The Bones of our Mountains

Aoraki / Mt Cook National Park

Bruce Waterhouse

GLOBAL GEOCHRONOLOGY IN PERIODS (not to scale)		**EVENTS IN AORAKI MT COOK NATIONAL PARK**	
QUATERNARY Holocene, Pleistocene			
CENOZOIC		Kaikoura Orogeny starts	
CRETACEOUS		Rangitata Orogeny ends	
JURASSIC		Rangitata Orogeny starts	
TRIASSIC	UPPER	MALTE BRUN GROUP Frind Ftn Aiguilles Rouges Ftn Barkley Ftn Walpole Ftn	MANNERING GROUP Baker Ftn
	MIDDLE	Chudleigh Ftn	Acolyte Ftn
	LOWER	Novara Ftn	
PERMIAN	UPPER?		LIEBIG GROUP Burnett Ftn
	MIDDLE		Rose Ftn
	LOWER		Wheeler Ftn
CARBONIFEROUS			

Correlation Table. Hard rock formations and groups in the Aoraki Mt Cook National Park Group, set against the International Time Scale. The periods concerned range from Carboniferous to Cretaceous, and their international time ranges are provided in the Illustrated Glossary. The Cenozoic is of comparable duration to these periods, but is treated as an era, and the Quaternary is very short, but is also treated as an era, because they both are known in much finer detail than the older periods. The match is highly provisional, because few fossils are found in most of the formations (abbreviated to Ftn).

THE BONES OF OUR MOUNTAINS

In the Aoraki Mt Cook National Park

by Bruce Waterhouse

Frontispiece. Aoraki Mt Cook from the lower Hooker valley.

Earthwise 13
ISSN (PDF): 3021 - 2111
ISSN (print): 1176 - 1555
ISBN 978-0-9864601-1-3-5
Date of publication November 2015

25 Avon St., Oamaru, New Zealand 9400

List of Contents

INTRODUCTION

This book provides an illustrated overview of the mountains and the older rocks which shape them in the Aoraki Mt Cook National Park, how and when the rocks were formed under the sea, the order in which they accumulated, and their likely sources, as a presentation of what is called stratigraphy in geological science. And how and when those rocks were caught up in later mountain building. Rocks that develop as beds under the sea normally lie almost flat as vast sheets, whereas the rocks of the Aoraki Mt Cook National Park are steeply inclined – they stand on their heads – which offers a challenge to geologists and to climbers accustomed to climbing in many other parts of the globe. The study does not enquire into recent glacial deposits and structures – that is a vast topic deserving of a separate volume, but does explore active faults and folds and touches on a different mountain massif that existed not so long ago.

The approach is centred on actual rock, that may be stood on and inspected. It starts with mountains to be seen from the Hermitage area, and travels around the Park to look at different kinds of rocks in different settings. There are three major kinds of rocks – all similar in that they were laid under the sea, but derived from different sources, and revealing different characteristics. With that established, at least provisionally, the faults and folds in the rocks can be better appreciated and interpreted. A glossary explaining or illustrating some of the terms and concepts is at the end of the book. Geological maps and a generalized time-table for the rocks and mountain building are placed at the end of the text, and the index summarises page and figure references to the place-names, peaks, glaciers and valleys.

Chapter 1

GEOLOGICAL PLACES OF INTEREST AROUND THE PARK

This first section looks at individual examples of geology around the National Park, starting at the Hermitage, and taking in the Mount Cook Range, Sealy Range and Mt Sefton, then on to the lower Tasman Glacier, Aoraki Mt Cook and west wall of the Tasman Glacier, the Malte Brun Range, Grey Glacier and ending in the Murchison valley and Liebig Range, as summarized in Fig. 1.1

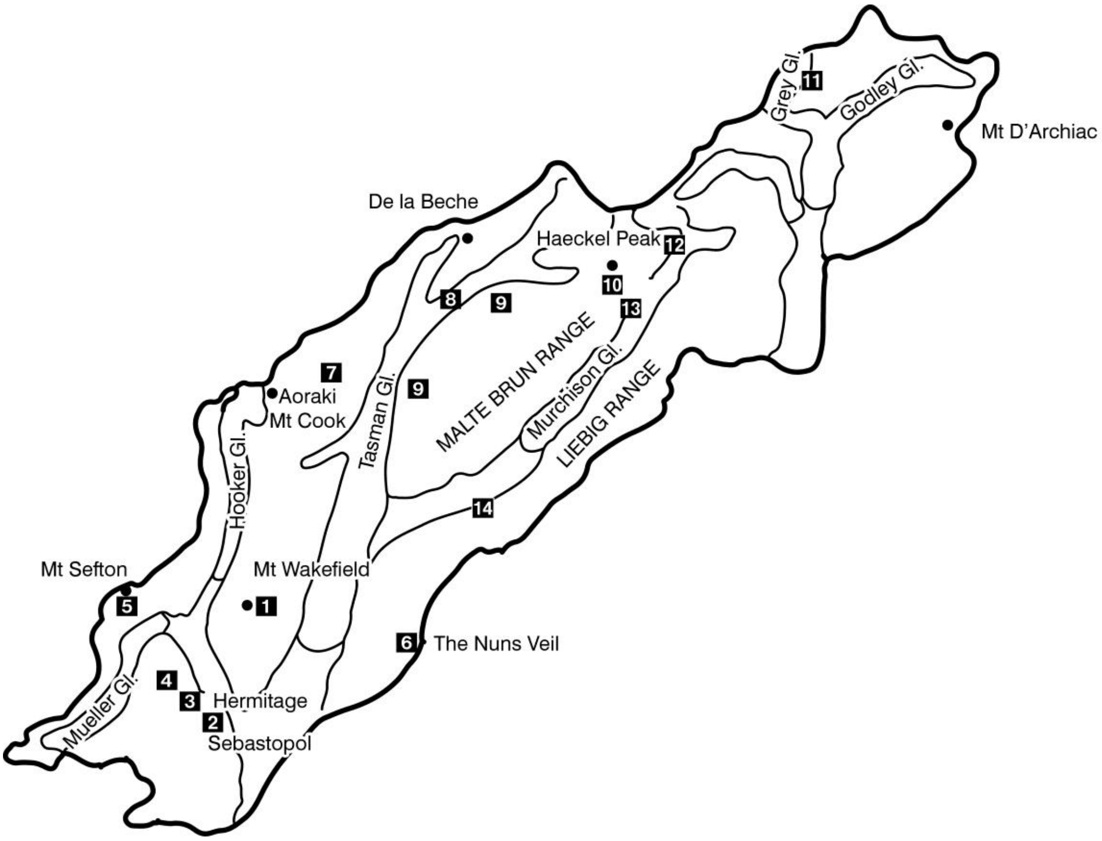


Fig. 1.1. Sketch-map of the Aoraki Mt Cook National Park, showing by number some of the places of geological interest, which are discussed and illustrated in the following text.

THE HERMITAGE AREA

Mt Wakefield (1)

Across the Hooker Valley, looking from The Hermitage and Aoraki Visitor Centre, lies Mt Wakefield. Towards the peak, the lines of rock left by the beds are curved, folded into what is called a syncline, in which the oldest beds lie on the outside, and younger rocks towards the inside, as outlined in the Glossary, p. 146. The Wakefield syncline is unusual[1]. Most synclines and their opposite structure called anticlines are subhorizontal, whereas this syncline stands almost vertical (Glossary, Fig. 10.4, p. 143). That is a common feature of the folds in the Aoraki Mt Cook National Park. The folds are described as steeply plunging, and further examples are provided in Chapter 3, which discusses the cause of such steep plunges, and why they are unusual. To the right of the Wakefield Syncline are black rocks, as illustrated, illustrating a "marker" band.

Fig. 1.2. Mt Wakefield (W), the peak on the skyline to the left, as viewed from the area of the Park headquarters and The Hermitage. The beds seen as layers at a are inclined steeply to the left, and beds (b) are inclined more gently the other way, and slope away from the viewer. To the right along the ridge crest are beds of the Acolyte Formation, illustrated in the next figure.

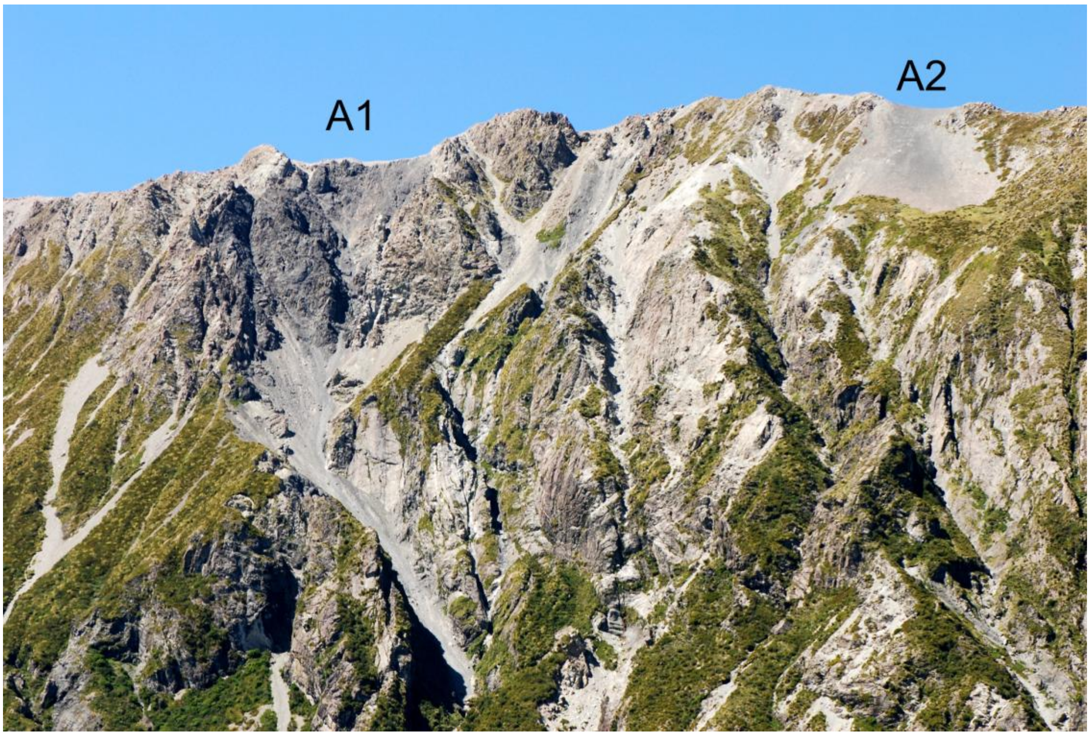


Fig. 1.3. To the right along the sky-line from the peak of Mt Wakefield lies black rock in two bands A1 and A2, made up of fine silty and muddy rock. This thick black rock is easily recognized at a distance, through binoculars if need be, and so is useful for reconstructing the bones of the mountains. It is what is called a “marker band”, one of the few available in the park, and shows that the rocks of Aoraki Mt Cook National Park are not as “monotonous” as claimed. These particular thick bands of black argillite, with accompanying thick sandstone, are referred to the Acolyte Formation[2].

Beds and deposits under the sea (2)

Fig. 1.4. Beds exposed at Black Birch Stream, just across the bridge, to demonstrate strike, dip and younging. **see cook22**

One thing we had better understand right from the start – you may know it already, but many regard it as unlikely, or at least surprising. Well it is surprising, but true. All of the rocks of the Aoraki Mt Cook National Park were formed at the bottom of the sea, in layers called beds or strata, that spread for 10 to 100km or more over the sea-floor, made up of sand and mud that had been washed into the sea during storms especially, and then slowly settled out in calmer deeper water. The nearest beds for inspection at the park lie near the bridge across Black Birch Stream. They are no longer horizontal, but have been tipped up, and the edge of the beds, exposed by the stream, runs along the strike, and the beds are tilted, to indicate dip.

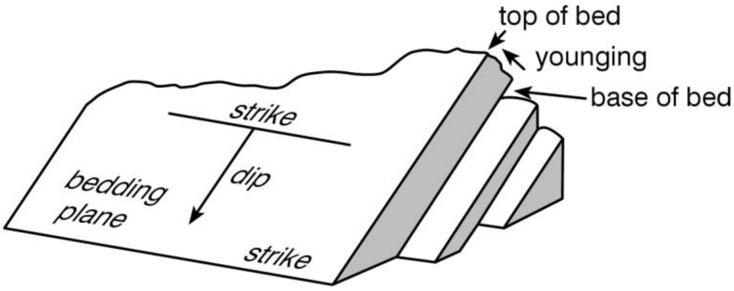


Fig. 1.5. Beds deposited on the sea-floor as more or less flat sheets have been tipped up, and show “strike” and “dip”and “ÿounging”.

There is one more feature. If you look carefully, you will notice that coarse grained sandstone passes gradually into black fine mudstone or siltstone. This is natural: on the sea-floor: the coarser heavier material naturally settles first through the water, and is followed, over a longer period, by the finer material. This is called grading or facing, and the direction of grading is said to indicate younging, as showing the direction in which the sediments gradually become younger, by perhaps only a few years. If all the beds were flat and largely in their original position, there would be no worry about finding the direction of younging. Where rocks have been tilted steeply, faulted, squeezed, and distorted by mountain-building, younging can be very useful for unravelling past distortions, and learning of original dispositions. But science and nature are never simple, because there can be reverse grading, where there has been an influx of coarser sediment, so that beds "young" against the direction of grading.

Hermitage rocks (3)

Above The Hermitage to the west, where the water storage tanks are, and making up the rounded massif of Sebastopol and its fore-knob, are different rocks. There is no sign of the black rock of the Wakefield ridge, which may have been squeezed out by mountain-building. The rock is remarkably jagged and steep, yet seems to endure well, standing at a very steep angle. Whereas the black rock of the ridge south of Mt Wakefield is made up of fine material – mostly mud and silt, these rocks are made up of coarse grains of sand, forming sandstone.

Fig. 1.6. Massive sandstones on Mt Sebastopol and behind or west of The Hermitage. The letter s indicates the Sebastopol Member and u the Unwin Hut Member, belonging to the Acolyte Formation, as described on pp. 54-55.

