is continuous from Cook Strait to Milford Sound, and extends south-west off the Fiordland coast. It is presumed to pass through the North Island, the most probable line being north from Feilding, passing between the Rimutaka Mountains and the Kaweka Range, and thence to the coast west of Whakatane. The 300-mile horizontal shift was largely completed in the Rangitata Orogeny (late Jurassic and early Cretaceous). During the Kaikoura Orogeny (late Tertiary and Quaternary), vertical uplift in the South Island may have amounted to at least 60,000 feet in central Westland, where the amount of horizontal movement seems to have been about the same.

INTRODUCTION

It is now over 50 years since Morgan (1908), referring to the Wanganui River area of South Westland, wrote: "The coincidence of thrust or slip of the Paleozoic rocks over modern alluvia in two spots not far apart on the line of the fault furnishes food for thought". The offering was small, and as no more was forthcoming, almost a whole generation of geologists discussed the structure of New Zealand with only a passing reference to what Morgan had called "a great fault". Perhaps if Morgan had named it—he referred only to the "Gregory Valley" developed along it—perhaps too if he had made a bolder distinction between the rocks of the two sides, others would have paid more heed. Attention was directed more to other major faults—Hope and Awatere, Wellington and Wairarapa—because of historic displacements at times of destructive earthquakes. There was little to bring the Alpine Fault to the attention of most New Zealand geologists, preoccupied with problems in more populated regions.

In 1929 Henderson, in discussing the importance of faulting in the structural development of New Zealand, judged the western face of the Southern Alps to result from the vertical rising of the arcuate fronts of a series of rotating blocks, showing four major arcs (Fig. 1A). These arcs are clearly illustrative of the type of fracture he thought probable from his concepts of the mechanics of earth movements, for the Fault Map of New Zealand (Henderson, 1928), based more

* This paper is slightly expanded from the Presidential Address to the Geological Society of New Zealand, August, 1962; subsequently Mackie (1962) summarised much of the information on the Alpine Fault published up to early 1959, particularly that relating to young displacements.

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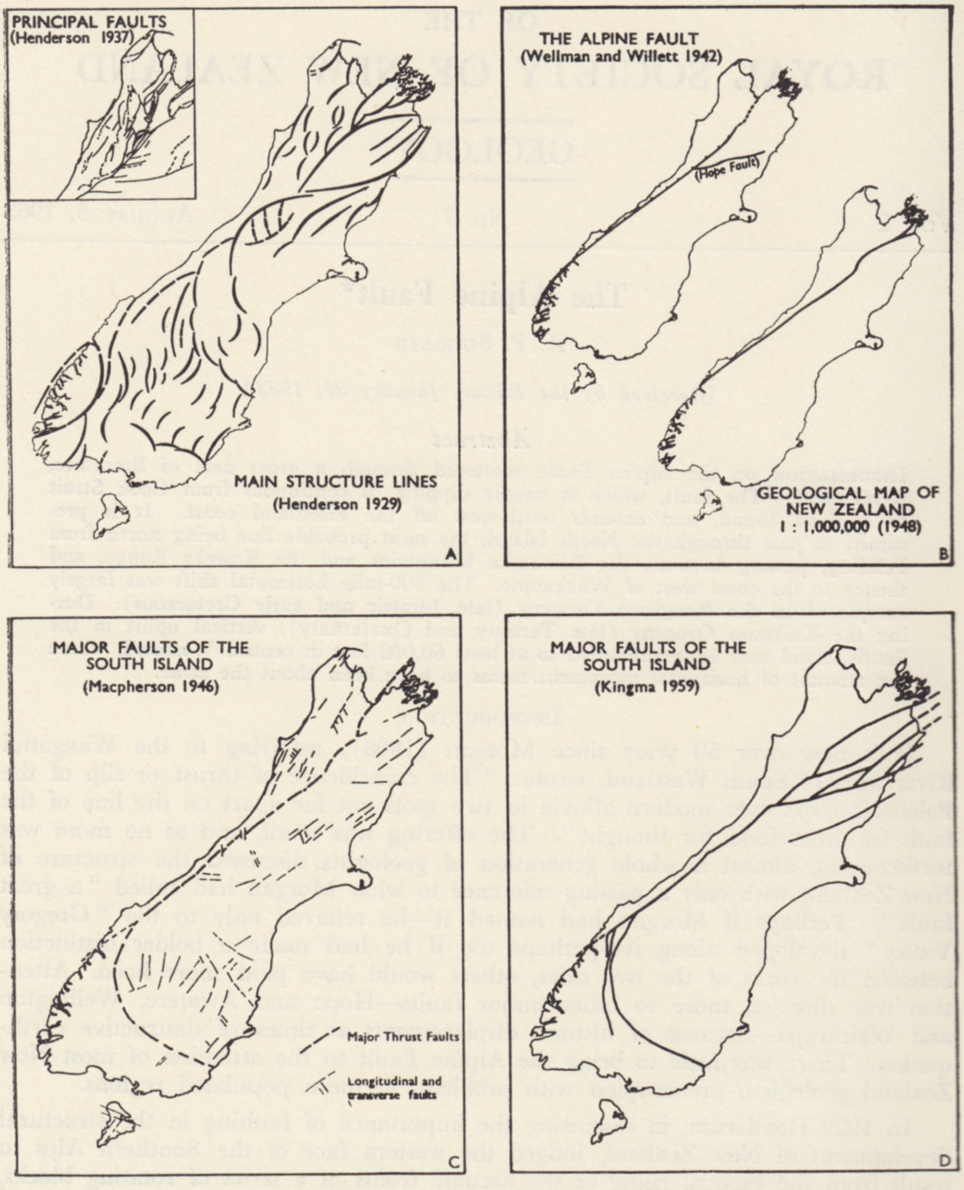


FIG. 1.—Various interpretations of the major faults of the South Island.

closely on field observations, shows fault lines much less arcuate. In 1937 Henderson favoured a brittle crust fragmented into wedge-like blocks, but retained segmentation of the front of the Alps in the Nelson and North Westland region similar to what he had shown in 1928, with main breaks in continuity at the Taramakau and Ahaura Rivers (Fig. 1A). In a diagrammatic section that crossed the fault on the west side of the Spenser Mountains, a little south-west of Lake Rotoroa, he used the name "Alpine Fault"; in the text he used "Wairau Fault" in describing the same area, and the introduction of "Alpine Fault" seems to have been almost inadvertent. It may be justifiable, however, to speculate that the

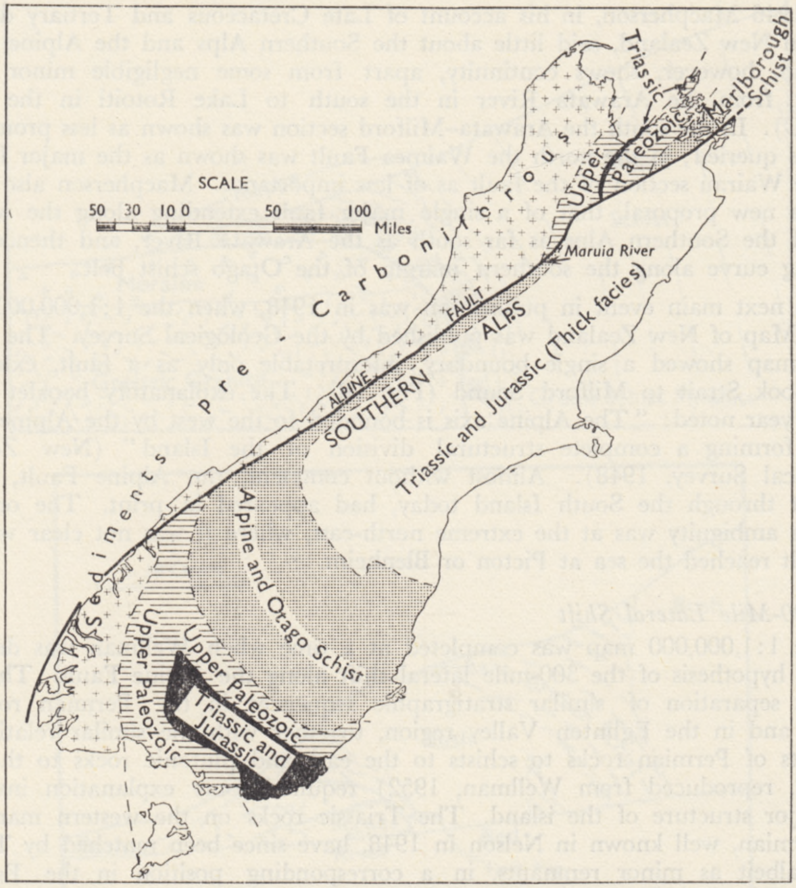


FIG. 2.—Sketch map showing the Alpine Fault and pre-Cretaceous rocks of the South Island, reproduced from Wellman (1952). The 300-mile lateral shift is based on the correspondence of regional sequences on opposite sides of the Alpine Fault in the north and south of the Island.

concept of continuity along the Alpine front may have been in the background, for why otherwise was "Alpine" rather than "Wairau" used for a fault that does not bound the Southern Alps proper?

It was only five years from Henderson's paper to that of Wellman and Willett (1942), in which the name Alpine Fault was adopted and in which continuity was accepted from Lake Rotoroa to Milford Sound, with an inferred probable extension south along the Fiordland coast (Fig. 1B). The criteria used in mapping the fault were: (1) a scarp or sudden change in summit heights from west to east; (2) crush zones and slips; (3) rivers with co-linear courses, with low saddles between them; (4) change in rock type; (5) off-setting of river courses, resulting from late Pleistocene horizontal movement.

One curious point in Wellman and Willett's paper was that of the northern continuation from Lake Rotoroa. They stated: "Farther north it . . possibly continues as the Waimea Fault along the east of the Nelson Lowlands." Thus the continuity from Lake Rotoroa past Lake Rotoiti and down the Wairau Valley, indicated by Henderson, was apparently rejected.

In 1946 Macpherson, in his account of Late Cretaceous and Tertiary diastrophism in New Zealand, said little about the Southern Alps and the Alpine Fault. His map, however, shows continuity, apart from some negligible minor cross-faulting, from the Arawata River in the south to Lake Rotoiti in the north (Fig. 1C). In the south the Arawata–Milford section was shown as less prominent, and was queried; in the north the Waimea Fault was shown as the major feature and the Wairau section of the fault as of less importance. Macpherson also introduced a new proposal, that of a single major fault extending along the western front of the Southern Alps as far south as the Arawata River, and thence in a sweeping curve along the southern margin of the Otago schist belt.