Great Groove Fault (4)

There are many faults in the park, visible today as steps or breaks in the slopes of mountain sides, and as steeply inclined straight-line fissures through the rock. Some examples are illustrated in Chapter 2. The nearest obvious fault to The Hermitage is the Great Groove Fault[3], in which the eastern side has moved upwards by one to two metres, to form a trench passing along the Sealy Range into the Ben Ohau Range. In places the trench has trapped water in small tarns or ponds, as may be seen along the track leading up the hill-slope to Mueller Hut at the Sealy Tarns. Such faults are related to the Alpine Fault, shown in Fig. 10.1, p. 135, which lies west of the park, and started rupturing a few million years ago. The faults of the Aoraki Mt Cook National Park are comparatively recent in origin, many not even a million years old, and criss-cross the rocks of the Park, mostly lying in a northnortheast and southsoutheast direction. The best example is found in the Malte Brun Range (see Fig. 1.15, p. 12). And there are other hidden faults, of much greater age, as discussed in Chapter 6.

The fact that it is the valley side of the fault that has moved upwards could suggest that maybe the melting of ice – the loss of the glacier hundreds of metres thick, would have reduced the weight pressing down on the valley, and allowed the rock to move upwards. Climate, including glaciation, and other events influence faulting and distortion, probably to only a minor degree. In this case, the Great Groove Fault persists southwards for a long distance through the western side of the Ben Ohau Range, well away from the glacier, so that mountain building would seem to have been the main and perhaps only agent.

Fig. 1.7. Along the track to Mueller Hut, a tarn or pond, one of the Sealy Tarns, is formed by water trapped between the down-thrown western side of the Great Groove Fault, and the upthrown eastern or Hooker valley side. The Hooker Glacier and Mount Cook Range lie in the background.

Mt Sefton and the schist divide (5)

Mt Wakefield and the Sebastopol rocks are humble accessories to the dramatic partly ice-clad face of Mt Sefton and the Main Divide ridge to the west. The rocks are less uniform that those of the black band west of Wakefield, or the green sandstone behind The Hermitage. Numerous layers can be seen, black and shades of brown and grey as a rule, with yellow or orange staining in patches. Rocks towards the top of Mt Sefton are amongst the youngest of solid rocks in the park, and they display one extra special feature – they are made up of schist, which is a metamorphic rock, as illustrated on pp. 8 and 9. Schist is rock that has been metamorphosed or changed from ordinary rock such as sandstone or mudstone under shear strain into a softer rock easily split apart, and so is not very strong in some directions. The mineral mica, or related mineral, has grown along closely spaced layers, under great pressure, often related to faulting or deep burial. During and after metamorphism, the rocks have not only become schistose, but have been subject to folding and intricate refolding, and the thick bands of schist which make up Mt Sefton continue to the north, taking in the peak of La Perouse and rocks further west beyond the Park boundaries[3].

Fig. 1.8. The east face of Mt Sefton, as viewed from The Hermitage. The north end of the Sealy Range lies in the foreground, showing Sebastopol Member (s, S) with brown or orange patches and older rocks.

Fig. 1.9. Detail of schist rock, showing the fine layers due to reoriented and newly grown minerals under shear strain or directed pressure. This sample is from the Walpole Formation in the Mueller valley. Scale bar 1cm long.

Fig. 1.10. Surface view of schist (the same sample as in Fig.1.9). Note the silky or lustrous appearance.

TASMAN VALLEY

The Acolyte Formation in the lower Tasman valley (6)

Drive and walk to the viewpoint on the lateral moraine above the Tasman glacial lake, or any nearby station. Across the valley lie several thick bands of black rock. These are made up of siltstone, mudstone and fine sandstone, deposited under the sea. The

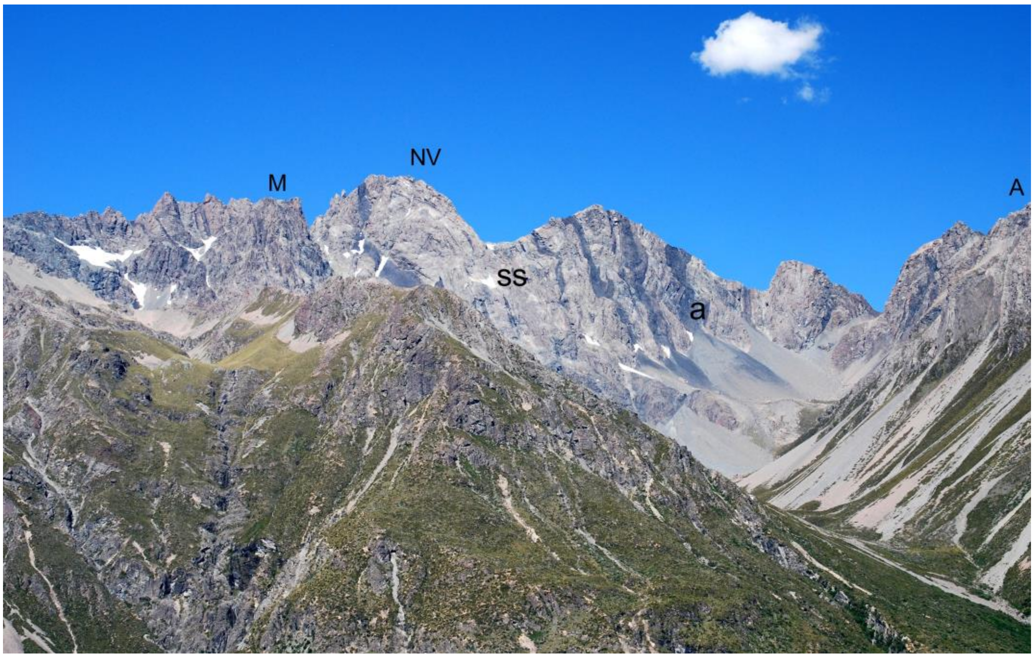


Fig. 1.11. The bands of thick black mudstone, also called argillite or claystone (a) and greenish sandstone (ss) of the Acolyte Formation, which makes up the sky-line ridge. Also showing Biretta Peak (M), The Nuns Veil (NV), and The Acolyte (A), looking across the Tasman Valley.

beds of black argillite are just the same as those near Mt Wakefield (Fig. 1.3), and so demonstrate that they are good marker bands. We know their approximate age, because such rock is widespread through the Southern Alps, and the rocks contain fossils[5] of Middle Triassic age (Table, inside front cover). In between the black argillite bands are equally thick or thicker bands of coarse greenish sandstone, like the sandstones towering above The Hermitage. The two rock types are grouped as Acolyte Formation, named after The Acolyte, a peak near these particular rocks. Whereas the black rocks are soft, and can easily be squeezed, the green coarser rocks are solid and tough, but break apart rather than flow, and the two rock types have slid and been deformed into complicated shapes, as illustrated in Fig. 7.43, p. 107.

Fig. 1.12. Black argillite and greenish sandstone typical of the Acolyte Formation, on Botanical Spur west of The Acolyte.

Folds in the Park: the Zurbriggen ridge folds (7)

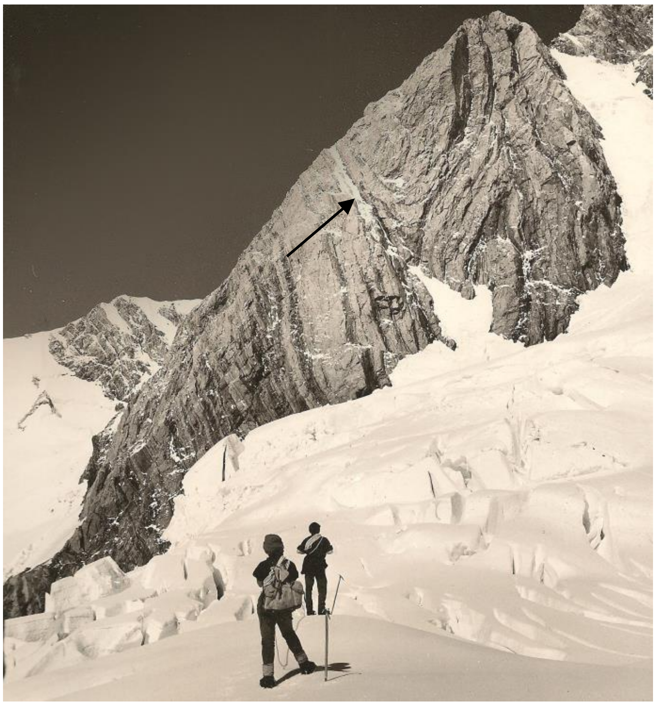


Fig. 1.13. Lower Zurbriggen ridge of Aoraki Mt Cook at the Grand Plateau. Here are two beautifully clear folds, a syncline (arrowed) and a squeezed anticline to the right, facing northeast towards the camera[6]. Photo D. L. Homer.

Rocks of the Aoraki Mt Cook National Park are Permian to Triassic in age, almost 300 million years to roughly 200 million years old, as we know from comparisons with other better dated rock around the globe. The rock has endured two prolonged episodes of mountain building, when rocks were squeezed and faulted under great pressure, and over a lengthy span of time, rocks have been folded, just as though they were blankets. The present mountains date from the younger mountain-building phase, called the Kaikoura Orogeny. The older mountain-building took place during the Rangitata Orogeny, and although those mountains have long been worn away, traces of their structures are preserved in the rocks (see Chapter 6).

De la Beche chert (8)

A rare rock type is found north of De la Beche corner just above the Tasman Glacier. It is made of narrow bands of flint or chert[7], a pure quartz rock solidified from a gel on the ocean floor, and probably formed from hot submarine springs. It used to lie along a track leading north to the Tasman Glacier, which we would take on our way to Elie de Beaumont and other peaks in the upper Tasman Glacier. Last time I looked, it seems to have disappeared, buried by scree. But times change, and the rock may be revealed again by further erosion.

Fig. 1.14. Chert, a rare outcrop of siliceous rock with colour bands, closely folded soon after it was formed.

MALTE BRUN RANGE

In the Malte Brun Range, there are several geological treasures which show geological features exceptionally well. Here there is less ice than to the west along the Main Divide, and so more rock is exposed. What is more, the weather is better than over the Main Divide. So although the peaks are lower, and are less popular with mountaineers, and less scenically distinguished, the advantages of weather and exposure of rock allow the Malte Brun Range to be the focus of geological study more readily than the Main Divide. The rocks are very complexly arranged, but have provided the template and exemplar for the rocks and geological features of the Park.

Beetham Fault (9)

The Beetham Fault[8] is best seen from the air, and is visible from the Grand Plateau and from the end of the trail to the Ball Glacier. The fault extends along the western side of the Malte Brun Range, and divides older rocks to the west from younger rocks to the east, and is a left lateral fault, meaning that rocks on the west – or left side of a person looking at it from the right, have moved to the left, or south (see Fig.10.6, p. 145). Contrariwise, someone standing on the west side of the fault also sees the rocks as moving left, yet to the north. This direction is unusual for New Zealand faults. The great Alpine Fault is a right lateral fault – the rocks of the western South Island have moved north – to the right, from a viewpoint in the eastern South island. The Wellington Fault along the west side of the Wellington harbour is the same. But the Beetham fault has moved westerly rocks to the south, not north, and even displaced valleys such as the Walpole Stream. It tracks south to enter the Tasman Glacier under Novara Peak, but whether it crosses the Tasman Glacier is not certain, though it may enter the southern end of the Mount Cook Range. A little more detail on the movements has been provided in a sketch in Fig. 2.2, p. 20. The direction of movement, opposite to that along the Alpine Fault, points to counter forces developing locally. As well as lateral or horizontal movement, there has been at the same time vertical movement over recent years, the rocks to the west being upthrown against rocks to the east, as shown below in Fig. 1.16.

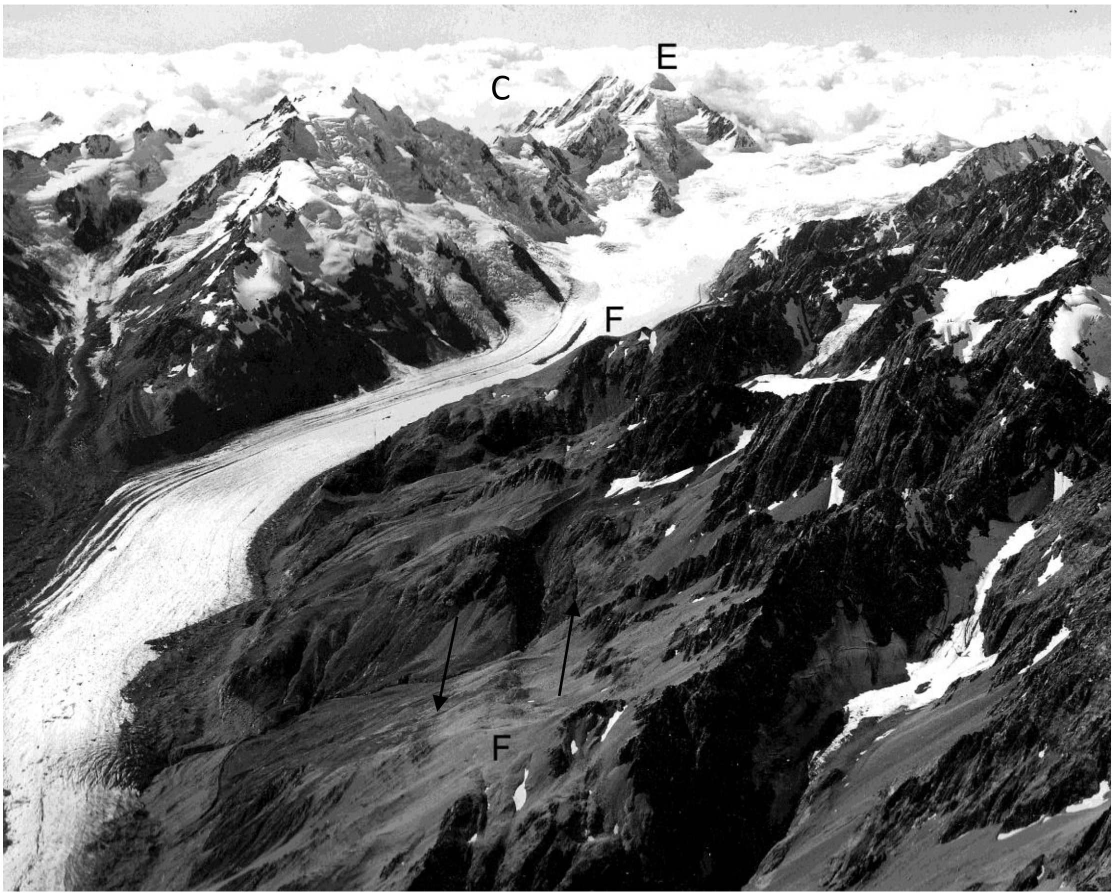


Fig. 1.15. The Beetham Fault F - F, passing through the landscape along the west side of the Malte Brun Range, and moving rocks in a left lateral sense, as arrowed. The active fault if projected north, would seem to pass across the Tasman Glacier into Mt Elie de Beaumont (E), but the fault stops well short of this mountain, or, as a possibility to be explored, swings to the left (west) just south of Coronet, through Climbers Col (C) below C. Photo D. L. Homer.

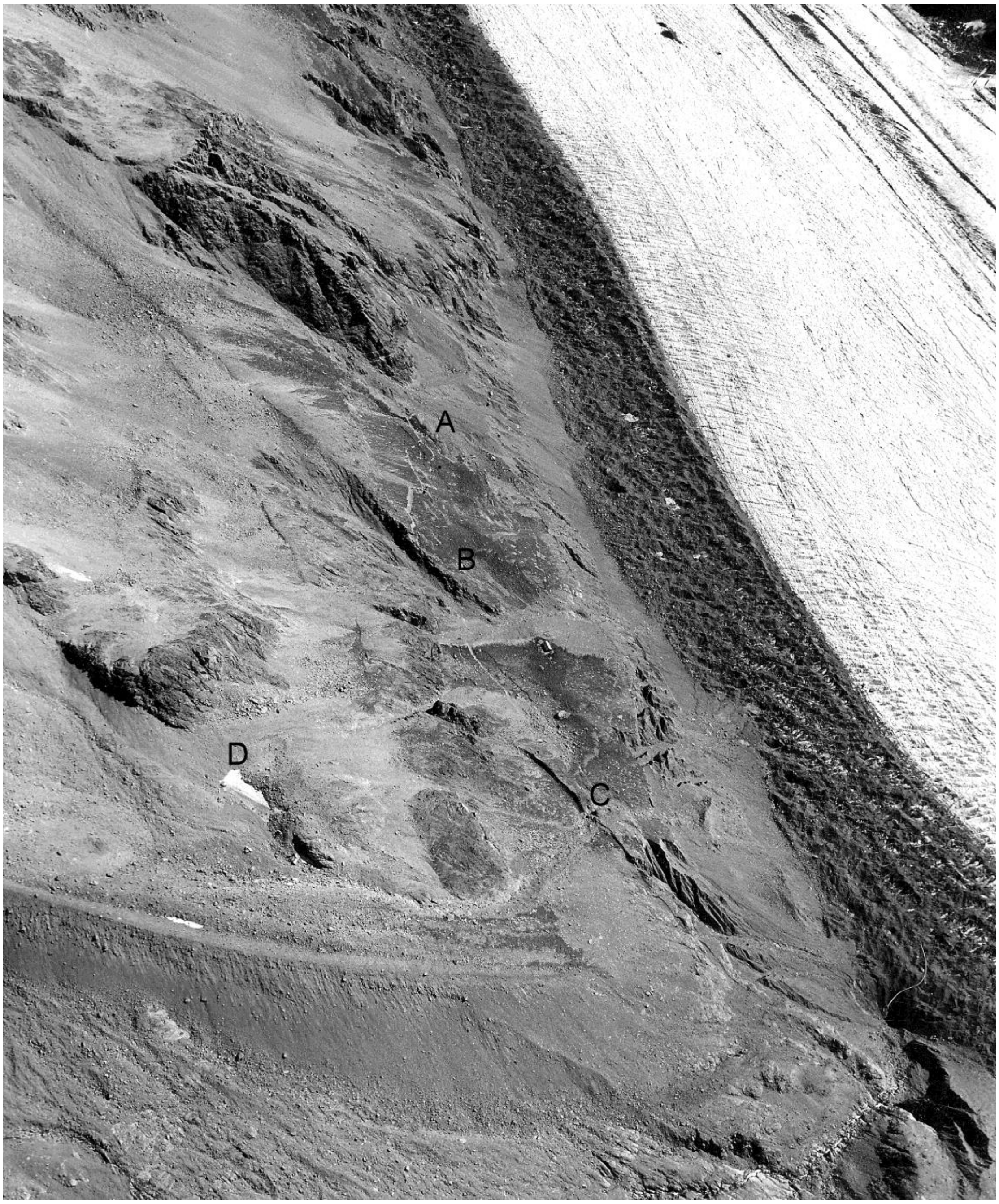


Fig. 1.16. An outstanding aerial photograph of the Beetham Fault at its northern end in the Malte Brun Range, where it meets the south-moving Tasman Glacier, showing that the fault complex has been recently active. Recent fault traces (A, B, C, D) enter the Tasman Glacier (to the right), and splinters at different angles lie between the traces, with several other scarps visible. Other fault-scarps lie further south. The most fascinating aspect is that the fault scarps disturb geologically young and thin fan and moraine deposits. Photo D. L. Homer.

Haeckel Syncline (10)

Folds occur everywhere throughout the park, and were first described by Julius Haast and later by James Park along the western side of the Tasman Glacier, below Mts Dixon and Haidinger. The finest example of an Aoraki Mt Cook fold is shown over the southwestern face of Haeckel Peak, at the head of the Darwin Glacier[9].

Fig. 1.17. Perhaps the most striking syncline in all New Zealand may be seen on the southwest face of Haeckel Peak, at the head of the Darwin Glacier, photographed from Mt Darwin, with Mt Hutton in the distance. The fold is nearly 1km across and high, and has smaller subsidiary and sympathetic folds on both sides, especially the north (to the left). At first sight, the fold could be an ordinary fold, but in fact it is steeply plunging away from the observer. This is my original photograph, now somewhat the worse for wear. Subhorizontal gigantic cracks (such as K - K) run across the face of the mountain, apparently without disturbing the rocks very much. Such cracks developed widely during the compression of beds into folds. They can be closely studied as an aid to understanding the direction of pressure and the nature of deformation, used especially where folds themselves are not so well exposed as in this example.

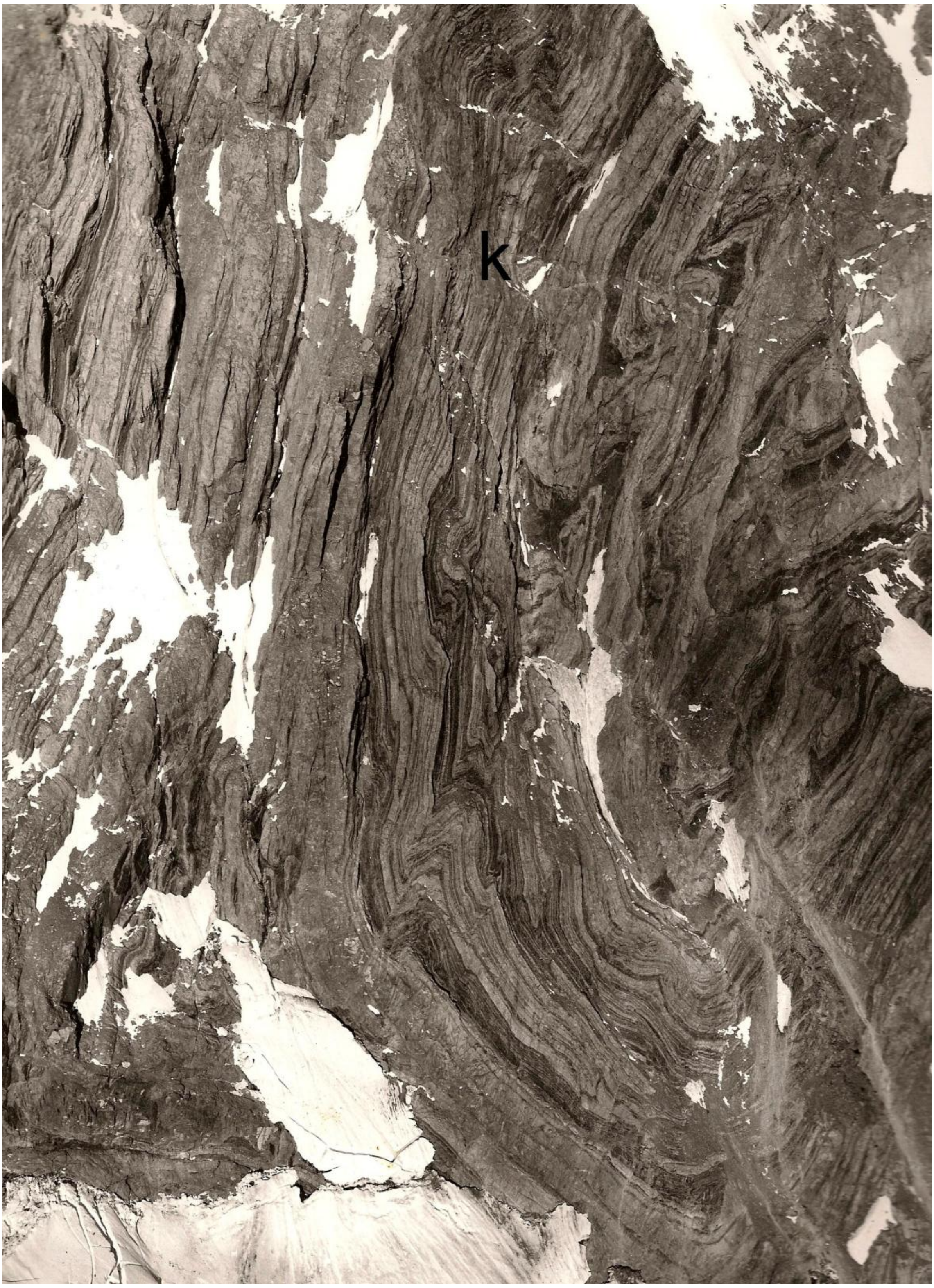


Fig. 1.18. Close-up view of part of the Haeckel Syncline on Haeckel Peak, showing in detail some of the intricacies in deformation, including an adventitious syncline to lower left. One of the substantial subhorizontal cracks is signalled by k, and another crack lies above. Photo D. L. Homer.

Grey Glacier (11)

Yet another striking series of folds is exposed along the western wall of the Grey Glacier, immediately below the peaks of Alamein and Takrouna. These folds are smaller than the huge Haeckel fold. Discovered in 1953, they are shown in a photograph by John Harrison in the book on his life by John Wilson[10], called "Joy of the Mountains". Their nature strongly suggests that they were formed when sediment was not fully consolidated into hard rock. The potential causes are mutiple: an earthquake, a sudden lowering of sea-level, or collapse of undersea sediments due to gravity. Or, as suggested later in Chapter 6, p. 70 ff, the sliding seawards of huge masses of sediment at the start of mountain building.

Fig. 1.19. Western wall of Grey Glacier under the peaks of Alamein and Takrouna. Photo John Harrison.

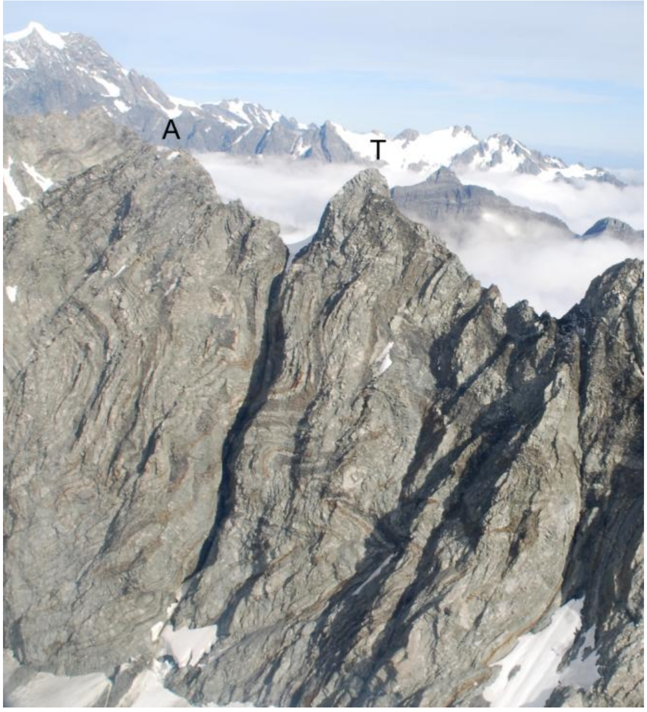


Fig. 1.20. Detail of folds in Rose Formation on the west wall of Grey Glacier below peaks of Alamein (A) and Takrouna (T), with Mt Elie de Beaumont at upper left. The small snow and ice-sheets shown in John's photo taken in 1953 have melted by the time of 2015.

MURCHISON VALLEY

Murchison Hut schist (12)

Much of the rock in the National Park has been hardened, so that sand has turned into sandstone, and mud has become mudstone or argillite. Sediment can be altered by deep burial, and may be squeezed by folding and faulting to subtly change the rock into schist, with the introduction of minerals called micas and zeolites. In a few places, the pressure has been so great that rock grains have been elongated in the direction of least resistance, so that they readily split or cleave along cleavage planes, and veins of quartz have grown along the cleavage planes. At the New Zealand Alpine Club hut in the upper Murchison valley, there are outcrops of schist. The greatest amount of schist in the park is found at less accessible parts, including Mts Sefton and La Perouse, where rocks are finely bedded schist that is flaky and breaks all too readily, as FitzGerald found on Mt Sefton, when he fell off, to be saved by the rope attached to his companion. The Sefton schists show a simple lineation of minerals (Fig. 1.9, p. 8), but near the Murchison hut as on Mt La Perouse[4], the lineations have been intricately folded.

Mannering Lake folds (13)

At the end of the ridge leading south from Mt Cooper, there is a small lake just above the Mannering Glacier, shaped by the glacier when the ice was thicker. The ice has carved and polished the rock to reveal some spectacular small scale folds. These folds are not like those of the Haeckel fold in their symmetry or origin: they indicate slumping of soft sediment a short time after it was deposited on the sea-floor, rather than great pressures under mountain building or faulting.

Fig. 1.21. Folded rock near the Mannering Glacier, east Malte Brun Range, formed under submarine slumping before the black-coloured mudstones between the lighter coloured sandstones were completely consolidated. Enterolithic folds are indicated by the double arrow. Photo David Waterhouse.