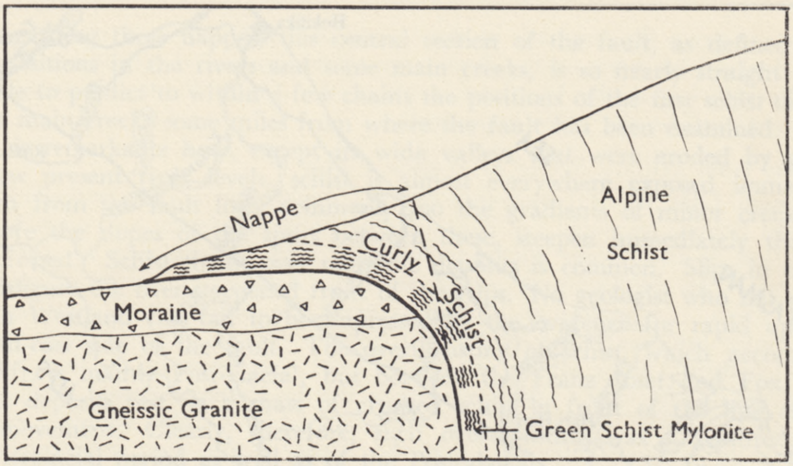
The next main event in publication was in 1948, when the 1:1,000,000 Geological Map of New Zealand was published by the Geological Survey. The South Island map showed a single boundary, interpretable only as a fault, extending from Cook Strait to Milford Sound (Fig. 1B). The explanatory booklet issued in that year noted: " The Alpine axis is bounded to the west by the Alpine Fault . . . forming a complete structural division of the Island " (New Zealand Geological Survey, 1948). Almost without comment, the Alpine Fault, as we know it through the South Island today, had appeared in print. The only remaining ambiguity was at the extreme north-east, where it was not clear whether the fault reached the sea at Picton or Blenheim.

The 300-Mile Lateral Shift

The 1:1,000,000 map was completed at a time when Wellman was developing the hypothesis of the 300-mile lateral shift along the Alpine Fault. The geographic separation of similar stratigraphic sequences in the Permian rocks of Nelson and in the Eglinton Valley region, together with the similar relations of the belts of Permian rocks to schists to the east and plutonic rocks to the west (Fig. 2, reproduced from Wellman, 1952) required some explanation involving the major structure of the island. The Triassic rocks on the western margin of the Permian, well known in Nelson in 1948, have since been matched by Triassic rocks, albeit as minor remnants, in a corresponding position in the Eglinton Valley (Wood, 1963), and add weight to the comparison. The belts of late Paleozoic and Triassic rocks ending abruptly against the Alpine Fault in the two regions have given rise to the hypothesis of lateral shift of 300 miles—perhaps 280 miles would be more accurate. This hypothesis was introduced by Wellman at the Pacific Science Congress in 1949 (Benson, 1952) and again at the Seventh New Zealand Science Congress in 1951, and it crept indirectly into the literature. But it has at no time been fully documented, although Wellman himself later (1955a; 1956) referred to it in print. Perhaps there is little to say, except to point out the match of the Nelson and Eglinton sequences; but alternatives have been suggested and cannot be ignored.

Recording of Quantitative Data on Fault Movement

In 1952–56 there was partial shift of interest to recent movement on the Alpine and other major faults. In 1952 both Wellman and Munden, in discussing Recent displacement of terraces at the Maruia and Haupiri Rivers respectively, showed that successive movements had taken place along the same lines of faulting, a phenomenon recorded previously by Ongley (1943) at the Wairarapa Fault. Wellman (1952) and Munden (1952), however, accurately recorded both horizontal and vertical displacements of successive river terraces, and in the next year Wellman (1953a) extended the recording of such numerical data to all the young fault displacements he knew of in the South Island. In his interpretation of these records, and of North Island data, Wellman (1955a) showed the Wairau Fault



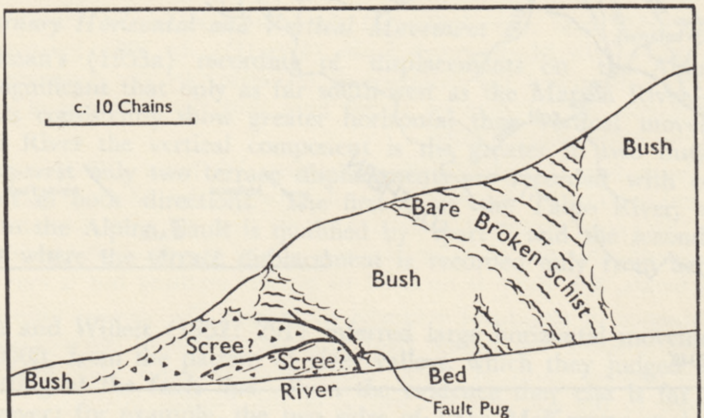


FIG. 3.—Superficial overthrusting at the Alpine Fault. Above: Diagrammatic representation by Wellman (1955). Below: Section exposed at Gaunt Creek, Waitangi-taona River, South Westland, from a sketch by the author. (Note that to match the diagram above, the sketch is shown in mirror image of the actual exposure on the south-west bank of Gaunt Creek.

as a branch of the Alpine Fault. The Alpine Fault proper was shown to end at the marked bend north of the Maruia River, continuing north and north-east as the Wairau Fault, but the 300-mile shift, which was attributed to the Alpine Fault alone, requires movement along the two faults. Clearly the case for distinction of the Alpine and Wairau Faults must either rest on criteria other than the 300-mile shift or, preferably, must be abandoned, because that shift is their major feature. In the same paper Wellman made some estimates of the rates of tectonic movement, and expressed doubt as to whether the actual displacements at the Marlborough faults themselves accounted for the whole of the regional displacement indicated by geodetic evidence that he cited. One significant point about Wellman's figures is that roughly similar amounts and rates of Late Quaternary movement can be ascribed to the Wairau—that is the Alpine—Fault as to other major faults.

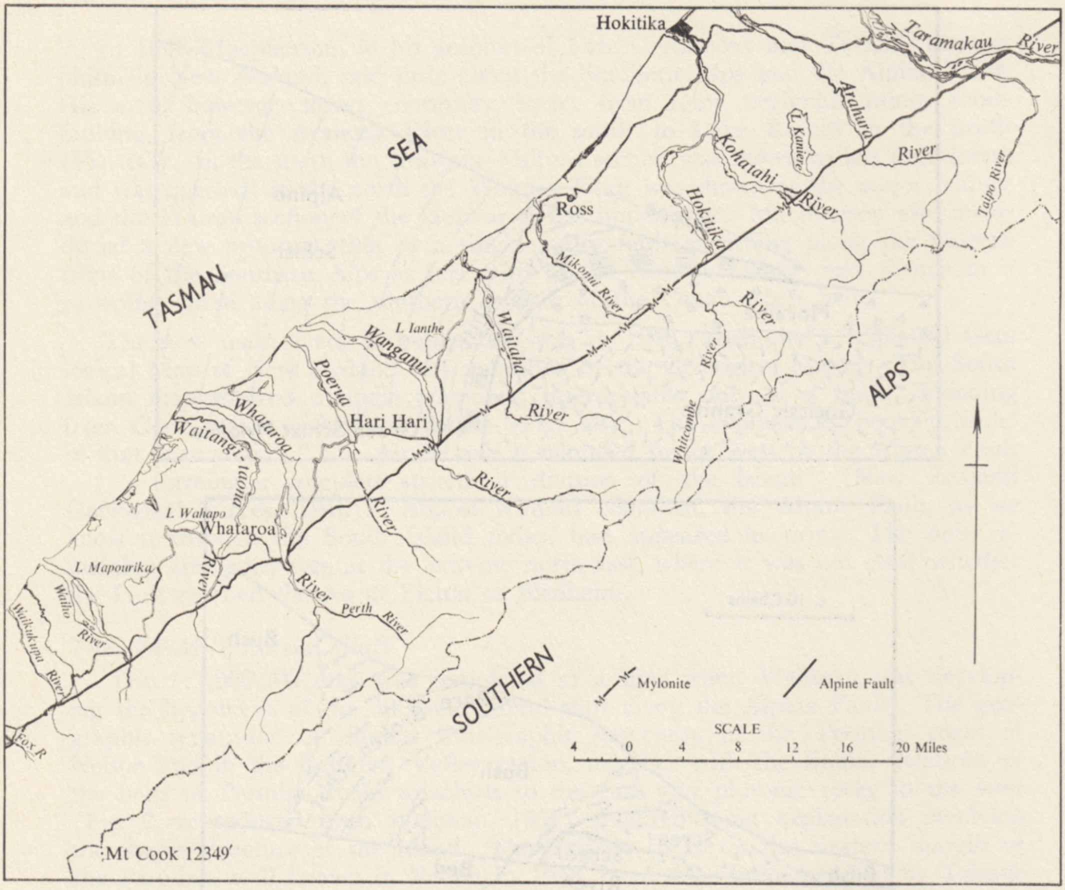


FIG. 4.—The Alpine Fault in central Westland, showing irregularity of outcrop resulting from superficial overthrusting, and also distribution of mylonite.

Recent Overthrusting

Another aspect of the Alpine Fault, that of Recent overthrusting, received attention from Bowen (1954) and Wellman (1955b). Although on small-scale maps the fault is amazingly straight for most of its length from Milford Sound to the Maruia River, this straightness is deceptive. Where the fault crosses ridges it reaches the surface further to the north-west than it does in the valleys, a relation to be expected with a fault that dips to the south-east. Both Bowen and Wellman showed the planes of schistosity as parallel to the fault plane, and Wellman figured the fault plane as first turning over to be horizontal and then dipping slightly north-west away from the Alps so that the schist rests on morainic deposits (Fig. 3). Wellman attributed the nappe so formed to uplift on the south-east side of a steeply-dipping fault plane taking place more rapidly than could be coped with by erosion, so that under the influence of gravity the broken schist collapses and is pushed over the moraine to the north-west. Probably all geologists who have studied the fault in the central part of the Southern Alps concur in this explanation. It may be noted that the furthest forward that a nappe is known to extend is nearly a mile and a half, between the Whataroa and Poerua Rivers (Fig. 4).

Disregarding these nappes, this central section of the fault, as defined by its known positions in the rivers and some main creeks, is so nearly straight that it is possible to predict to within a few chains the positions of the first schist outcrops in other main creeks some miles from where the fault has been examined. Moreover, it is remarkable how, except in wide valleys that were eroded by glaciers far below present river levels, schist is almost everywhere exposed immediately upstream from the fault line; commonly too the gradients of minor creeks, and even more the slopes of the spurs between these, steepen immediately the fault line is crossed. Schist thrust over morainic deposits is common. Slips in crushed schist disfigure the over-steepened front of the Alps. No geologist who has worked in South Westland can fail to be impressed by the evidence for rapid uplift on the south-east side of the fault. The overthrusting of schist, which accompanies this uplift, is mainly Post-glacial, but between the Franz Josef and Fox Rivers morainic deposits rest on a mass of crushed schist in front of the line of most recent movement. Clearly, therefore, such overthrusting was a feature of the Last Interglacial period as well as of the Post-glacial.

Late Quaternary Horizontal and Vertical Movement

In Wellman's (1953a) recording of displacements on the Alpine–Wairau Fault it is significant that only as far south-west as the Maruia River do terrace displacements consistently show greater horizontal than vertical movements. At the Haupiri River the vertical component is the greater in two instances, and farther south-west only two terrace displacements are recorded with components of movement in both directions. The first is at the Taipo River, where the attribution to the Alpine Fault is qualified by "part", and the second is at the Haast River where the terrace displacement is recorded only from aerial photographs.

Wellman and Willett (1952: 291) inferred large horizontal movements, from 2,000 to 6,000ft, from the pattern of river valleys, which they judged to indicate lateral offsetting at the fault line. Even the evidence they cite is far from conclusive, however; for example, the two sides of Lake McKerrow could be interpreted as showing opposing movements rather than the similar movements given by Wellman and Willett. And it is hardly to be expected that in crossing the fault the rivers will have found the easiest routes westward immediately opposite the easiest routes through the schist.

Large vertical displacements cannot be accurately recorded because erosion of the front of the Southern Alps rapidly destroys reference surfaces. Wellman (1953a), however, recorded *c.* 2,000ft displacement at Mount Brown Creek, judged by the assumed altitudes of the base of morainic deposits preserved to the west but removed to the east. When he published details of this area in 1954, Bowen considered the displacement to be "at least 1,000ft" and the deposits to be no older than the Last Glaciation. Judged by the now better known glacial sequence in north Westland, the moraine is more likely to be about 25,000 years old than 100,000 as tentatively suggested by Bowen, and it is most improbable that it is "possibly penultimate glacial" (Wellman, 1955a: 252). Wellman (1955a, 252) records that at the Hokitika River, 10 miles south-west of Mount Brown Creek, a terrace "considerably younger than the maximum of [the Last] Glaciation" has been elevated about 400ft on the Alpine side. This terrace is unlikely to be more than 10,000 years old. The rapid uplift thus recorded in north Westland is entirely in keeping with the general physiographic evidence, which seems to be substantially similar along the whole western front of the Southern Alps at least as far south as the Arawata River.

In recent years the emphasis in discussions of late Quaternary tectonic activity in New Zealand has been on the dominance of the horizontal component of movement. Nevertheless in the Westland sector of the Alpine Fault the vertical component may well be the more important.

Continuity from Milford Sound to Wairau Valley

Although Lillie in 1951 evidently did not doubt that a fault extended as far as Milford Sound, he stated (p. 235) that he preferred to see any main southern prolongation of the Alpine Fault as following the western side of the Waiau Valley, for "the displacement would then be defined in terms of deformed Tertiary strata". Kingma, in 1959, was even less prepared to take the main line of major faulting as far as Milford Sound, instead inferring it to continue as a major thrust, along which ultramafic rocks were intruded, a little south of the southern margin of the Otago schists; in this he closely followed Macpherson's earlier interpretation. But Clark and Wellman, later in 1959, supplied evidence, in contrast to previous inference, that the Alpine Fault does indeed extend to Milford Sound.

Kingma (1959) had also challenged the unbroken line of the Alpine Fault, showing it offset by the Marlborough faults (Fig. 1D). In 1961, however, Suggate, Gair and Gregg disproved the evidence of off-setting by the Awatere Fault suggested by Kingma, and it may be stated here that the evidence of offset is no stronger at any other major faults.

At the Tenth New Zealand Science Congress, Wellman (1962) suggested that the meridional section of the Alpine Fault between the Maruia and Matakitaki Rivers (Fig. 5) could represent a separate fault that cut and displaced the main line of movement. But the schist on the east side of the Fault is continuous round the marked bends, and there is no need to invoke anything but a curved fault.

In the absence of structural evidence supporting the various alternatives that have been put forward, the Alpine Fault may be considered restored to its former place as the premier fault of New Zealand, continuous and unbroken from Milford Sound to the sea near the mouth of the Wairau River.

Time of Schist Uplift in Westland

The general parallelism of the high-grade schist zones to the Alpine Fault is clearly a crucial feature of the large-scale tectonic pattern of the South Island, and there can be little doubt that the uplift so evident at the present time is tending to bring rocks of increasingly high grade to the surface. Some at least of the schist uplift must clearly be young, and Mason (1961, 1962) has recently recorded four young potassium-argon dates of garnet-oligoclase zone schist, the dates ranging from 4 to 8 million years, and averaging 6 million. He considers the dates to be of the times at which the rocks were brought up to levels high enough for the argon to cease to be lost by diffusion, which, he states, takes place at temperatures attained at depths between 30,000 and 45,000 feet, according to the geothermal gradient. These dates appear to support a very young uplift of the schist.

It is necessary to turn back at this point to Wellman and Willett's paper (1942), because one suggestion that they made has rather unexpectedly been renewed recently, the suggestion that generalised contours on Alpine summit heights can be used to indicate the deformation of a peneplain. The suggestion of a peneplain over the Southern Alps was first made by Bell and Fraser (1906), who described the "Wainihinihi Peneplain", of mid-Tertiary age, extending across the valley where the Alpine Fault is now known to be. In contrast, Wellman and Willett (1942) judged the peneplain to be of late Tertiary age and to

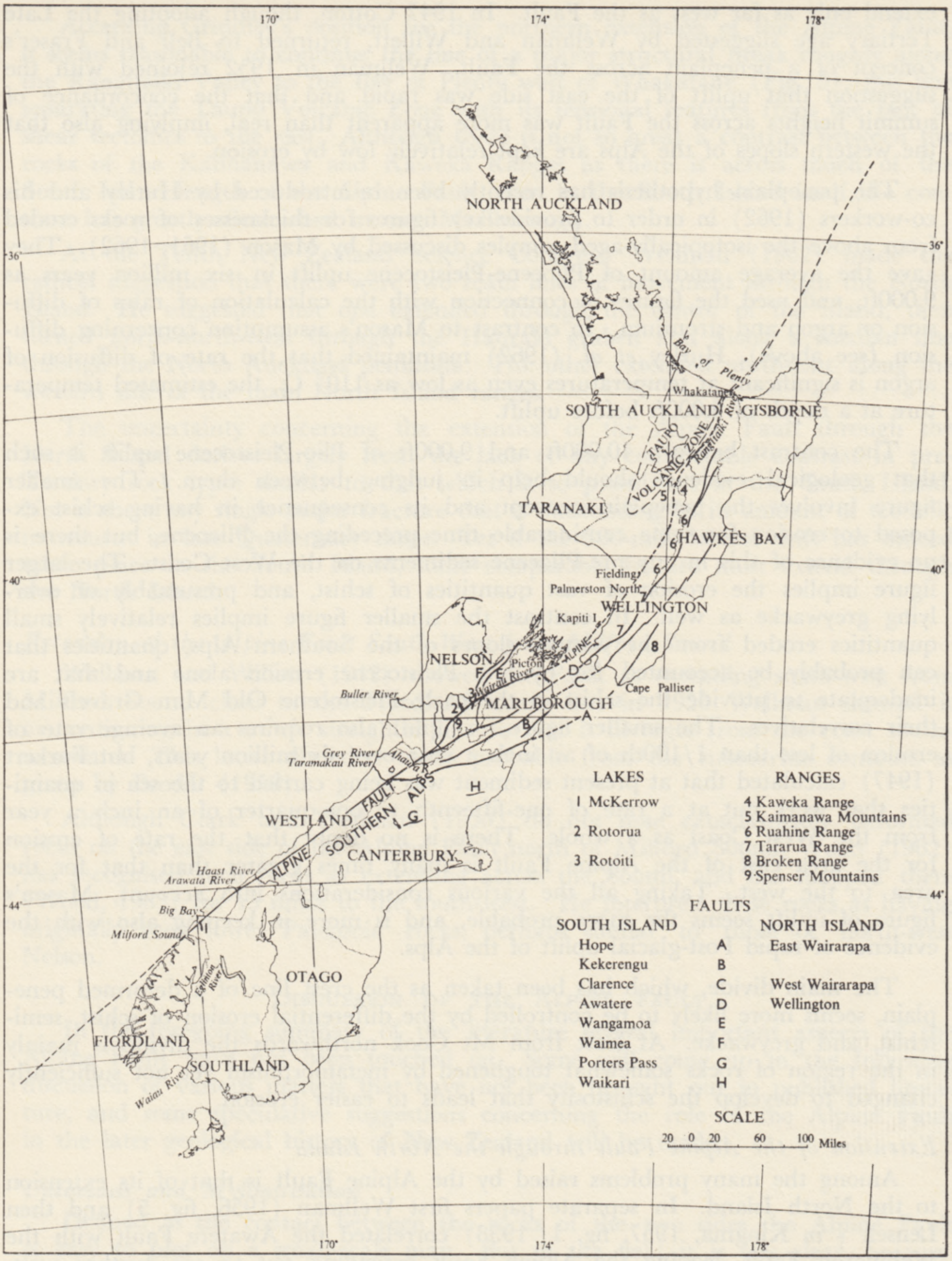


FIG. 5.—The Alpine Fault and the Marlborough–East Coast faults, showing inferred extension of the Alpine Fault through the North Island. The map also serves as a locality map for rivers and ranges not shown on other text figures. (Note: For Broken read Brocken.)

extend only as far west as the Fault. In 1947 Cotton, though adopting the Late Tertiary age suggested by Wellman and Willett, returned to Bell and Fraser's concept of a peneplain across the Fault. Wellman in 1952 rejoined with the suggestion that uplift of the east side was rapid and that the concordance of summit heights across the Fault was more apparent than real, implying also that the western slopes of the Alps are kept relatively low by erosion.

The peneplain hypothesis has recently been re-introduced by Hurley and his co-workers (1962) in order to provide key figures for thicknesses of rocks eroded from above the isotopically-aged samples discussed by Mason (1961, 1962). They gave the average amount of Pliocene-Pleistocene uplift in six million years as 9,000ft, and used the figures in connection with the calculation of rates of diffusion or argon and strontium. In contrast to Mason's assumption concerning diffusion (see above), Hurley *et al.* (1962) maintained that the rate of diffusion of argon is significant at temperatures even as low as 110° C., the estimated temperature at a depth of 9,000ft before uplift.