Liebig red rock (14)

On the east side of the lower Murchison valley, in the second side valley below the Liebig or Forestry hut, is thick red rock, made up of argillite, formed by washing off sediment from lava. Well, we will call it red, though maybe it is a rich brown, or purply red. There are subtle terms applied by geologists to rock colours, and no doubt artists or at least some of them, would apply different terms. But red will suffice. Red rock is further discussed on p. 46 ff.

Fig. 1.22. Red argillite as arrowed in the lower Murchison valley, in the Liebig Range. This red rock forms a "marker band", and so allows the rocks to be surveyed and traced over great distances. Faint traces of the same rock may be seen to the left, indicated by the short arrow.

Fig. 1.23. Detail of red argillite and pale greenish siltstone. It is believed that the coloured rock was eroded from lava flows which covered small areas of the sea-floor, the red due to abundance of iron. Note the green siltstone grades subtly up into the red mudstone. The hammer is 27cm long. Photo Greg Retallack.

Chapter 2

ACTIVE AND RECENTLY ACTIVE FAULTS

The rocks of the Aoraki Mt Cook National Park are cleaved by faults ancient and modern. Those of recent vintage are as a rule readily discerned, because they visibly split the rocks, and through understanding of the rock types, can be ranked in importance as a rule. Some are still active, and they mark one of the features of what is called the Kaikoura Orogeny, in the present ongoing phase of mountain building. Not that uplift of the mountains is solely due to faulting[1].

In the southwest, the best known fault is called the Great Groove Fault[2], which extends as a scarp one or two metres high from the Mueller Glacier for more than 50km through the Ben Ohau Range, and as a rule it divides rocks belonging to the Baker Formation, or veers to the junction with the Sebastopol Member of the Acolyte Formation (see Chapter 5). Further north what may be the same or closely related fault, without a visible scarp, divides the Acolyte Formation from the Baker, but seems too minor to map. In both cases, the displacement or throw is not very great, separating rocks that are normally in or almost in stratigraphic contact. Upthrow is on the eastern side, pushing the Acolyte Formation up against the Baker Formation. Other recently active faults are shown in the geological Map 1, p. 159 in the area of the Main Divide and Mount Cook Range south of the Hochstetter Glacier, but more faults are present. The mountain slopes on the east side of Mts Sefton and La Perouse are so steep that faults are hard to discern, and quickly eroded – or their movements were swallowed by

Fig. 2. 1. Fault F – F passing through the Mount Cook Range near Mt Mabel, between fault-disturbed Burnett Formation to the right and Rose Formation below to the left. The Mueller Glacier lies beyond.

the lustrous nature of the schist rock, in which there are numerous small upwardly concave faults. Most of the faults are oriented northeast and southwest, but there are several faults oriented northwest-southeast in the eastern Sealy Range, and other faults are directed east-west on the western flank of Mt Wakefield. Here the largest clearly defined fault lies below and west of Mt Mabel and Mt Rosa, with a further subparallel fault to the south, but their tracks on the east side of the range are obscure, although they seem to head into the southern side of the Ball Glacier.

To the north of Aoraki Mt Cook, and involving the peaks along the Main Divide, such as Mt Tasman through the Minarets as far as Mt Elie de Beaumont and West Peak, visible faults are few, not surprisingly, because much of the area is covered by ice. A well defined fault-fissure lies each side of the Hochstetter ice-fall and possibly extends below the Freshfield Glacier, and there are further possible fault lines, where walls of rock are more or less abruptly separated from ice.

Malte Brun Range

The most active fault in the National Park is the Beetham Fault[3], passing along the lower slopes on the western side of the park, and splintering into several close-set branches to the north, and associated with several subparallel faults to the south. The moraine wall at its southern terminus has been unstable, and has collapsed, possibly affected by the same fault. It is not entirely certain that the fault crosses the Tasman Glacier to enter the south end of the Mount Cook Range, although air-photo SN 8595 D/17 shows a well defined line of surface scars passing along the slopes south of Mt Wakefield and crossing the southernmost extent of the ridge, and a possible fault has

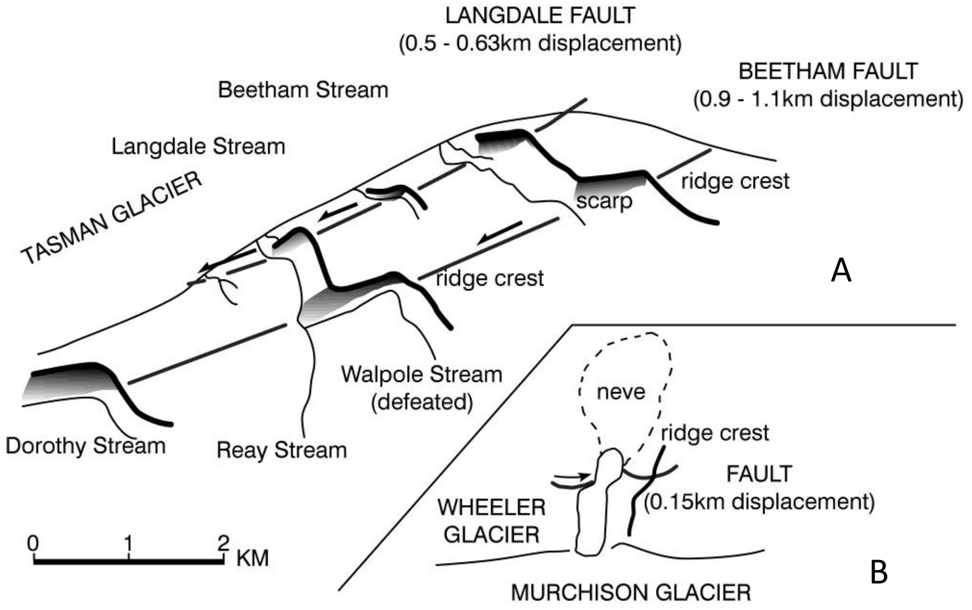


Fig. 2.2. A, simplified sketch-map of the major faults of the western Malte Brun Range (the Langdale Fault being a subsidiary of the Beetham Fault), showing how movement along the faults has shifted ridges (shown as thick black lines) and streams, with an estimate of the amount of lateral movement and the rate of movement per year. Evaluation of Pleistocene data, not scoped in this study, suggests a rate of displacement of 50km per million years for the Beetham Fault. B, part of Starvation Saddle Fault on eastern side of Malte Brun Range, with approximate movement of 6 to 10km per million years. But the faults probably have had a much shorter life than a million years.

been mapped in a similar position, marked by dashes[4]. A lesser fault lies nearby, nearer the Tasman Valley, and both show signs of left lateral movement, that is the west side moving south. By standing one or other side of the fault, the rocks appear to have moved to the left. Spurs leading west from Malte Brun Range have been shifted sideways by the fault, and streams such as Walpole flow along the fault boundary for some distance, before resuming their normal course towards the Tasman Glacier. Minerals have percolated along the fault fissure, and rocks especially on the western side have become enriched in the mineral chlorite. Elsewhere, such fault fissures have been filled with quartz, or partly by the mineral zeolite. The Beetham Fault runs along a major rock boundary, the rock to the east being mostly Triassic, the rock to the west of different origin, and of Triassic and Permian age. Movement along the fault has continued into recent times, because shingle fans that developed after the last glaciation have been shifted upwards by 2m (see Fig.1.16, p. 13).

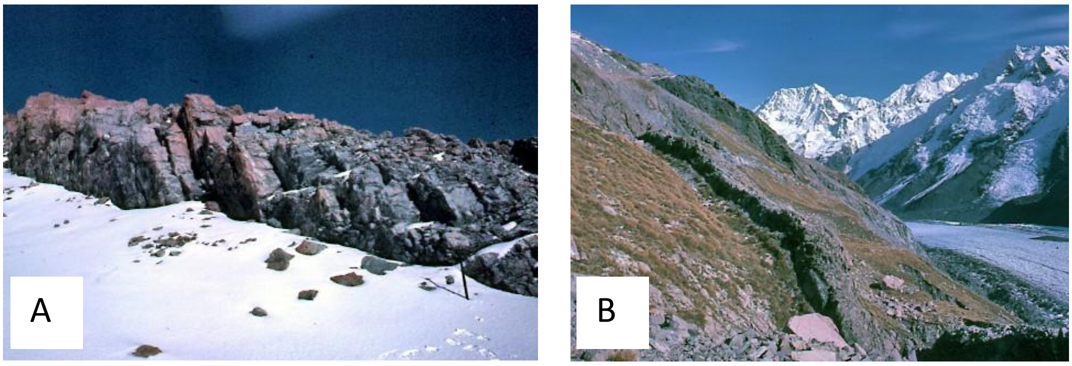


Fig. 2.3. Beetham fault scarp north of former Malte Brun hut site. Note that the beds run obliquely into the fault scarp in A..Ice axe 0.7m high.

Fig. 2.4. Fault in the Mannering Group, east Malte Brun Range, looking south with Liebig Range in background.

There are a number of relatively short faults in the Malte Brun Range, which extend for only one or two kilometres, and stop abruptly, either in higher overlying sediment, or laterally, where they suddenly end, and are not necessarily connected to other faults. These are termed rotation faults or blind faults by some authorities, although a different meaning has been imparted in some circles. A number of other comparatively short faults are oriented roughly east-west across the crest of the Malte Brun Anticline. Some particular east-west faults receive attention on pp. 119-121. Others are transfer faults, forming lateral side-steps, like those described for the Alpine Fault.

Fig. 2.5. Mineralized fault fissure as arrowed. The splitting of rock has allowed minerals to percolate up the crack and crystallize in the Chudleigh Formation of the Malte Brun Range.

In addition there are fractures and fissures, along which little or no movement has occurred. These may impart the appearance of faults, or even mimic bedding, and their arrangement records past stresses, and analysis of the fractures and joint planes indicates pressure directions and deformation history.

Starvation Saddle Fault complex

Another major fault, named from Starvation Saddle, lies on the east side of the Malte Brun Range, and separates rocks of different ages and compositions. In the main, recent faulting seems to have joined up several older faults[2]. It is now a thrust system of moderate dip westwards of 45°, and has crushed rock on the western side, with local shattered rock, zeolitised on the east side, forming a plexus for which some segments display dextral displacement, and other segments show sinistral movement. There are a series of narrow tight folds with parallel limbs, and low angle small faults, dipping west at 30-50°, too small to be shown on the geological map. Below the ridge northwest of the Burnett Glacier, a fault scarp is uplifted on the eastern side, and there is geomorphic evidence for right-lateral movement. But north of the Wheeler Glacier, evidence based on geomorphology and direction of fold plunges suggest left lateral movement, east of Mt Rose, possibly persisting as far as Starvation Saddle. The fault is certainly complex, and strands link different parts of the earlier faults, termed tractator or ancient faults 10 and 11 (see p. 71). One of the southeast Malte Brun faults possibly crosses the Murchison Valley, being aligned with a fault on the other side of the valley, to pass east of Monastery Peak, but there is no visible scarp on the valley floor, and if one were ever present, it has been removed by river erosion. In the northern part of the Malte Brun Range, the faults extend mostly west-east, mostly parallel to the bedding, and in one or two instances, there is evidence for right lateral movement, the rocks moving to the right on the other side of the fault. This is further discussed in Chapter 8.

Malte Brun Pass Fault

Some of the faults indicated in Map 2 differ from the other and active faults in that they may have been formed early in the Kaikoura phase of faulting, and show no previous history. One is called the Malte Brun Pass Fault[3], and cuts through Malte Brun saddle between the peaks of Malte Brun and Aiguilles Rouges[5] The fault extends roughly east-west rather than north-south. On the south side of the fault, the rocks belong to the Frind Formation, of upper Triassic age. On the north side of the fault, the rocks are Permian, much older, with Rose Formation, underlain by possible thin and crumpled Wheeler, and followed mostly by Triassic Chudleigh Formation, with Permian Burnett Formation apparently faulted out and early Triassic Novara Formation reduced (thanks to yet another fault – see ancient fault 9, p. 71). The fault seems to have a rather sinuous, S-shaped outline (see Map 5, p. 162), as though it had been caught up in the folding of the Malte Brun Anticline, although the full extent of the fault is murky to both east and west. Much of the movement may be ascribed to early phases of the present regime of Kaikoura mountain building, followed by folding. The S-shape is less severe than the bending of the sedimentary beds, which may imply that the beds began to fold, then the fault developed, and then beds were folded further, with the fault, no longer active, also bending.

Liebig Range

The Liebig Range is characterised by several long faults on each side of the range, continuing for many kilometres, but with little obvious lateral movement, except for two just east of the park south of Rankin Stream, and these indicate right lateral displacement (aerial photo SN 8595 B/15). There are two persistent faults along the western side of the range above the Murchison valley, with visible scarps uplifted on the western side, and signs, not strong, of lateral movement. Both faults lie within the Rose Formation, so that they were probably young faults, without much displacement.

Godley Valley and tributary glaciers

A few faults are present, shown by fissures through the rock. Recently active faults are few over the D'Archiac massif.

Main Divide fault

There have been claims that a Main Divide Fault passes close to or along the Main Divide in the Park[6], but so far there is limited if any field evidence in support.

Overview

The Beetham Fault indicates some 4mm a year of strike slip, 1-2mm vertical slip, and the total sum of the fault movement overall could rival that of the Alpine Fault for a part of its recent history. However Pleistocene sediments still await attention for accurate calibration of fault displacements. Importantly, the rocks of the Park are probably decoupled from the underlying plate, and have therefore have been free to act in response to substantial isostatic uprise along the Southern Alps, allowed by deglaciation, and also to inherited strain within structures and rocks. There are at least six active essentially upright faults in 20km between the Hooker and Godley valleys, and many more or less active or now inactive faults. Some form cross links between powerful faults, and a number seem to be rotational, as they stop abruptly – or are replaced by warping. Several indicate mainly vertical movement. The total number of faults in the Park probably exceeds fifty, and it would seem idle to hope that all have been detected or correctly assessed. Additional complexity stems from the translation of some faults into sharp flexures, and the growth of folds that laterally shift faults or warp them, and were sometimes followed by fresh rupture close to the old now translated position. Compensating for this complexity, exposures are very good, and because the region is of considerable topographic relief, it should be possible to achieve a three dimensional picture unmatched elsewhere in New Zealand. The inception of the regime of sinistral dominated faults has not been dated, but at least some of the present generation of faults may not have active for more than one million years.

Major faults over much of the National Park tend to trend within 30-40° northeast. Examples include three faults north of Mt Wakefield at N35°, N37° and N47°, Beetham Fault N30°, Starvation Col Fault N33° and the west Liebig Range fault swinging from to N50° to N235°. There are a number of northnorthwest directed folds and faults in the southern and middle part of the Aoraki Mt Cook National Park, and these seem to be reactive or counterbalancing faults, rather than acting in the dominant direction of orientation. But in the northern part of the Park, from the upper Tasman Glacier and Murchison Glacier northwards, faults are oriented differently. North of the Classen Glacier, one fault lies at N10°, and another nearer Mt Moffat is at N148°, one crosses the Elizabeth Glacier at N163°, and a Maud Glacier fault is directed at almost N5°. Faults further west over the D'Archiac massif are more normal in orientation, and the orientation of faults to the south is as a rule weakly oblique to the Alpine Fault. This variance partly reflects capture of rotated and folded thrust sheets of much greater age, and partly may be traced to the influence of uparching along the Alpine Fault.

Chapter 3

FOLDS

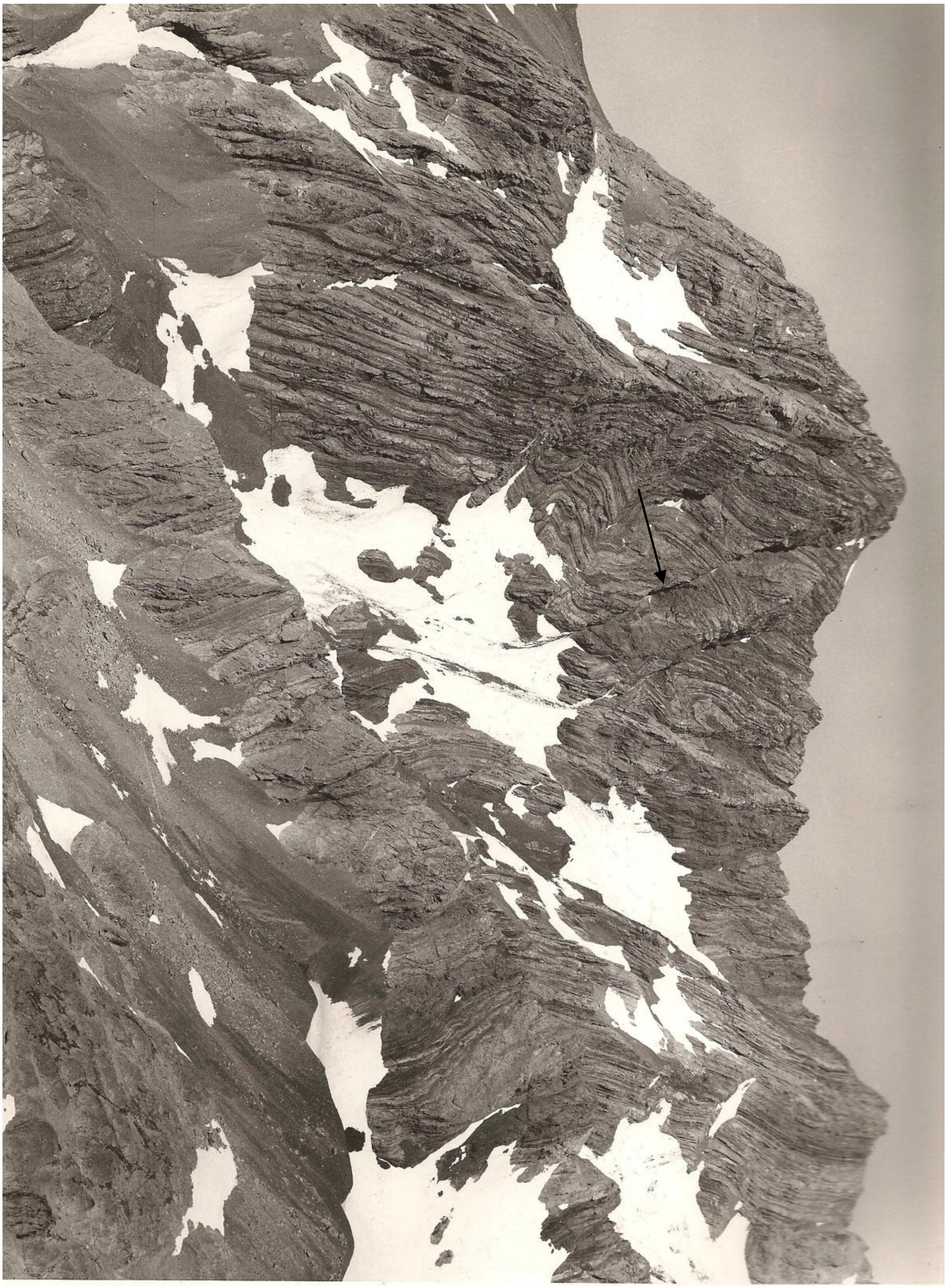
Slump folds

Folds - such a commonplace word, and it means in geology exactly what it says, so I find it hard to paraphrase. Folded or crumpled blanket, folded or crumpled bed of sediment, or usually a lot of beds of sediment. There are many kinds, and a first distinction may be made between those folds that have arisen early in the history of the rock, often through what is termed "submarine slumping", or "penecontemporaneous slumping", meaning slumping shortly after the beds were formed on the one hand, and on the other hand, tectonic folding, due to earth forces acting often long after burial. Submarine slumping is perfectly relevant to some of the folds in the Park. One example is seen near the little lake beside the Mannering Glacier (Fig. 1.21, p. 17). Slumping is aided by the presence of soft mud, which can obviously be slippery and unstable, and results are magnified where sandstone is also present, because this hardens and consolidates more quickly, and provides mass that weighs on the mud. It may also contain a lot of water, which squirts out when folding starts. The slumping may follow the jolting due an earthquake, or sudden influx of more sediment, or collapse of nearby sea-floor. Small slump-folds are widespread, and as a rule each affects only a few beds.

Larger scale submarine slumping is also visible, where the strata are folded often without any relationship to faults, and where the folding does not conform with the general northeast to northnortheast orientation of major structures. One example is offered in the Aiguilles Rouges Formation (Fig. 3.1, p. 26). Along the west wall of the Grey Glacier and nearby glacial valleys, as illustrated and discussed on pp. 110-114, Fig. 7.49-7.54, large intricate folds lie at a broad angle to the tectonic trends of the rocks and folds, and the high proportion of mudstone seems to have encouraged instability. Possibly such slumping developed penecontemporaneously, that is, almost at the same time as sedimentation, when the mud was still unconsolidated and unstable. But more likely the slumping occurred somewhat later, when the sedimentary pile was raised and began to move away in the development of massive slides at the start of the Rangitata Orogeny (see Chapter 6), during the Jurassic Period (Table, inside front cover).

Ordinary folds

I don't know that there are any ordinary folds in the Aoraki Mt Cook National Park, if by ordinary, we mean the type of folding found widely in rocks of various ages around the country, as illustrated in the Glossary on p. 142, Fig. 10.4a. Such folds are caused by mountain building activity, involving compressive forces under the regime of converging Pacific and Australian plates, but they are usually horizontal, whereas the folds around Aoraki Mt Cook "stand on their heads" and plunge steeply northeast[1] or southwest (see Glossary, Fig. 10.4b, p. 142). Everywhere throughout the Park, there are many such folds, and only a few are illustrated. There have been various explanations offered, and here it is suggested that the sedimentary beds were steeply dipping, usually to the west, after uplift due to the Kaikoura Orogeny, related to rock squeezing connected with the Alpine Fault, before they were folded. A little later, under further mountain building, new faults arose, related to the Alpine Fault, with lateral movement, and this lateral movement deformed the steeply dipping beds into steeply plunging folds[2]. The folds were, and are, fault-drag folds, caused by drag of beds along the neighboring fault. But there are some much larger structures, such as the Wakefield, Malte Brun and Haeckel folds, which appear to arisen much earlier, when low angle



[Opposite page] Fig. 3.1, Folds in the Aiguilles Rouges Formation on the western flank of Aiguilles Rouges, the peak on the left, in turbidites of the Malte Brun Group. These folds are near the axis or centre of the Malte Brun Anticline. If they had been caused by tectonic folding, they would trend in the opposite direction. There are also minor faults or major fractures, one of which is arrowed. Frind Formation lies mostly to the left (north) of the peak of Aiguilles Rouges, Aiguilles Rouges Formation extends southwards to the foot of the slopes up to Mt Nathan on the right side of the picture, and Barkley Formation lies to the south, on far right side of picture. Photo D. L. Homer.

Fig. 3 2. A major north plunging complex fold, synclinal according to early studies, on the western wall of the Murchison Glacier, mid-Liebig Range, in Rose Formation. Yet beds suggest an anticline in their grading, so the nature of the fold and direction of plunge need checking.

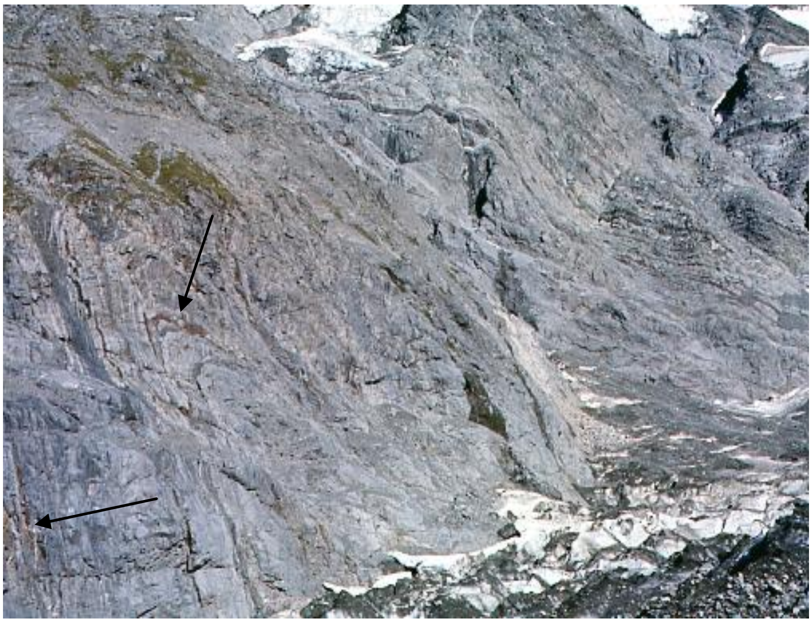


Fig. 3.3. Tight syncline, north plunging, in the Rose Formation, Dixon Glacier, eastern Malte Brun Range. Arrows point to red argillite.

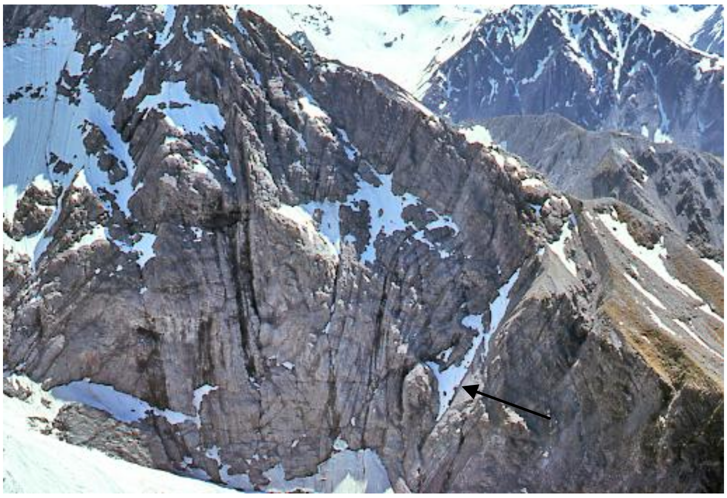


Fig. 3.4. Folds in Baker Formation along the north wall of the Baker Glacier, the upper figure with fault (arrowed) on the right, the lower figure illustrating folded folds.

Fig. 3.5. Anticline (arrowed) on the south side of Darwin Glacier, plunging south, with Darwin ridge in the foreground, and Bonney Glacier (b) in background. Bonney shale Member (B) lies west of the fold.

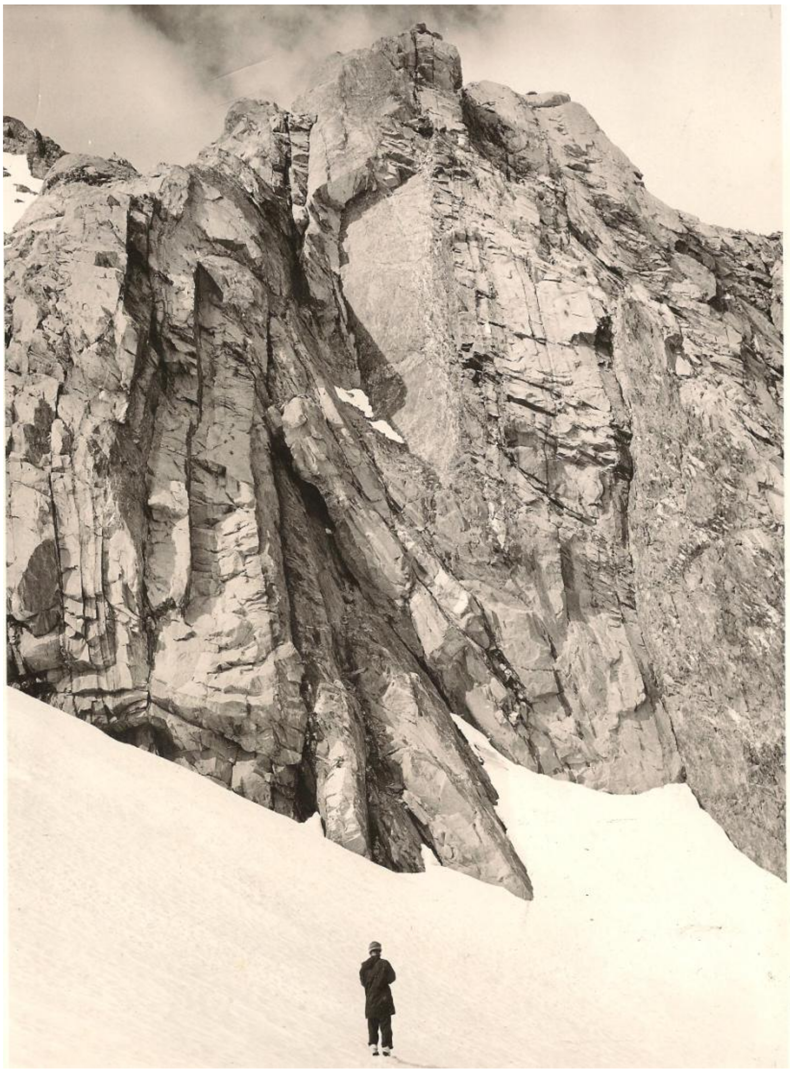


Fig. 3.6. Verging folds on the north flank of Darwin west ridge, pointing to a major syncline to the left and anticline to the right, looking south from upper Tasman glacier. Photo D. L. Homer.

folds slowly became more steeply inclined. As well, small tightly constricted folds, mostly in Permian rocks, are not matched in Triassic beds, and so are probably pre-Triassic in age.