The contrast between 40,000ft and 9,000ft of Plio-Pleistocene uplift is such that geological evidence should help in judging between them. The smaller figure involves the peneplain concept and its consequence in having schist exposed to erosion for some considerable time preceding the Pliocene, but there is no evidence of this in any pre-Pliocene sediments on the West Coast. The larger figure implies the erosion of vast quantities of schist, and presumably of overlying greywacke as well. In contrast the smaller figure implies relatively small quantities eroded from the western slopes of the Southern Alps, quantities that can probably be accounted for by late Pleistocene erosion alone and that are inadequate to provide the schist in the early Pleistocene Old Man Gravels and their correlatives. The smaller figure for uplift also requires an average rate of erosion of less than 1/100th of an inch a year over six million years, but Furkert (1947) calculated that at present sediment was being carried to the sea in quantities that work out at a rate of one-fifteenth to one-quarter of an inch a year from the West Coast as a whole. There is no doubt that the rate of erosion for the area east of the Alpine Fault is many times greater than that for the area to the west. Taking all the various considerations into account, Mason's figure of uplift seems the more probable, and is more in keeping also with the evidence of rapid Post-glacial uplift of the Alps.

The main divide, which has been taken as the crest line of a deformed peneplain, seems more likely to be controlled by the differential erosion of schist, semi-schist, and greywacke. At least from Mt Cook northwards the divide is mainly in the region of rocks somewhat toughened by metamorphism yet not sufficiently changed to develop the schistosity that leads to easier erosion.

Extension of the Alpine Fault through the North Island

Among the many problems raised by the Alpine Fault is that of its extension to the North Island. In separate papers first Wellman (1956, fig. 5) and then Lensen (*in* Kingma, 1957, fig. 1; 1958) correlated the Awatere Fault with the Wellington Fault, leaving the Alpine Fault extending out to sea further west. Wellman (1956, fig. 4) has implied that the Alpine Fault extends to Kapiti Island and through Palmerston North to Whakatane, but Kingma (1957, 1959), though similarly showing it extending to Kapiti Island, took it well to the west of the Rimutaka and Ruahine Ranges. Grindley (1960), on the Taupo 1:250,000 Geological Map, notes that the Ngamatea Fault separating the Kaimanawa Mountains and the Kaweka Range is probably a continuation of the Wairau—that is, of the Alpine Fault.

Accepting Grindley's position for the northern extension of the Alpine Fault, it seems reasonable to continue the line of a major structural break roughly along the Rangitaiki Valley to the Bay of Plenty west of Whakatane (Fig. 5), this line separating the Taupo Volcanic Zone with its tensional features from the belt of shear tectonics to the east. Although there is not so great a contrast between the rocks of the Kaimanawa and Kaweka Ranges as there is across much of the South Island length of the Alpine Fault, even in the South Island itself the contrast has greatly diminished in east Marlborough.

At the Tenth New Zealand Science Congress, Wellman (1962) made the radical suggestion that there were two main lines of movement through the North Island. He suggested that one extended through the centre of the island, then turned north-north-west through the Hauraki graben and along a median line through the North Auckland peninsula. The other extended north-east along the western side of the main North Island ranges.

The uncertainty concerning the extension of the Alpine Fault through the North Island derives largely from the lack of any considerable contrast in pre-Tertiary rock types similar to that which is so prominent in the South Island. Nor is there any single major fracture that is outstanding in its amount of tectonic movement in late Quaternary times. Yet if the 300-mile lateral shift has indeed taken place in the South Island, some comparable feature must extend through the North Island.

Extension of the Alpine Fault South-West from Milford Sound

Wellman and Willett (1942) showed the Fault as extending south-west from Milford Sound close to the Fiordland coast, but in 1956 Wellman showed it as continuing in a much straighter line so that it diverges from the coast south-westward. This latter direction seems probable from the submarine contours as given by Brodie (1958).

Although Clark and Wellman (1959) do not note cataclastically deformed rocks on the east side of the Alpine Fault north of Milford Sound, Wood (1962) has recognised such rocks as extending across the Sound, and has mapped them (Wood, 1963) for 15 miles to the south-west. He interprets these rocks as having originally been lower Paleozoic rocks, perhaps similar to those of north-west Nelson.

DISCUSSION OF THE ALPINE FAULT

In the foregoing summary of the literature several important aspects of the Alpine Fault have not been touched on. Some will come up in the following discussion of various matters that have not been brought out in published literature, and some speculative suggestions concerning the role of the Alpine Fault in the later geological history of New Zealand will be made.

Cataclasis and Mylonitisation

Defined as the contact between the rocks of the two sides the Alpine Fault is easy to plot on a small-scale map. But in the field it is less clear, because, locally at least, there is a belt of grossly sheared rock up to a quarter of a mile wide whose original character is in doubt. This belt comprises the "dark schists" of Morgan (1908), and is best known from the Poerua to Mikonui Rivers in central Westland, a stretch where the West Coast basement rocks are commonly exposed close to or adjoining the fault. Where thick late Quaternary rocks form the western side the characteristic cataclastic rocks are rarely seen. In outcrops some of the "dark schists" are clearly of western origin, for a transition of rock types can be obtained from gneissic or granitic rock to cataclastically-deformed banded rock with large rolled feldspars. Other dark schists, however, even some adjoining rocks clearly of western origin, appear more likely to be formed from Alpine schist, though the negative evidence of the lack of large rolled feldspars is stronger than any positive evidence. Rather than the apparent eastern origin, these mylonitic rocks may result from a further stage of cataclasis of western rocks. Certainly Morgan (1908: 82, 87–93) favoured an igneous (i.e., western) origin for the " dark schists ", but the possibility of a mixture of the rocks of the two sides cannot be entirely discounted. More recently petrography has not assisted conclusively in deciding the origin of the dark schists, because the general mineral assemblages of the gneissic granite to the west and the schist to the east are not greatly different.

The main fault pugs—greenish or purplish, clayey or gritty comminuted rock —are found along the eastern margin of the dark schists, and mark the band, restricted to tens of feet in width, along which by far the greater part of the present-day movement is taking place. The next rock east of the fault is commonly a schist with crinkled schistosity—the " curly schist " of Wellman (1955b)— or a schist with a foliation rather finer and more broken than normal. There is no doubt that the rocks east of the main fault pugs are Alpine schists.

Elsewhere along the fault, in areas where the western basement rock is not exposed close to the fault, schist rests against fault pug and this in turn against late Pleistocene or Recent deposits. It is certain that, at least along the central section of the Alpine Fault, it is only the schists and not the western rocks that are being rapidly elevated.

Dip on the Fault Plane

Where it has been observed, the fault plane is steeply east-dipping, except beneath the superficial gravity nappes. But observations are rare, applying to only tiny vertical sections, and the superficial nappes themselves prevent inference from the 2,000–3,000ft of vertical height from the major valley bottoms to the ridge crests along the line of the fault.

The near straightness of the fault as mapped in the main valleys encourages a belief in the steepness of the fault plane, for if it were a low-angle thrust from the east it would be necessary for either (a) the west side to have remained stationary with the fault plane cutting the earth's surface in a straight line; but the west side has not remained stationary; or (b) the west side to have been uniformly uplifted or to have been uniformly tilted either north-east or south-west during uplift, along the length along which the fault is substantially straight; this seems most improbable, judged by the Cainozoic history of the West Coast region. Moreover when the region of the major bends is considered it seems easier to postulate a near-vertical fault plane than to postulate two large-scale warpings in opposite directions of an otherwise uniformly east-dipping low-angle thrust plane.

If the 300-mile shift is accepted (and I think it is the most likely answer to the structural problem presented by the geology) then the Alpine Fault would seem necessarily a major crustal feature—Cotton (1956) has suggested using Cloos's term " geosuture " or Sonder's " regmatic joint ". However, an alternative to such a major crustal feature may perhaps be implied in Evison's (1960) concepts of plastic deformation and of a crust lacking in strength adequate enough for continental rocks to rise more than about 10,000ft above an adjacent ocean deep without a slice of the crust of that order of thickness tending to slide off the uplifted area. The detailed application of these concepts to New Zealand's structural development will require careful study by geologists; but in the meantime I will confine myself to more orthodox tectonics.

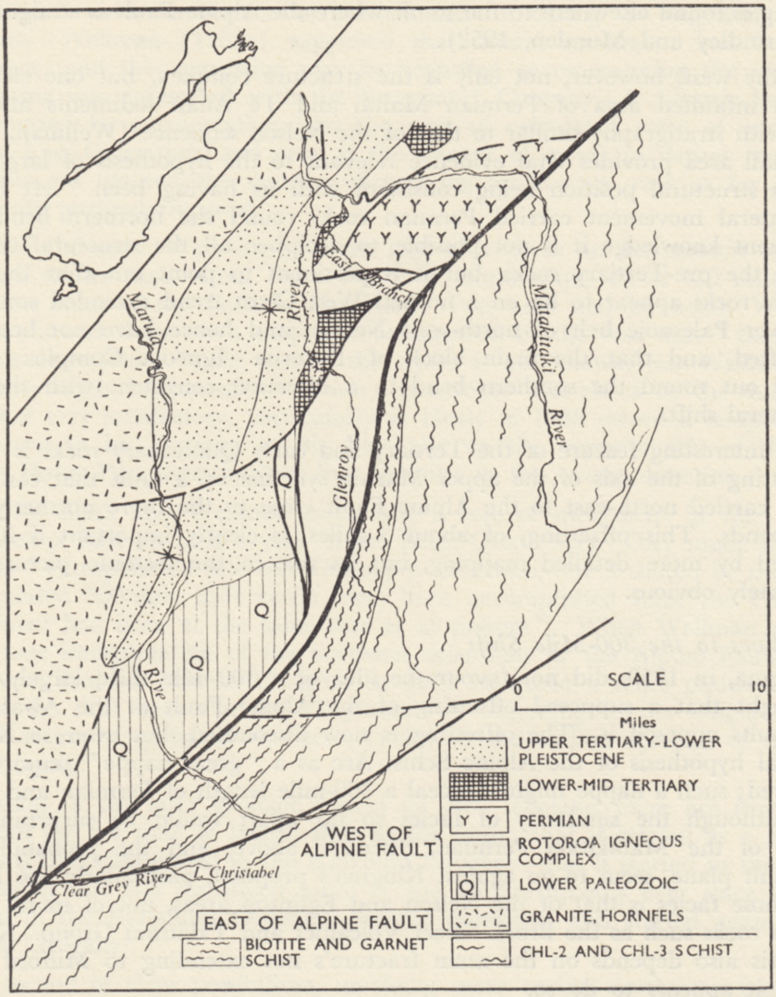


FIG. 6.—Geology adjacent to the Alpine Fault between the Clear Grey and Matakitaki rivers (late Pleistocene deposits omitted). Geology modified from Fyfe (1935), Wellman (1953b), and Suggate, Gair, and Gregg (1961).