The relationship between faults and folds

It has been shown that folds throughout most of the Park plunge steeply north or south, and the next question needs to be – why?, or at least, is there a reason for the difference in direction? Evidence centred on the medium-sized folds over the Malte Brun Range signifies a relationship to currently active faults. Over the terrain to the west of the Beetham Fault, the faults plunge south. To the east of the fault, the folds plunge northwards (in a general way, northnortheast to be a little more precise). The rocks east of the fault have moved north, and the faults plunge north; the rocks west of the fault have moved south, and the rocks plunge south. If the rock beds were steeply dipping, and then cut by a fault, and moved south or north, fault-drag folds would develop along each side of the fault, with anticlines arching in the direction of movement, and the fault

Fig. 3.7. Drag fold f, f f, developed along a fault F – F in Chudleigh Formation of Malte Brun Group in the Malte Brun Range. Thin packets of sediment seem to have moved leftwards, curled over, and been overtaken by further packets. Deformation on the lower side of the figure is less than clear, and the block may have been stationary, although the strata seem to be cut obliquely by the fault. As well, strong cross-jointing has developed.

would not only be a focus or break-plane for moving the rock, but would be dragging the rocks along its fault-plane, as illustrated in Fig. 3.8. Moreover the folds seem to indicate adnormally high thicknesses for constituent formations[3].

There is what appears to be an intriguing additional complexity to the anticlines and synclines that form as the result of drag-folding along faults with a strike-slip or lateral component. Anticlines can form – that is folds that bulge outwards – which have their strata younging inwards, as if they were synclines according to common definition based on younging direction. That makes the anticlines, bulging forward, appear to be upsidedown synclines, - as if they were synclines that had been completely overturned. This happens when strata young towards the fault. When strata young outwards away from the fault, then folds conform with the standard definition. To discriminate this type of folding, it is suggested that drag-folds formed by strike-slip faulting in steeply dipping strata be called extrocline folds, where the strata young away from the fault, and extrocline folds will correspond with normal anticlines and synclines. Fault-drag folds that have been formed by strike-slip faulting in steeply dipping strata that young towards the fault, will form contradictory anticlines that bulge outwards and young inwards, and synclines that arch inwards and yet young outwards. They may be called introcline folds. In Fig. 3.8, both sides are pictured as moving. But it seems likely that often only one or other side of the fault will move, while the other side remains stationary. Does that mean, as seems probable, that folds will develop only in the side that moves? And if so, do opposing folds each side of the fault suggest that movement along the fault has been in different directions at different times?

It is not possible to decipher the relationship between recent fault lines and folds over all of the Park, but it seems feasible to consider that many of the folds throughout the Park are young. That is they have arisen in the rocks under the influence of the Kaikoura Orogeny, when two tectonic plates centred on Australia and Pacific converged to steepen the dip of rocks, and that the Alpine Fault, when it developed, was accompanied by a host of subsidiary faults and folds.

And complexity grew. Where the strata younged to the west, and were moved northwards along a strike slip fault, the resultant anticlines and synclines will have grown northwards, and, at least during early phases, plunge northwards. As time progressed, the plunge may have reversed, so that the fold curled forward, and direction of plunge changed from north to south. If the strata younged east, and the movement along the fault to the east was northwards, the buckling of strata will have yielded an anticline, or northward bending strata, that actually young inwards, like a syncline, and may mimic an overturned syncline, although there has in fact been no overturning. There are thus a number of permutations. The practical approach is to first resolve the direction of movement along the fault, from geomorphic evidence or analysis of fractures and cleavage trends, and then an array of information becomes available, from the interplay between faults and their neighboring strata.

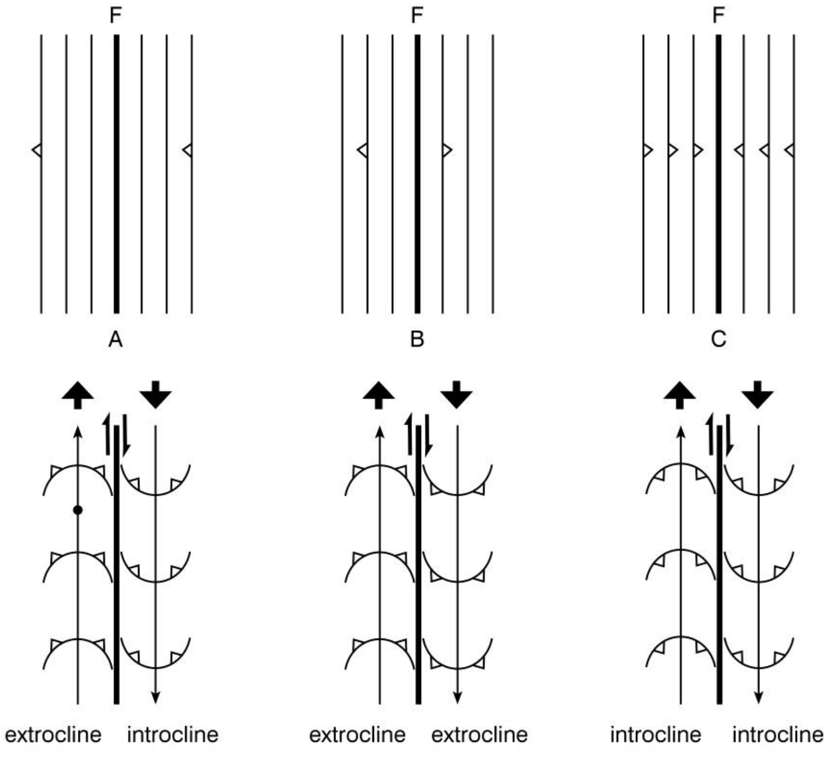


Fig. 3.8. Figures showing how the direction of younging beside a fault (F) affects the nature of fault-drag-folds. A, beds younging in the same direction each side of a strike-slip fault. Movement of the blocks each side of the fault, as signalled by thick arrows, bulge in the direction of movement, forming an anticline younging outwards for the fold in which strata young away from the fault, and an anticline younging inwards for strata younging towards the fault, and so making the fold look like an upsidedown syncline. This latter arrangement shows that the terms anticlines and synclines do not apply: the rules have to be rewritten for fault-drag folding of steeply inclined strata. Therefore outwardly younging forward bulging folds are termed extroclines, conforming exactly with anticlines, and the inwardly younging bulge is termed an introcline, rather than inverted syncline. B, example where strata young away the fault. C, example where strata young towards the fault. And see note 4.

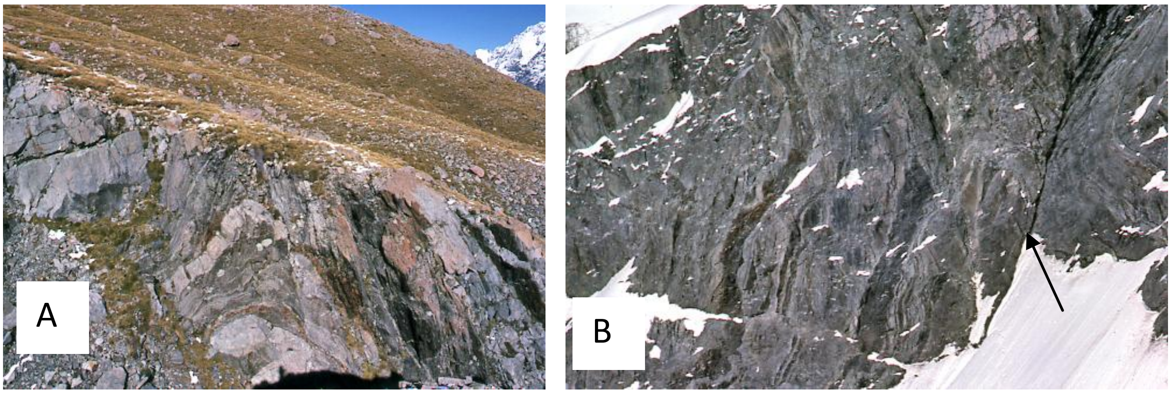


Fig. 3.9. A, south plunging folds in the Baker Formation along the western side of the Beetham Fault, on the western side of the Malte Brun Range. B, arrowed fault in Rose Formation in the Malte Brun Range, with detritus trickling down the crack. Synclines to left (east) plunge north towards the viewer, whereas the syncline to the right plunges away from the viewer, implying origin from left lateral or sinistral fault.

The Malte Brun Anticline

Evidence for a recent origin of folds and faults does not mean that there were no much more ancient folds and faults, but of course they are harder to unravel, because they have been masked by the dynamics of the Kaikoura Orogeny. A close study recognised four phases of folding in rocks along the western side of the Hooker Glacier, in which folds were refolded, and folded again, and then again[5]. In the upper Murchison valley, near the Alpine Club hut, four phases of folding are also visible, in Chlorite 3 rocks. These folding phases are very complex and on a very small scale, and require highly specialized analysis. For a larger scale study, in which many aspects can be seen on maps and by climbing or flying over the mountains, the Malte Brun Range provides its own special witness to complicated geological processes of building mountains.

The rocks of the range, as shown in Map 4, p. 162, lie mostly in a Malte Brun Anticline, plunging north, with a large Haeckel Syncline to the northeast. Along the crest of the range, the rocks dip north, and they are mostly of Triassic age, younger than the Permian rocks along the east and west flanks of the range. This may suggest the possibility that long ago, the rocks actually formed a syncline, with Triassic in the middle, and older rocks each side, with rocks later everted – the Malte Brun Group formerly at the core of the syncline being squeezed up into an anticline, but interpretation of the Malte Brun Group as a thrust sheet or tract simplifies the interpretation, and such eversion may not have occurred. On the western side, the Liebig and Mannering Groups still dip and young west, as for the west side of an anticline. And the east, the Liebig and Mannering rocks also dip and young west, to imply that a syncline once lay between them and the anticlinal rocks along the crest.

There is a second of the many complications. The Malte Brun Range rocks are split by a cross fault, called the Malte Brun Pass Fault[6], which lies between the two major fault systems. The rocks to the north, starting on the south face of Malte Brun itself, repeat the sequence, and include at the core rocks of the Permian Rose Formation, distinguished by the greenish sandstone and red argillite, and possibly Wheeler Formation. The fault appears to be of sinuous outline, and the S-shape suggests that the fault is no longer active, but has itself been folded under the continuing pressure that has buckled the rocks and tightened the anticline. Movement along the Malte Brun Pass Fault has been up on the northern side of the fault.

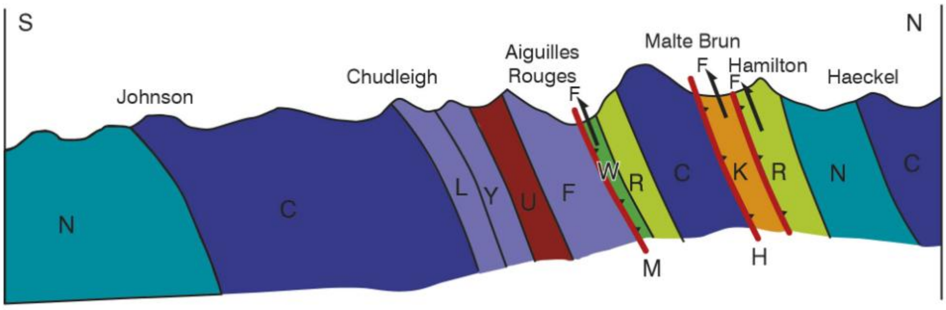


Fig. 3.10. Geological cross-section, illustrating. a cross-section through the Malte Brun Anticline along the crest of the Malte Brun Range, extending from Mt Johnson in the south to Mt Haeckel in the north. The rocks south of the Malte Brun Pass Fault (M) form a simple succession, younging from south (left) to north. North of the fault (to the right of the figure), Permian Liebig Group is present north of a second fault (H), followed by an incomplete succession that belongs to the Haeckel Syncline. Formations are lettered and colour-coded to the geological key, on the inside of the cover at the back of the book.

The Haeckel Syncline

Most of the Haeckel Syncline is preserved, in distorted form, north and east of the Malte Brun Pass Fault, but partly passes to the south into a shallower and younger structure, called the Burnett Syncline[7]. The shape of the Haeckel Syncline as mapped is unusual and must have been distorted. It looks ordinary enough on the southwest face of Haeckel Peak at the head of the Darwin Glacier – except that the rocks are steeply plunging northeast. But the base is elongated, to judge from mapping the rocks further down the Darwin Glacier, and the core squeezed, as shown in the geological Map 2, p. 160, and Map 4, p. 162, and the ais to the northwest has been overturned. The sides of the Haeckel fold are stratigraphically incomplete, and considerable faulting has reduced the thickness of formations, or even obliterated them.

Fig. 3.11. The Haeckel Syncline at the head of the Darwin Glacier. Arrows point towards some of the small anticlines to the north of the major syncline. Mt Hutton lies in the background to the right of the peak. Photo Kerry Bellringer.

Annan Anticline

On the northern side of the syncline, the younger Triassic beds of the Malte Brun Group are steeply dipping, and form a deformed Annan Anticline, with faults and subsidiary folds, well exposed along the Darwin – Annan ridge (Fig. 7.29, p. 98).

In a sense, the complexity may be greatest in the Malte Brun Range and areas of similar distance from the Alpine Fault. Further west, rock structures have become somewhat homogenised under increased influence of the Alpine Fault, which has heavily overwhelmed, although not entirely obliterated, earlier deformations. Further from the Alpine Fault, recent deformation has diminished in scale, and earlier structures are better preserved, as over much of the Liebig Range.