Geophysics has indeed an important, perhaps vital, part to play in determining the dip on the Alpine Fault, the most critical area being central Westland, where the fault is substantially straight. We must await the publication of the results of detailed gravity or seismic work, and must hope that the answers are reasonably unequivocal.

The Major Bends

Another question is that of the prominent bends in the section of the fault between the Maruia and Matakitaki Rivers (Fig. 6). It is not unexpected that these bends should be accompanied by complexity of structure adjacent to the fault, but it is perhaps surprising that the complexity should appear to be confined to the west side. For it is not justifiable to consider the offsetting of the schist zones at the Awatere Fault and at a branch of it (Suggate, Gair, and Gregg, 1961) as being connected with the major bend on the Alpine Fault, when similar offsetting is found elsewhere to the south where the Alpine Fault is straight (Wellman, Grindley and Munden, 1952).

To the west, however, not only is the structure complex, but one element in it is an infaulted area of Permian Maitai and Te Anau sediments and ultramafics with stratigraphy similar to that of the Nelson sequence (Wellman, 1953b). This small area provides vital evidence relevant to the hypothesis of large lateral shift, its structural position being consistent with its having been "left behind" when lateral movement carried Permian rocks round the northern bend. With our present knowledge it is not possible to decipher all the structural complications in the pre-Tertiary rocks, but it is pertinent to point out that the Lower Paleozoic rocks appear to lie on a normal West Coast trend extended south from the Lower Paleozoic belt of north-west Nelson, and hence have not been laterally shifted, and that the main block of Rotorua Igneous Complex appears dragged out round the southern bend in a direction consistent with the postulated lateral shift.

One interesting feature of the Tertiary and early Quaternary rocks is the hint of offsetting of the axis of the upper Maruia syncline by a fault that can reasonably be carried north-east to the Alpine Fault close to the more northerly of the major bends. This offsetting, of about 3 miles, is clearly important if it is substantiated by more detailed mapping, but its role in the tectonic picture is not immediately obvious.

Alternatives to the 300-Mile Shift

Kingma, in 1959, did not favour the idea of a 300-mile shift, largely because he thought that a supposed offsetting of the Alpine Fault at the Awatere and other faults opposed it. The offsetting is now discounted, but even so Kingma's structural hypothesis of the Alpine Schist Arc as a "great nappe" requires to be considered; such a nappe might conceal a 300-mile length of Permian and Triassic rocks, although the similarity of facies so far apart would be surprising. The position of the Matakitaki Permian, discussed above, and the probability of a steep fault plane, seem to go against Kingma's proposal, particularly the Permian area, whose facies is that of the Nelson and Eglinton areas, not of more westerly Permian rocks such as the Brook Street Volcanics and Takitimu Group. Kingma's hypothesis also depends on the main fracture's not extending to Milford Sound, whereas it appears to do so.

An ingenious suggestion was made by Schofield in 1960. The Alpine Fault was assumed to be transcurrent, though but little longer than its known South Island length; transverse buckling on opposite sides and at opposite ends of this fault produced the Nelson and North-west Otago synclines. But Schofield needed also to postulate that the fault was active during deposition of the rocks of the New Zealand Geosyncline, so that similar sequences were developed on opposite sides and at opposite ends of the fault. That this similarity occurs at all, and certainly without any evidence of the effects of transcurrent faulting showing in the stratigraphy, is surprising. Of course, the position of the Matakitaki Permian is also most difficult to explain.

It seems that the hypothesis of the 300-mile shift is easier to maintain than the hypotheses of either Kingma or Schofield.

Dating the Movements at the Alpine Fault

Quaternary movement at the Alpine Fault is quite certain, both early Quaternary, when the schist was eroded in enormous quantities, and late Quaternary, when features of the present landscape were displaced; but speculation must largely replace evidence for earlier periods and for dating the beginning of the movement. Wellman (1955a) suggested that lateral movement had begun in the Jurassic, and this suggestion may be regarded as representing the view that its beginning was connected with the Rangitata* Orogeny. A Jurassic beginning was supported by extrapolation into the past of calculated rates of movement since the Last Glaciation, and even if the danger of errors in dating the young movements are ignored the dangers of carrying an average rate so far back in the past are particularly great.

In 1956, however, Wellman gave one hint of a check on the amount of lateral shift at an earlier time—from the presence of lamprophyre dykes 130 miles apart on opposite sides of the fault in the Haast Pass area and in north Westland. Wellman showed these on a map and commented in the text that " these areas may have once joined "; the age of the dykes is not known, but Wellman considered they might be Jurassic or Lower Cretaceous. The check on the shift, however, is not very satisfactory, particularly as Healy in 1938 recorded lamprophyres, these known to be Tertiary, at Big Bay, also on the opposite side of the fault from the Haast Pass lamprophyres but 65 miles in the wrong direction.

In 1959 Clark and Wellman calculated a rate of movement in the Milford Sound area of half an inch a year in the latest Quaternary. They made the comment that " extrapolation into the Tertiary is uncertain, but it should be noted that the postulated 300-mile shift could have been accomplished since the Oligocene if movement had been at the same rate as at present ". When Wellman put forward a new interpretation of the northern extensions of the Alpine Fault at the Tenth New Zealand Science Congress in 1962 he made a more positive suggestion that the shift began in the Oligocene. A beginning in the Oligocene may be taken as implying that it was connected with the earliest stirrings of the Kaikoura Orogeny.

In terms of the later geologic history of New Zealand there are three main possibilities for the time of lateral shift at the fault: that it started as a result of movements that culminated in the Kaikoura Orogeny; that it started in the Rangitata Orogeny and has continued more or less uninterruptedly ever since; or that it started in the Rangitata Orogeny, became quiescent, and started again in the Kaikoura Orogeny.

The second of these possibilities, involving more or less continuous movement, seems improbable; first, because the evidence of the sedimentary record implies a period of relative tectonic calm in the late Cretaceous, extending locally into the Paleocene and Eocene, and secondly because in the mid-Tertiary there was a change in regional tectonic conditions from those causing transgression to those causing regression, though the directional trends in tectonic movement were maintained.

The hypothesis of the 300-mile shift as essentially a Kaikoura Orogeny movement is perhaps the easiest to maintain, because there is no doubt that great movements did indeed take place during this Orogeny. Nevertheless several pieces of evidence or inference are against it. First, the directional trends in sedimentation in the upper Tertiary, when the early Kaikoura Orogeny movements took place, were a continuation of those of the lower Tertiary, at least over much of New Zealand, so that the trend shown in Kaikoura Orogeny movements, con-

* Kingma (1959: 5) revived " Rangitata ", which had been used by Park (1921) with a directional connotation. Kingma identified " Rangitata " with " Post-Hokonui ", a term that he considered misleading, and abandoned the directional for a time implication.

trasting with that of folding during the Rangitata Orogeny as shown by Lillie (1951), did not begin in mid-Tertiary but earlier. Secondly, the Pliocene and early Pleistocene deposits of southern North Island cross the probable extension of the Alpine Fault without any stratigraphic and structural indication of rapid lateral shift. Thirdly, the very difficulty of recognising the Alpine Fault in the North Island, while it must be considered to continue there, is an indication that it is not predominantly a Kaikoura Orogeny feature. Fourthly, in late Quaternary times the lateral movement on the Alpine Fault has been only of the same order of magnitude as on other major faults. It is perhaps the difficulty of recognising Kaikoura movement in the North Island that makes such a timing least easy to accept.

Thus a reasonable case can be made out for the Alpine Fault's being a major tectonic feature of the Rangitata Orogeny. As a feature of this orogeny it fits into place in the period of change from the Mesozoic to the Tertiary sedimentation pattern. The contrast between these two patterns could hardly be greater. The earlier one was geosynclinal in the grand manner; during the latter one, for all its complications, little more than a veneer of sediments accumulated as a result of the ups and downs in a mobile belt. It is not unexpected that the greatest tectonic feature of New Zealand should be associated with the deformation that followed the greatest period of sedimentation.

I envisage this major shear as developing across the declining New Zealand Geosyncline, and also the intimate association of the shear with the development of the eastern basin of Cretaceous sedimentation. The North Auckland Cretaceous basin is then seen as the southern shrinking end of the New Zealand geosyncline, which probably still persisted, though perhaps discontinuously, to and beyond New Caledonia. The paleogeographic interpretation shown on Fig. 7 is based on many sources, notably Wellman (1956), Kingma (1960), Grindley and Harrington (1961), and Fleming (1962).

By making the Alpine Fault a major feature of the Rangitata Orogeny, the "recurved arc" of Macpherson (1946), which is valid for Rangitata Orogeny structures but not for those of the Kaikoura Orogeny, is seen as resulting from that part of the shearing that was not relieved by slip at the fault itself. If this shear were removed, the rather disconcerting bend in the New Zealand Geosyncline would be largely removed also. The diagrams in Fig. 7, therefore, might perhaps have been drawn to undistort the distorted geosyncline in addition to reversing the shift at the Alpine Fault.

The Marlborough-East Coast Faults

Wellman (1955a: 249) stated: "At the north end of the South Island the Alpine Fault branches into the Wangamoa, Wairau, Awatere, Clarence, Kekerengu, Hope-Kaikoura, and Porter Pass faults". Of these the Wangamoa Fault to the north-west of the Alpine Fault, and the Porters Pass Fault to the south-east have not been traced either to the Alpine Fault or to any other fault that reaches the Alpine Fault, although the Wangamoa Fault may perhaps be connected through to the Alpine Fault. Regrettably, moreover, Wellman (1956), Grindley and Harrington (1961), and Lensen (1961) all show the Porters Pass Fault as extending west to the Alpine Fault and east to the North Canterbury coast. The eastward extension shown by Grindley and Harrington and by Lensen is along the Waikari Fault but is no more probable than that of Wellman. No such major fault lines have been traced, and neither the Porters Pass Fault nor the separate Waikari Fault appears more significant than other important faults of Canterbury as a whole, despite Kingma's (1959: 30) special mention of the Waikari Fault.