Significance of the geology of the Aoraki Mt Cook structures

Understanding of recent tectonics at the Park has some severe constraints as far as plate motions are concerned, primarily because large scale plate movement and indeed many aspects of theory and modelling as well as distant calibration become overwhelmed and compromised by geological realities, as outlined for the San Andreas Fault[8] in California. Of most importance, it seems highly likely that in the Southern Alps at Aoraki Mt Cook, the crust is decoupled from the underlying plate, so that the crust is responding to plate movement with some degree of independence and also counter-reaction. Arguably the degree of decoupling is exacerbated by the inheritance of several substantial low angle thrusts, which have been steepened and converted into strike slip faults. In addition, moderately well defined folds were inherited from a much older regime, which in places channelled and accommodated strain by modifying previous structures, resulting in compromised directional resolution and structures.

Orientation of folds or clusters of folds in the southern two thirds of the Park

The major folds are oriented as follows: Sefton and southern main divide schist belts N23-36°, Wakefield Syncline N25°, Malte Brun Anticline N30°, Haeckel Syncline N50°, Armchair folds N20° and Liebig anticline N34°. Most of these folds lie roughly but not simply en echelon to the Alpine Fault at N55-58°, consistent overall with Principal Horizontal Stress (PHS), and for example, the right stepping folds in Plio-Pleistocene south of the well-known San Andreas Fault in California, so they have been reinforced by movement along the Alpine Fault and oblique convergence with crustal shortening. But some folds such as the putative anticlinal crest that once lay between the Wakefield Syncline and west-dipping strata of the Sealy Range and Main Divide and other fold axes have either been expunged by deformation from the geological record, or concealed by close-set folding, and a high degree of irregularity in orientation prevails for parts of the Wakefield and Haeckel Synclines, and other fold axes. Minor folds of an order of 0.5km wave-length or less add considerably to the dissonance. In addition, some folds have been steepened or often rolled over lengthwise into ever increasing plunge, eventually overturning, as in the case of the western Haeckel Syncline, or more usually have partially disintegrated under multiple fracturing with normal or reverse displacement of tens of metres, controlled or at least influenced by internal inherited prestressed rocks as well as recent plate movement[9].

North of Mt Elie de Beaumont and Hochstetter Dome, folds are oriented at a different angle, as measured, including the Acland Anticline N165°, lower Grey Glacier fold, N160°, Mannering syncline N163° and Maximillian Range syncline N158°. This region has moved eastwards from the Alpine Fault, and is discussed further on pp. 119-121.

Chapter 4

MAKING SENSE OF THE ROCKS THROUGH STRATIGRAPHY

So far, the geology outlined has been of an anedoctal nature – here a fold, there a fault, somewhere else a type of rock. It does not hang together. It would be possible to examine all the folds, and record them on a map, and even easier to track down all the faults and map them, but the only way to interpret them to even a modest degree would be comparing the array with better known patterns and better known faults elsewhere. Tracking the strike and disposition of faults and folds will yield informative patterns, provided all have been detected, but even the direction of uplift may be hard to determine, unless the stratigraphy is under some degree of control. Moreover it will be virtually impossible to detect faults that lie parallel to bedding – and although there are a number of such faults in the Park, not one has been diagnosed as such before the present study. The way to put folds and faults into context, together with the different types of rocks, is through the practise of stratigraphy, which involves separating out and tracing the extent and nature of each broadly similar rock type, as it was laid down on the ocean floor (in the case of these National Park sediments). Basically, that amounts to preparing a geological map – not a fault map, or fold map or form-line map, but rock type or formation map. A form-line map, like several published for the Aoraki Mt Cook National Park, reproduces the direction of lines along the strikes of beds or schistose layerings. Such maps do not convey relative age or original position for each sedimentary formation, and are never employed where the geology is well known, anywhere in the world. The closely studied and well-known younger rocks of New Zealand are mapped by age or by formation, rather than presented as form-line maps.

The first geologists to visit the Park, Julius Haast, and later James Park[1], made only brief forays. The geology is so complex that there is no way that they had the time to unravel anything. Even the geologists of later decades were too much under the pressure of time – or lack of resources – to resolve the question of stratigraphic succession. For many years, New Zealand geologists in the main have had to be content with treating all the hard rocks of the Aoraki Mt Cook National Park, and indeed the Southern Alps as a whole, as “homogeneous”, meaning they had not done enough work to be able to subdivide them, which reflects on the time-imposed limitations of their work rather than the rocks. At best, a subdivision was suggested between schist and non-schist, which in one sense does not mean that much, because rock that is indurated and of a particular formation, may become schistose within a few kilometres, yet have shared the same origin and age. Unlike much of the younger rock of New Zealand, the rocks, although laid down in a marine environment, have few fossils – the sediments were laid down in sea too deep for shell-fish to flourish, and have been compressed or raised to temperatures that destroy palynomorphs which might have blown in from land-based plants. The rocks are mostly clastic detritus, that is sandstone, mudstone, siltstone, and a few lavas and ash-showers from volcanoes, but without chemical deposits such as salt, or biotic deposits built up of coral reefs, or even limestone, built up of shell fragments. Although we have already observed the presence of some striking rock types, such as the thick black argillites, red argillites, and chert, even these clue-bearing guides were too little understood in terms of distribution to allow any unravelling of the rock types, and the order in which they were deposited, and later deformed and moved. Some geologists, in their ignorance of the stratigraphy, even protested that such rocks had no stratigraphic meaning – as if they could tell. The fact is that compared with many parts of the earth, there have been too few geologists available to study the Aoraki Mt Cook National Park as a whole, except for a handful who have worked under severe time limitations. In the Himalayas where I have also worked, an area of comparable size from the Mugu Carnali (Dolpo) to Manang in Nepal, but with far higher mountains and huge unfordable rivers, has involved expeditions led by Dutch, French (two at least), Austrian (four) and myself (six expeditions), each often made up of several experts, and working for several months continuously. On top of which the geology despite logistic difficulties offered by altitude and distance, has been mapped stratigraphically: geologists have disdained any resort to form-line mapping. No need to indicate which area has been better understood and for much longer. Most of the New Zealand workers looked at too small an area to have any prospect of unravelling the full succession, and government geologists working for GNS, or the former New Zealand Geological Survey, were given huge areas to map, and very little time in which to do it[2], a matter not reflecting on the geologists or institution concerned, but on budgetary constraints.

Fig. 4.1. Crest of the Malte Brun Range, viewed from the west. Mt Nathan in the centre and Mt Chudleigh towards the right, with Chudleigh Formation to right, followed by Walpole turbidites, Barkley Formation with more sandstone over the left side of Mt Nathan, and then Aiguilles Rouges Formation to far left.

So the challenge is, to work out the stratigraphy. But how? And where? Stratigraphic mapping is an ongoing science of constant enquiry, a “test it, try it, be prepared to alter it, be prepared to abandon it”- sort of science. There is absolutely no link with the pseudoscience that pretends to base everything on experimentation – such at best tends to yield “proof” of what has already been conjectured, and therefore wins plaudits from the ignorant, and bemused disbelief from experienced practitioners. Worse, it can lead to false claims. Even some of the greatest of greats, John Newton with his gravity, and Mendel with his genetic inheritance studies, both of them "cooked" their experiments to "prove" their theories, according to the American magazine Science. In geology and much of the natural world, the problems of scale and duration of time are far too great, and often too uncertain, to allow any feasible form of verification based on experiments. How for example would you duplicate the conditions under which the rocks of Aoraki Mt Cook at first were eroded, accumulated under the sea, were upheaved it is believed in a Cretaceous mountain building orogeny, and then upheaved again in a second and current orogeny? Do you even know the age of the rocks, and how do you allow for their volume, their strength, or their structures, let alone the true dimensions of time? And if you don't know, or cannot accurately downscale the parameters in their true proportions, what will an experiment be worth in terms of so many uncertainties? Yet Aoraki Mt Cook is there, real, unproven by any experiment, and unreplicatable with accuracy, except in the eyes of ideologues.

MALTE BRUN GROUP

So where to begin? Let us start with what seems simplest. Move away from the ice-sheets which cover so much of the rock near the Main Divide to the Malte Brun Range, where much of the outcrop is fresh, and not weather-worn or covered by scree. And look high up to the peaks arrayed from Malte Brun peak southwards through the peaks named Frind, Aiguilles Rouges, Nathan, Chudleigh, Johnson, Malcher and Novara (Fig. 4.1), whether viewed from the east or west side of the range. The rocks are well and continuously exposed, and they vary subtly. The rocks over much of Novara have bands 3-8m thick of black mudstone with fine beds of sandstone 1-3cm thick, to form a finely bedded turbidite, called ribbonite. On Malcher, there is a band of pink mudstone. Over Johnson and Chudleigh, the beds are of sandstone 0.3 to 10m thick, alternating with mudstone. Then there is a band of thinner sandstone and much mudstone, followed by a thick band of sandstone, then sandstone alternating with mudstone over Aiguilles Rouges, and finally, a band of thicker sandstone with some mudstone over the northern flanks of Aiguilles Rouges, before reaching the Malte Brun Pass. That is a long stretch of rock, but the consistent differences in proportions of sandstone and mudstone from

Fig. 4.2. The thick sandstone (pale pink) beds of the Chudleigh Formation, with some dark argillite looking across the Reay valley southeast towards Mt Johnson (J). The shadow comes from Mt Chudleigh.

south to north suggest that the rocks display a succession of formations – a possibility to tested, of course, by further work.

Fig. 4.3. The well bedded Malte Brun Group (Novara and Chudleigh Formations), with the peaks of Johnson to the left and Chudleigh at the right, at the south end of the Malte Brun Range, above softer greener rock of the Liebig Formation. View looking west across the Murchison valley.

The rocks are called the Malte Brun Group, and have been divided into formations (see Glossary), named after Novara, Chudleigh, Aiguilles Rouges and Frind peaks, and Walpole and Barkley Glaciers[3]. Novara rock is characterised by its bands of ribbon-like black argillite and sandstone; Chudleigh by its numerous beds of thick sandstone with bands of turbidite. Walpole and Aiguilles Rouges formations are of turbidite – I could not tell them apart, but they are separated by a band of mostly sandstone called Barkley. The Frind Formation at the top of the succession has bands of mudstone, bands of turbidite, and some thick sandstone – a mixture of the other rock types. That leaves the pink mudstone, named Malcher Member. It is a puzzle, because there is little else in the National Park to match it. But in a larger context, there are reddish beds called Curraghmore Formation well to the east in Canterbury between Lake Heron and Benmore Dam that may prove related. As well thick sandstone north of Mt Johnson is called the Reay Sandstone, after the Reay Glacier.

From just one sequence, it is impossible to be sure that the sequence is complete and has no major faults which have removed beds, or even repeated beds through sliding, as elaborated in Chapter 6. To underpin the constancy of the arrangement, rock must be examined more widely, to see if they show the same attributes. What about the northern half of the Malte Brun Range, starting with Malte Brun itself, and moving north through the peaks of Hamilton and Haeckel, to the long east-west ridge passing through Annan and Darwin? Most of the rock over Malte Brun is Chudleigh Formation, which extends northwards to the ridge west of Darwin Peak. To the east, there is major folding, and Novara and Chudleigh reappear in the Haeckel Syncline, and younger rocks are present as well defined turbidite bands (Aiguilles Rouges, Walpole) and

Barkley sandstone. These rocks are magnificently exposed along the north face of the Annan – Darwin ridge, with turbidite units superbly exposed, which helps to compensate for their complicated structure (see Fig. 7.29, p. 98).

Questionably similar outcrops are also found on the northern side of the Murchison nevé, in the peaks of Graceful and Brodrick. Extensive outcrops of the formations also lie west of the upper Hooker Glacier, and pass south through the upper reaches of the Mt Sefton ridge and across on to the western end of the Sealy Range and north end of the Ben Ohau Range beyond the National Park. The turbidites and argillites have been altered into schist, under pressure perhaps from the Alpine Fault, or earlier compression regime, as discussed on p. 152, reference 17, for Chapter 5.

So how do these formations compare with those of the southern Malte Brun Range? On the whole, they are very similar, apart from variation in thickness, and the rock types and succession of formations are much the same. One difference is the failure to find examples like the massive sandstone unit called Reay Sandstone, in the lower Chudleigh Formation, apart from comparable rocks near Barron Saddle Hut, in the upper Hooker Glacier. The Reay rocks are exceptional, and were likely to have formed in a channel that had been carved out of the sea-floor by turbidite flows, and then infilled by sand. As well, examples of the Malcher Member are rare.

In summary, the Malte Brun Group is well developed in the Aoraki Mt Cook National Park, and it extends far to the north close to the Alpine divide and into the North Island. The turbidites are most spectacularly developed in the region of Arthur’s Pass, where they contain Late Triassic fossil shell-fish called *Monotis*[4]. Further north in the ranges south of Nelson, Chudleigh Formation is widespread. Outcrops are also found in the southern North Island, where *Monotis* is found rarely in the Tararua Range, and along the south coast around Wellington, where many of the rocks are those of the Chudleigh Formation.

Characteristics of the group include the composition of the beds, in which quartz makes up a major component of sandstone, with little development of limestone or red shales, rare pebble beds or conglomerate, and few fossils other than what are thought to have been pelagic (free-swimming) bivalves. The source of the formations, given the abundance of quartz, would appear to have been a land rich in granite or acid volcanics, or mature sediments in which the easily destructible minerals have been weathered to leave the more indestructible quartz. And where was source land to be found? The answer cannot come from within the park boundaries. Some may argue that current directions indicate by undersea currents will provide a guide, but this is not a simple key, because sediments have been twisted and turned from their original direction, thanks to folding and faulting, and anyway currents can be very complicated. On pp. 122-126, suggestions and diagrams are offered to illustrate the possible source and disposition of the sediments, based on the geology beyond the Park boundaries.

LIEBIG GROUP

On the east side of the Malte Brun Range, along the Murchison valley, a number of small glaciers extend from the mountains. Few reach the valley floor, other than the Mannering, Dixon and Baker Glaciers. The steep glacially carved rock walls offer fine exposures of rock, and differ from the Malte Brun rocks in several ways. The beds extend along the range, instead of across it, and contain a few bands of spectacular red rock, as discussed and figured in Chapter 1. Importantly, rocks have a greenish hue, which in the local context signals that the sand grains include chlorite and pumpyellite, and possibly mafic minerals rich in iron and manganese and other heavy minerals, suggesting that whereas the Malte Brun Group was sourced from granitic terrain, these rocks were eroded from a terrain rich in igneous rock such as andesitic and basaltic lava flows[5]–with only a moderate amount of quartz, and more heavy minerals. You can see the contrast in Fig. 4.3. Because many similar rocks are found on the other side of the Murchison Valley, in the Liebig Range, the rocks are called the Liebig Group.