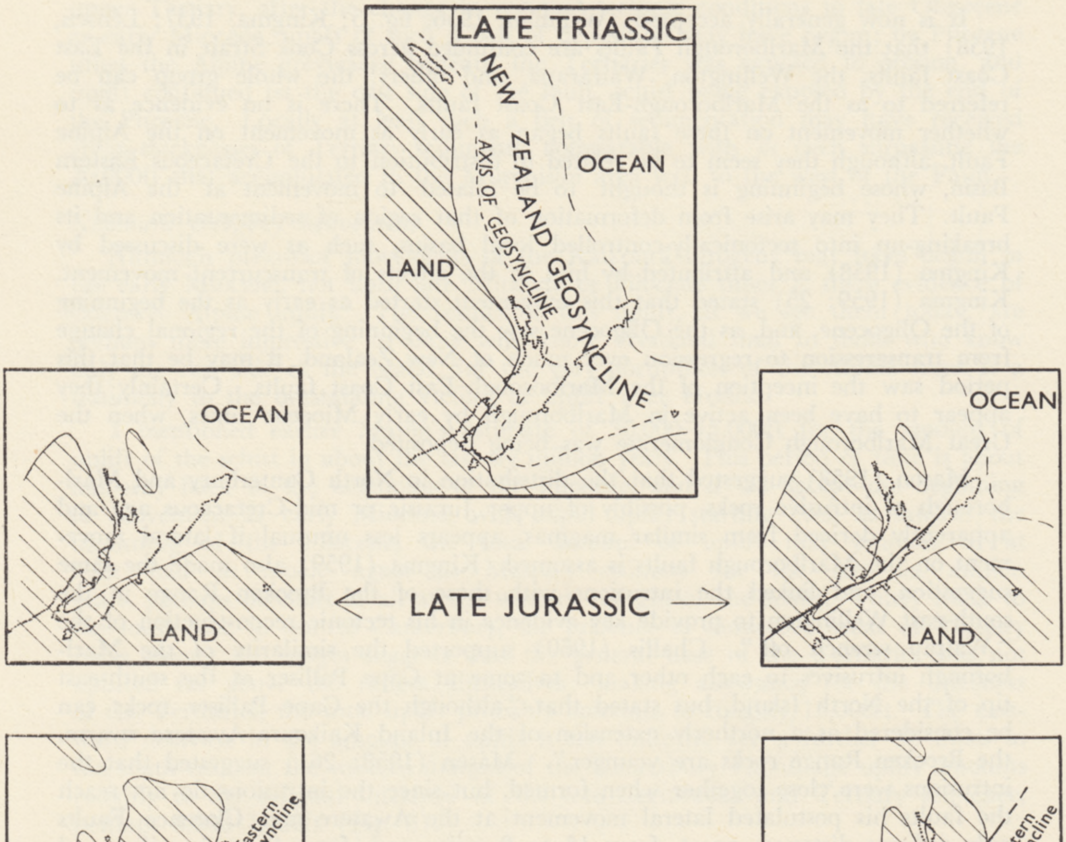


FIG. 7.—Alternative paleogeographic developments of the New Zealand region from late Triassic to the end of the Cretaceous. The sequence shown on the right, involving lateral shift on the Alpine Fault, is preferred by the author.

It is now generally accepted (Wellman, 1956, fig. 5; Kingma, 1957; Lensen, 1958) that the Marlborough Faults are continued across Cook Strait in the East Coast faults, the Wellington, Wairarapa, and others; the whole group can be referred to as the Marlborough-East Coast faults. There is no evidence as to whether movement on these faults began as early as movement on the Alpine Fault, although they seem to be related in distribution to the Cretaceous Eastern Basin, whose beginning is thought to be related to movement at the Alpine Fault. They may arise from deformation of that region of sedimentation and its breaking-up into tectonically-controlled local basins, such as were discussed by Kingma (1958) and attributed by him to the effects of transcurrent movement. Kingma (1959: 25) stated that this movement started as early as the beginning of the Oligocene, and, as the Oligocene saw the beginning of the regional change from transgression to regression over much of New Zealand, it may be that this period saw the inception of the Marlborough–East Coast faults. Certainly they appear to have been active in Marlborough by early Miocene times, when the Great Marlborough Conglomerate was being deposited.

Mason (1958) suggested that the distribution in North Canterbury and Marlborough of intrusive rocks, possibly of upper Jurassic or mid-Cretaceous age and apparently derived from similar magmas, appears less unusual if lateral movement on the Marlborough faults is assumed. Kingma (1959) also made the same suggestion, and linked the intrusions with those of the Brocken Range in the south-east Wellington to provide key evidence in his tectonic reconstruction of the "Wairau wrench off". Challis (1960) supported the similarity of the Marlborough intrusives to each other and to some at Cape Palliser at the south-east tip of the North Island, but stated that "although the Cape Palliser rocks can be considered as a northerly extension of the Inland Kaikoura–Awatere swarm, the Brocken Range rocks are younger". Mason (1958: 261) suggested that the intrusions were close together when formed, but since the intrusions do not reach the faults his postulated lateral movement at the Awatere and Clarence Faults only reduces distances apart from 15 to 9 miles and from 9 to 7 miles, and although the suggested movement at the Hope Fault reduces one distance apart from 66 to 15 miles it also increases the separation of the Cape Palliser and Inland Kaikoura rocks by about 60 miles. Nothing seems to be gained, therefore, by postulating lateral shift.

Thus in the Marlborough area the evidence of large lateral movement can be discounted, and Kingma (1959: 25) has stated that there is evidence "that no exceptionally great horizontal movements have taken place since the Cretaceous along the transcurrent fault zones on the East Coast of the North Island." Nevertheless vertical and lateral movement at these faults is a feature of late Quaternary tectonic activity, and must have been important throughout the Kaikoura Orogeny. The effects of the Kaikoura Orogeny at the Alpine and Marlborough-East Coast Faults will be discussed in a later section (Kaikoura Orogeny Movement).

The Region of the Alpine Fault During the Tertiary

In contrast to the Tertiary sediments on the east side of the South Island those on the West Coast show no evidence of a land area, continuous or discontinuous, roughly along the main axis of the island. The land area inferred from Canterbury and Otago sequences extended over such a distance that even if the 300-mile shift were a Kaikoura Orogeny event, the lack of evidence in West Coast sediments of a land area to the east would remain a problem. The solution may well be that the Alpine Fault controlled a linear, though probably complex, belt in which sediments accumulated, at least in the lower Tertiary. Some time in the upper Tertiary, after the change in regional tectonic conditions in late Oligocene or early Miocene, uplift of such a belt of deposition may have begun; by Pliocene times the Alpine greywacke beneath the Tertiaries was exposed to erosion, and uplift continued on the east side of the fault, schist being exposed by the end of the Pliocene. Locally at least such a belt of sedimentation may have received great thicknesses of Tertiary sediments, comparable with or even surpassing the 20,000ft that accumulated in the Murchison area well to the west of the Fault.

Kaikoura Orogeny Movement

Although precursor movements of the Kaikoura Orogeny may have begun in the early Miocene, not until late Miocene or Pliocene times is there evidence of extensive Alpine uplift. The results of this uplift, as we see them today, are perhaps more impressive to those who know Westland than to those who know only the east side of the island, for the very abruptness of the Alpine front is a testimony to the outstanding victory of uplift over erosion.

I mentioned earlier Mason's estimate of 30,000–45,000ft for the amount of uplift of the schist in about the last six million years. This period of time is about half-way back to the beginning of the Pliocene, and if we accept the beginning of movement as early Miocene, with rapid uplift starting even as late as the beginning of the Pliocene, the total amount of uplift may amount to at least half as much again as Mason's estimate for the last six million years, perhaps 60,000ft in all at the western margin of the schist. Thirty miles to the south-east, in central Canterbury, the presence of numerous areas of Tertiary rocks among the ranges suggests that the general base of the Tertiaries was not uplifted far above the ranges themselves; making allowance for the thickness of the Tertiaries, the total uplift probably amounts to roughly 15,000ft. The eastward decrease in the amount of uplift is not uniform, for a further 30 miles to the south-east, on the western margin of the Canterbury Plains, the uplift amounts roughly to the original thickness of the late Cretaceous and Tertiary sequence, perhaps 6,000–7,000ft (Fig. 8).

If in this central part of the South Island 60,000ft of uplift at the Alpine Fault is anything like right, even allowing for perhaps 20,000ft of the eroded rocks as Tertiaries, a considerable thickness of greywacke must have overlain the schist at the Alpine Fault at the beginning of the Kaikoura Orogeny. For otherwise higher-grade schists would be expected to have been brought to the surface. Consequently the present-day arrangement of the schist zones results from Kaikoura deformation, as indeed their simplicity itself would perhaps imply. The southward widening of the higher-grade schist zones may not be due to greater Kaikoura uplift but to the uplift starting with the schists fairly close to the surface before the Tertiary. In this respect south Westland may be intermediate between Otago, where the schists were at the surface in mid-Cretaceous times, and north Westland, where they are thought not to have been exposed before the end of the Pliocene.

I have mentioned the simplicity of the schist zones in the central and northern part of the Alpine schist belt, this being where the metamorphic grade decreases steadily away from the fault for 20 miles at least. If we accept that in this area the rocks of the New Zealand Geosyncline were isoclinally folded, with or without steeply plunging axes, during the Rangitata Orogeny, and that schistosity is essentially an accentuation of axial-plane cleavage under higher temperatures and pressures, then schistosity in this part of the country will have been steeply-dipping below the folded greywacke even before Kaikoura uplift. Differential uplift alone, greatest near the fault, is all that is then needed to produce the simplicity of the schist zones (Fig. 8).

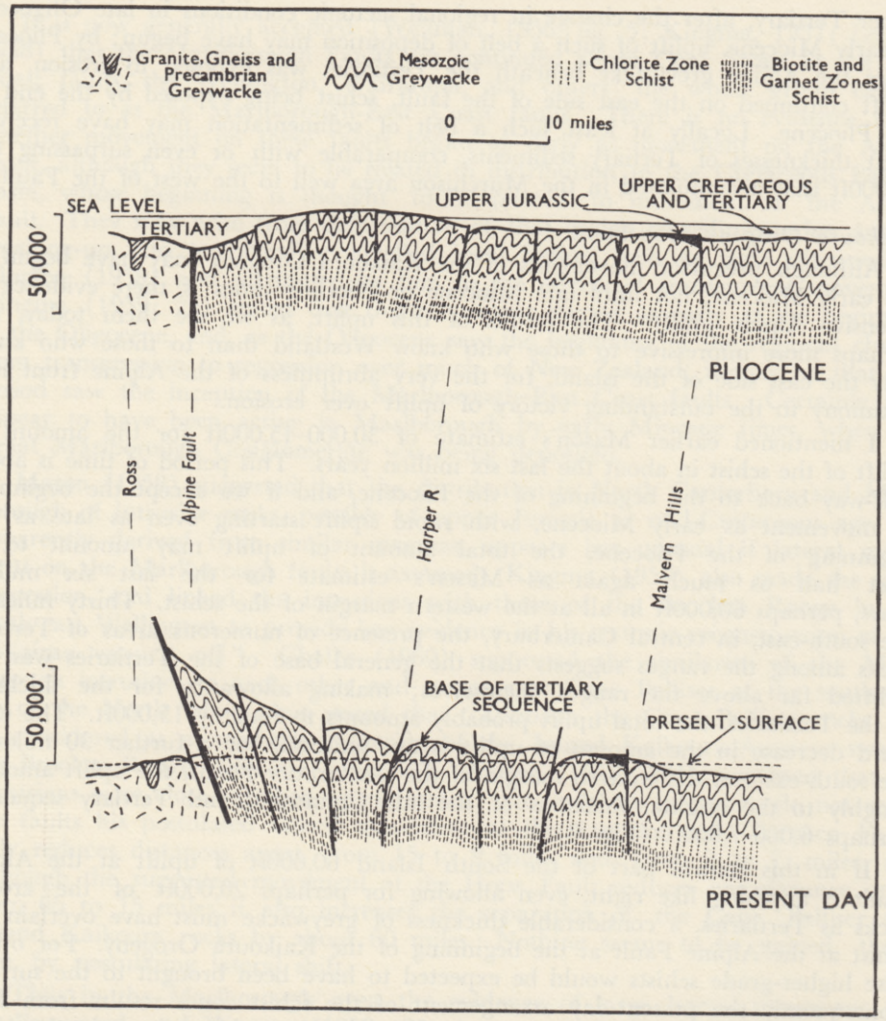


Fig. 8.—Diagrammatic cross-sections through central South Island showing structural development during the Kaikoura Orogeny. Note that the schistosity, shown steeply-dipping both before and after the orogeny, is thought to have developed as an accentuation of an axial-plane cleavage, so that it has never been horizontal in this region of isoclinally-folded sediments of the New Zealand Geosyncline.

In general the schistosity for a few miles east of the central part of the Alpine Fault dips south-east at steep angles, and I take it to be substantially parallel to the dip of the fault itself. If indeed the fault does dip south-east, as the uplift continued on the east side, accompanied by regional (though complex) north-west tilting on the west side, low altitude outcrops of sections of the fault where uplift has been greatest will have apparently moved south-eastwards relative to sections where uplift has been least, the greater the uplift the greater the apparent displacement. There is, perhaps, a hint of this, showing as a south-eastward-facing convexity on the fault line between the Kokatahi River in the north and the Arawata River in the south, where changes in direction of the fault of about 4° takes place (Fig. 9). The middle of this stretch is roughly west of Mount Cook, and here too is about the middle of the length of outcrop of the garnet-

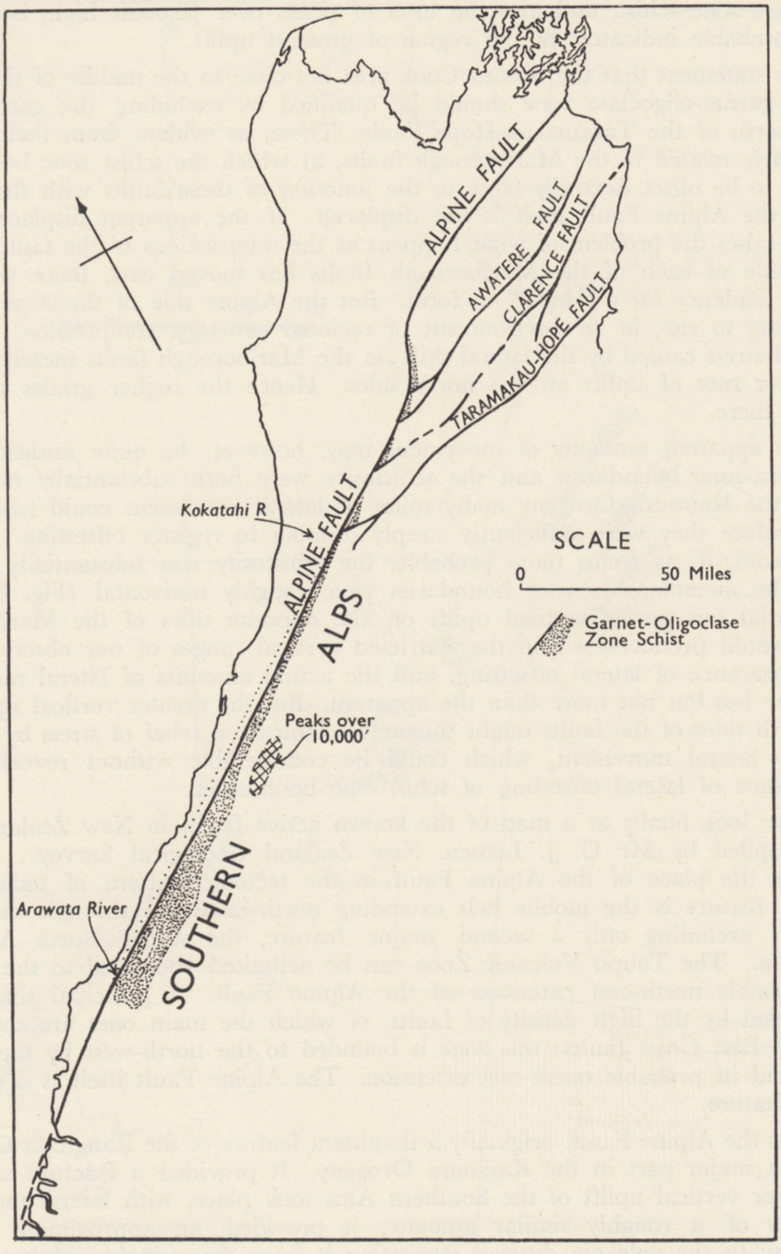


FIG. 9.—Quaternary (Kaikoura Orogeny) uplift of garnet-oligoclase zone schist at the Alpine Fault. The distance between the dotted line and the Alpine Fault is the apparent south-eastward displacement of the fault, resulting from differential uplift of the region on both sides of the fault and the development of a south-east dip on the fault plane (see Fig. 8).

oligoclase zone schist, and also the area of peaks over 10,000ft high, both these being probable indicators of the region of greatest uplift.

The statement that the Mount Cook area lies close to the middle of the length of the garnet-oligoclase zone should be qualified by excluding the garnet zone areas north of the Taramakau-Hope Fault. These, as evident from their shapes, are clearly related to the Marlborough faults, at which the schist zone boundaries appear to be offset dextrally close to the junction of these faults with the Alpine Fault; the Alpine Fault itself is not displaced. If the apparent displacement is real, it raises the problem of what happens at the intersections of the faults; if the north side of each of the Marlborough faults has moved east, there will have been a tendency for a " hole " to form. But the Alpine side of the Alpine Fault is tending to rise, in an environment of regional east-west compression, and the relief of stress caused by the lateral shift on the Marlborough faults merely permits a greater rate of uplift on the north sides. Hence the higher grades of schist appear there.

The apparent amounts of movement may, however, be quite misleading. If the schist-zone boundaries and the schistosity were both substantially horizontal before the Kairoura Orogeny many miles of lateral movement could have taken place before they were sufficiently steeply dipping to register offsetting. On the other hand, if, as seems more probable, the schistosity was substantially vertical while the metamorphic zone boundaries were roughly horizontal (Fig. 8), then differential but purely vertical uplift on the opposite sides of the Marlborough faults would produce—within the restricted vertical ranges of our observations—the appearance of lateral offsetting, and the actual amounts of lateral movement could be less but not more than the apparent. But the greater vertical uplifts on the north sides of the faults might themselves indicate a relief of stress by a tendency to lateral movement, which could be considerable without revealing any appearance of lateral offsetting of schist-zone boundaries.

If we look finally at a map of the known active faults in New Zealand (Fig. 10, compiled by Mr G. J. Lensen, New Zealand Geological Survey), we can consider the place of the Alpine Fault in the tectonic pattern of today. The greatest feature is the mobile belt extending north-eastwards through the whole country, excluding only a second major feature, the stable North Auckland peninsula. The Taupo Volcanic Zone can be delimited—bounded to the east by the probable north-east extension of the Alpine Fault. A principal shear zone is revealed by the high density of faults, of which the main ones are the Marlborough–East Coast faults; this zone is bounded to the north-west by the Alpine Fault and its probable north-east extension. The Alpine Fault itself is a separate major feature.

Thus the Alpine Fault, originally a dominant feature of the Rangitata Orogeny, played a major part in the Kaikoura Orogeny. It provided a fracture at which the major vertical uplift of the Southern Alps took place, with lateral movement probably of a roughly similar amount; it provided an approximate eastern boundary to the volcanic district, separating it from the principal shear zone of the East Coast, extending south to Marlborough. But it is a prime feature related to the others not because it was fundamentally caused by the tectonic processes of the Kaikoura Orogeny, but because the contrasts of the rocks of the two sides and the line of weakness the fault provided were great natural features that inevitably tended to guide the results of those processes.

Although the lateral movement was predominantly a Rangitata Orogeny feature, the vertical movement during the Kaikoura Orogeny is what is so impressive about the Alpine Fault. It may be noted that the idea of separation of

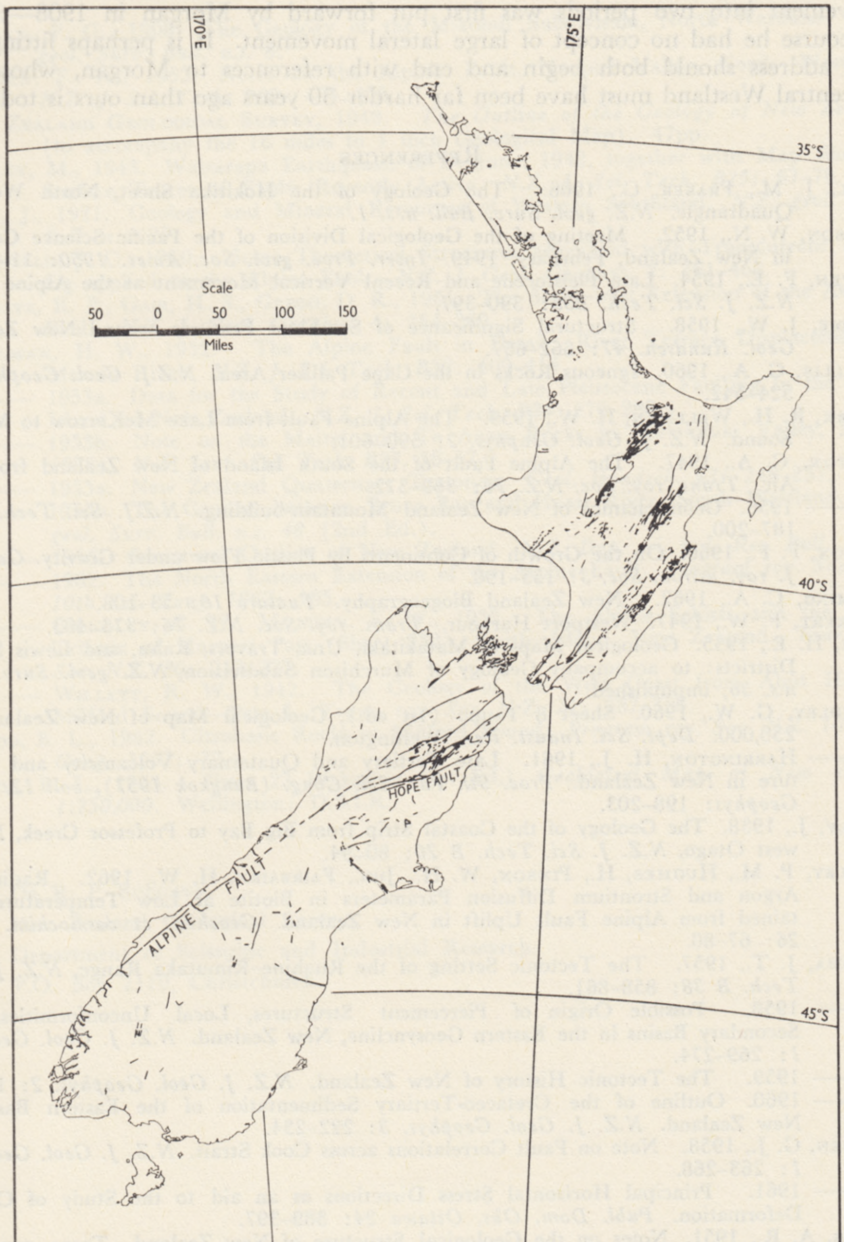


FIG. 10.—Active faults of New Zealand, compiled by G. J. Lensen, New Zealand Geological Survey. All the fault displacements are of late Quaternary age; most are Recent.

movement into two periods was first put forward by Morgan in 1908—though of course he had no concept of large lateral movement. It is perhaps fitting that this address should both begin and end with references to Morgan, whose task in central Westland must have been far harder 50 years ago than ours is today.

REFERENCES

BELL, J. M., FRASER, C., 1906. The Geology of the Hokitika Sheet, North Westland Quadrangle. *N.Z. geol. Surv. Bull. n. s. 1.*

BENSON, W. N., 1952. Meeting of the Geological Division of the Pacific Science Congress in New Zealand, February, 1949. *Inter. Proc. geol. Soc. Amer. 1950*: 11–13.

BOWEN, F. E., 1954. Late Pleistocene and Recent Vertical Movement at the Alpine Fault. *N.Z. J. Sci. Tech. B35*: 390–397.

BRODIE, J. W., 1958. Structural Significance of Sea-Floor Features around New Zealand. *Geol. Rundsch. 47*: 662–667.

CHALLIS, G. A., 1960. Igneous Rocks in the Cape Palliser Area. *N.Z.J. Geol. Geophys. 3*: 524–542.

CLARK, R. H., WELLMAN, H. W., 1959. The Alpine Fault from Lake McKerrow to Milford Sound. *N.Z. J. Geol. Geophys. 2*: 590–601.

COTTON, C. A., 1947. The Alpine Fault of the South Island of New Zealand from the Air. *Trans. roy. Soc. N.Z. 76*: 369–372.

——— 1956. Geomechanics of New Zealand Mountain-building. *N.Z.J. Sci. Tech. B38*: 187–200.

EVISON, F. F., 1960. On the Growth of Continents by Plastic Flow under Gravity. *Geophys. J. roy. astron. Soc. 3*: 155–190.

FLEMING, C. A., 1962. New Zealand Biogeography. *Tuatara 10*: 53–108.

FURKERT, F. W., 1947. Westport Harbour. *Trans. roy. Soc. N.Z. 76*: 373–402.

FYFE, H. E., 1935. Geological Maps of Matakitaki, Una, Travers, Rahu, and Lewis Survey Districts: to accompany Geology of Murchison Subdivision, *N.Z. geol. Surv. Bull. n.s. 36,* unpublished.

GRINDLEY, G. W., 1960. Sheet 8 Taupo (1st ed.), Geological Map of New Zealand 1: 250,000. *Dept. Sci. Indust. Res.,* Wellington.

——— HARRINGTON, H. J., 1961. Late Tertiary and Quaternary Volcanicity and Structure in New Zealand. *Proc. 9th Pac. Sci. Cong.* (*Bangkok 1957*), *vol. 12. Geol. Geophys*: 198–203.

HEALY, J., 1938. The Geology of the Coastal Strip from Big Bay to Professor Creek, North-west Otago, *N.Z. J. Sci. Tech. B 20*: 80–94.

HURLEY, P. M., HUGHES, H., PINSON, W. H., Jun., FAIRBAIRN, H. W., 1962. Radiogenic Argon and Strontium Diffusion Parameters in Biotite at Low Temperatures obtained from Alpine Fault Uplift in New Zealand. *Geochim. et cosmochim. Acta. 26*: 67–80.

KINGMA, J. T., 1957. The Tectonic Setting of the Ruahine–Rimutaka Range, *N.Z. J. Sci. Tech. B 38*: 858–861.

——— 1958. Possible Origin of Piercement Structures, Local Unconformities, and Secondary Basins in the Eastern Geosyncline, New Zealand. *N.Z. J. Geol. Geophys. 1*: 269–274.

——— 1959. The Tectonic History of New Zealand. *N.Z. J. Geol. Geophys. 2*: 1–55.

——— 1960. Outline of the Cretaceo-Tertiary Sedimentation of the Eastern Basin of New Zealand. *N.Z. J. Geol. Geophys. 3*: 222–234.

LENSEN, G. J., 1958. Note on Fault Correlations across Cook Strait. *N.Z. J. Geol. Geophys. 1*: 263–268.

——— 1961. Principal Horizontal Stress Directions as an aid to the Study of Crustal Deformation. *Publ. Dom. Obs. Ottawa 24*: 389–397.

LILLIE, A. R., 1951. Notes on the Geological Structure of New Zealand. *Trans. roy. Soc. N.Z. 79*: 218–259.

MACKIE, J. B., 1962. A project for making Precise Measurements on the Alpine and other Major Faults in New Zealand. *N.Z. Surveyor 23*, 626–655.

MACPHERSON, E. O., 1946. An Outline of Late Cretaceous and Tertiary Diastrophism in New Zealand. *N.Z. geol. Surv. Mem. 6.*

MASON, B. H., 1958. The Intrusive Rocks of the Kaikoura Mountains, New Zealand. *Trans. roy. Soc. N.Z. 85*: 247–262.

——— 1961. Potassium-argon Ages of Metamorphic Rocks and Granites from Westland, New Zealand. *N.Z. J. Geol. Geophys. 4*: 352–356.

——— 1962. Metamorphism in the Southern Alps of New Zealand. *Bull. Amer. Mus. nat. Hist. 123*: 215–247.

MORGAN, P. G., 1908. The Geology of the Mikonui Subdivision, North Westland. *N.Z. geol. Surv. Bull. n.s. 6.*

MUNDEN, F. W., 1952. Notes on the Alpine Fault, Haupiri Valley, North Westland. *N.Z. J. Sci. Tech. B33*: 404–408.

NEW ZEALAND GEOLOGICAL SURVEY, 1948. *The Outline of the Geology of New Zealand* (to accompany the 16 miles to 1 inch Geological Map). 47pp.

ONGLEY, M., 1943. Wairarapa Earthquake of 24 June, 1942, together with Map Showing Surface Traces of Faults Recently Active. *N.Z. J. Sci. Tech. B25*: 67–78.

PARK, J., 1921. Geology and Mineral Resources of Western Southland. *N.Z. geol. Surv. Bull. n.s. 23.*

SCHOFIELD, J. C., 1960. Some Theoretical Structures associated with Transcurrent Faulting applied to the Alpine Fault. *N.Z. J. Geol. Geophys. 3*: 461–466.

SUGGATE, R. P., GAIR, H. S., GREGG, D. R., 1961. The South-west Extension of the Awatere Fault. *N.Z. J. Geol. Geophys.* 4: 264–269.

WELLMAN, H. W., 1952. The Alpine Fault in Detail: River Terrace Displacement at Maruia River. *N.Z. J. Sci. Tech. B33*: 409–414.

——— 1953a. Data for the Study of Recent and Late Pleistocene Faulting in the South Island of New Zealand. *N.Z. J. Sci. Tech. B34.* 270–288.

——— 1953b. Note on the Maitai and Te Anau Rocks in Matakitaki Valley, Nelson (S32). *N.Z. Jour. Sci. Tech. B35*, 36–37.

——— 1955a. New Zealand Quaternary Tectonics. *Geol. Rundsch. 43*: 248–257.

——— 1955b. The Geology between Bruce Bay and Haast River, South Westland. *N.Z. geol. Surv. Bull. n.s. 48* (2nd Ed.).

——— 1956. Structural Outline of New Zealand. *N.Z. Dep. sci. ind. Res. Bull. 121.*

——— 1962. The North Eastern Extension of the Alpine Fault. *Program roy. Soc. N.Z. 10th Sci. Cong. 1962*: 105.

——— GRINDLEY, G. W., MUNDEN, F. W., 1952. The Alpine Schists and the Upper Triassic of Harpers Pass (Sheet S52), South Island, New Zealand. *Trans. roy. Soc. N.Z. 80*: 213–227.

——— WILLETT, R. W., 1942. The Geology of the West Coast from Abut Head to Milford Sound—Part I. *Trans. roy. Soc. N.Z. 71*: 282–306.

WOOD, B. L., 1962. Ultrabasic Rocks at Milford Sound. *Program roy. Soc. N.Z. 10th Sci. Cong. 1962*: 72.

WOOD, B. L., 1963. Sheet 22 Wakatipu (1st Ed.) *Geological Map of New Zealand 1:250,000.* Wellington: D.S.I.R.

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