The most striking formation is the Rose Formation, characterised by pale green sandstone, with bands of red rock, such as seen in the lower Murchison Valley (Fig. 1.22, 1.23, p. 18) and near the old Malte Brun hut (Fig. 5.5, p. 47). The Rose Formation is well exposed in the Dixon Glacier, and is readily recognized, even at a distance, by the striking red bands, set in greenish-coloured sandstone (Fig. 5.3, p. 46).

Two formations are associated with the Rose Formation. Underlying the Rose Formation below Novara Peak is a formation made up mostly of green tuffaceous (volcanic) siltstone, called Wheeler Formation after the Wheeler Glacier. This is distinctive, and the rocks can be very unstable and slippery. Above the Rose Formation is the Burnett Formation, made up of thick bands of green sandstone and thick black silty mudstone; it is is very like Rose, but has more mudstone, and no red beds.

Fig. 4.4. The crest of the Malte Brun Range, with the Malte Brun Group, viewed from the east, and featuring from the left the peaks of Chudleigh, a subdued Nathan, Aiguilles Rouges, Malte Brun, Hamilton and Haeckel. Softer, less well bedded rocks of the Mannering and Liebig Groups lie along the lower eastern slopes, above the terminus of the Murchison Glacier, and include Rose, the low peak on the skyline to the right,

Mapping these formations along the Murchison Valley is not easy, because of vegetation, landslides and rock fall. Across the valley, the Rose Formation is distinctive, making up most of the west face of the Liebig Range, and especially well exposed on the north wall of the unnamed glacier leading northwest from the gorgeous if neglected peak of Hutton. Burnett beds appear to be developed at intervals. Thin developments of the three formations are scattered along the western side of the Malte Brun Range, and in the older beds of the Haeckel Syncline in the Darwin Glacier.

Good outcrops are also developed across the Tasman Glacier along its western wall north of the Ball Glacier, and south of this glacier, the flanking ridge is made up of the Wheeler Formation. Liebig rocks are also developed close to the crest of the Sealy Range, with thin Rose Formation extending north along the east face and south into the Ben Ohau Range. The Rose Formation is particularly widespread in the northern part of the Park, around the Godley Glacier.

One more area remains – in the southeast corner of the Park, near Mt Blackburn and over the crest of the range in the Jollie River valley, beyond the Park boundary. Here there are extensive exposures of Rose Formation, with scattered red bands, and a band is clearly seen from the roadway. The Rose beds are associated with thick black argillite bands and thick green sandstone, and make up a common association well to the east of the Park boundary.

So what is the source of the Liebig Group? The chemical and mineral compositions of the rock grains point to an igneous source, and to the west, the Aspiring and Wanaka lithological associations include extensive greenish schist, altered from igneous rock, near Queenstown, Wanaka and Mt Aspiring[6]. The general age is indicated by small fragments of a Permian fossil bivalve *Atomodesma*[7].

MANNERING GROUP

There are still some rocks not accounted for by either the Malte Brun or Liebig Groups. They include the thick black mudstone bands already noted on Mt Wakefield and south of The Nuns Veil, and thick sandstones of Sebastopol. These belong to the Acolyte Formation, made up of several bands of coarse sandstone 50-300m thick as a rule, and black argillite of similar or lesser thickness[5]. The scattered occurrences of fossil shell-fish in similar rocks beyond the Park boundaries suggest that the units may have formed on the outer continental shelf (Glossary, Fig. 10.2, p. 137), developed around continents.

Above the Acolyte Formation comes the Baker Formation, which is well exposed along the south wall of the Mannering Glacier. It is made up of rhythyms of prominent sandstone bands 1-10m thick alternating with black mudstone bands, 1-5m thick. These beds are overlain by a distinctive Cooper Peak Member, with thick beds of sandstone interleaved with thinner mudstone, which became folded under submarine slumping (Fig. 1.21, p. 17). Then comes the Bonney Member of thin-bedded sandstones and mudstones, some 25-70m thick, as exposed near the Bonney Glacier and Darwin Glacier. The upper part of the Baker Formation contains the Onslow Member with six units of sandy and argillaceous turbidite in bands 30-50m thick, alternating with arkosic sandstones in beds up to 5m thick, in bands 50-100m thick. The Steffan Member is found towards the top of the Baker Formation, and may be readily seen at a distance, because it consists of beds of white quartzite, alternating with beds of black mudstone, some 7 to 20m in thickness.

These members, Steffan, Onslow, Bonney and Cooper Peak, are found mostly in the southern regions of the Park, and only the Baker Formation has been recognised more widely, extending with the Acolyte Formation well to the east of the Park boundaries.

Relationships of the Mannering Group with Liebig and Malte Brun Groups are less than clear within the Park domain, but the group is not only younger than the Liebig Group, but formed a natural upward progression with increased component of quartz and diminishing volcanic input. Although uncertainty remains, because so far no independent age determinations, whether from fossils or radiometric evaluation, are available for the Baker Formation anywhere within the National Park, or beyond its boundaries, the underlying Acolyte Formation beyond the borders of the Park contains good fossil evidence for a Middle Triassic age, distinctly younger than the Liebig Group, so that the Baker Formation is regarded as Late Triassic.

Geological Maps

Geological maps are presented at the end of the book to show the distribution of rock formations and their stratigraphic presence throughout the Aoraki Mt Cook National Park. Each different colour with code letter represents a rock formation, as shown in the key to the formations, and these formations are examined more fully in Chapter 5, with illustrations. In the preparation of geological maps, the prime outcrops are as a rule limited in extent, and, according to the strike and dip of the beds, the rocks are extrapolated beyond what can be actually seen, perhaps beneath a grassy field, or across a river or town, or dense forest, or under a river. The geological map thus shows what the rock would be, according to what is known, if there were no soil, or water, or buildings, or forests. In the National Park, outcrop is unusually good, but much of the park is covered by snow and ice. For the maps in this book, some of the small ice-fields are ignored – they are rapidly disappearing anyway, but major valleys, filled with thick ice or proglacial lakes or with Quaternary sediment, are shown, and extrapolation of the rock formations has been left to the reader. The glacial lakes at the terminus of glaciers, as taken from 1:50 000 topographic maps, have expanded beyond the limits shown on the maps, and many ice-fields and nevés have diminished. There are two further complications. It would be highly desirable to show topographic contours, because the shape and extent of outcrop depends on the steepness or gentleness of the terrain, and thick formations can seem to be thin from an aerial view, if exposed over a steep mountain face. The contours are too difficult to reproduce on the maps, but they are shown in the New Zealand toposeries 1:50 000, and better still, the topography may be studied through using Google Earth – scans of these excellent presentations may be assessed side by side with the maps. There are many complicated arrangements of rocks exposed on steep mountain faces that can scarcely be conveyed on a geological map focused on a view from above, and this is compensated by a number of photographs. A second difficulty is the scale on which the maps are reproduced. The Malte Brun Range in particular, and some other segments have been mapped in detail sufficient to produce a geological map at 1:10 000, but that would require the production of an expensive and large map. Reproduction of the present maps has resulted in a considerable loss of information, and strikes and dips and a lot of other observations have been omitted, because known detail would overwhelm the maps, and obscure the overall patterns, so that I have opted for a simplication that shows general pattern. To partly make up for these omissions, photographs are used to convey the complexities and interrelationships of the rocks, and indeed my earlier publications follow some dispositions more accurately.

WHAT DIFFERENCE DOES IT MAKE TO CLIMBING?

In climbing over graded beds that are upright, with younging oriented upwards, there may be small ledges which require upward hand-pressure, because the sandstone base is left overhanging more easily eroded mudstone. Overturned beds form the ledge on the upper side. Over recent years some climbers have preferred to follow one band of sandstone that lies vertically, and offers a steep route with limited spectrum of challenges – all of them often severe. These beds or bands are found especially in the Rose Formation and the Chudleigh Formation. To climb up a band of mudstone is more tedious, because the mudstone is often closely fractured, with sharp edges, and likely to break away. The Malte Brun Range has long been favoured by climbers as offering solid rock, and although this is not always true, the present study confirms the special nature of the rock, which has more quartz than in other groups. The worst of formations is the Wheeler Formation, with its rather slippery volcanic tuffs, and the thick argillites of the Acolyte Formation are brittle and riven with fractures, but these formations do not form high peaks.

One would not expect schist to form relatively high peaks, but uplift has been so rapid along the main divide south of Mt Hicks that it has outpaced erosion, and climbing over such fragile rock requires care and technique. The infamous so-called weetbix rock, soft and crumbly, varying to highly fractured and therefore unstable, is found widely – as over much the globe – and grumbling about its treachery serves to put the blame on the rock instead of on the initial assessment of the route selected, and skill of the climber.

Slab climbing is followed locally, climbing up the comparatively uniform and solid undersurface or top surface of a single bed. Other variants could include following a subvertical fault fissure, or a fissure infilled by minerals such as quartz.

Fig. 4.5. A slab of Novara rock in the southern Malte Brun Range.

Chapter 5

STRATIGRAPHY OF THE LIEBIG, MANNERING AND MALTE BRUN GROUPS IN THE AORAKI MT COOK NATIONAL PARK

This section summarises the occurrence of Triassic and Permian formations in the Aoraki Mt Cook National Park. It can be used as a reference, looking at the pictures, or the reader may wish to move on to Chapter 7, p. 79. Rock units have to be named after place names published on a geographic map and approved by the Geographic Board: any suggestion otherwise, no matter how frivolous or descriptive, cannot be accepted.

LIEBIG GROUP

Name: The Liebig Group is named after the Liebig Range, south and east of the Murchison valley, composed substantially of Permian rocks and close to type sections of the constituent formations. Liebig by the way is pronounced Leebig, not Lybig.

Definition: The Liebig Group includes the Wheeler, Rose and Burnett Formations[1], and consists of Permian rock, mostly volcaniclastics derived from an andesitic or basaltic volcanic arc or from rocks so-derived. The sandstones are typically green, with less quartz and more mafic minerals than found in Triassic rock, and there are small and scattered accumulations of basalt lava, and widespread red argillite, green siltstone and dove-grey siltstone.

History: These three formations were initially included in the Mannering Group, and are now separated, because they are Permian rather than Triassic in age, and have less quartz. In initial studies, the Liebig Group was thought to lie above the Baker and other formations of the Mannering Group, and now these are reinterpreted as being of Triassic age, and no base is known for the Liebig Group.

Wheeler Formation

Name: The unit was originally named, as a member, from the Wheeler Glacier in the Murchison valley[1].

Fig. 5.1. Wheeler Formation in the Wheeler glacial valley, the ice above constituting most of the glacier, and the ice below making up a reconstituted glacier, offset by a side-step thanks to a fault (see Fig. 2.3, p. 21). Mt Hamilton and Rose Peak to the right lie in the background.

Type section: The type section is provided by the amphitheatre in the lower valley of the Wheeler Glacier. The north wall of the Murchison valley just north and east of the Burnett Glacier provides good sections.

Content: The distinguishing feature of the formation lies in the abundance of green and dark tuffaceous siltstone, associated with massive green volcaniclastic sandstone, v furnished with small chips of quartz pebbles, and bearing zeolite and chloritic tuffs. There are 1-10m bands of calcareous black argillite interbedded with green sandstone in beds 0.2-0.3m thick. Rarely the mudstone lies in thin beds 2cm thick between sandstone layers which are as thick or thicker. Thickness of the formation varies from 60m at the type section to 300m east of the Burnett portal along the Murchison valley side. No fossils are known. Beds are often broken, and the rocks may be unstable, sliding over fractures, because of the tuff component with its chlorite.

Distribution: The formation is of limited distribution, along the north and western wall of the Murchison valley, and south of Aoraki Mt Cook along the south side of the Ball Glacier, with thin fault-reduced outcrops on the east side of the Sealy Range and west of Mt Hicks, as well as close to the crest of the middle Liebig Range.

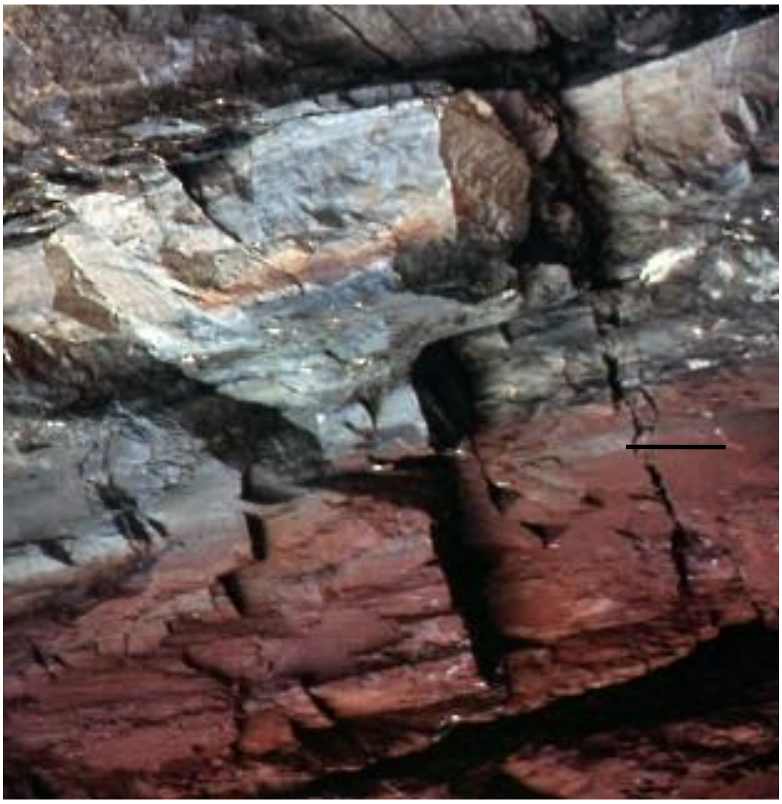
Fig. 5.2. Wheeler Formation looking north above the Murchison valley and east of the Burnett Glacier. The formation is preserved as broken rock, slippery to traverse.

Rose Formation

Name: The formation was named from Rose Peak[1].

Type section: The type section is provided by the south side of the Dixon Glacier. This is of glacially-smoothed rock and is very well displayed. Many accessible and thicker sequences are found in the nearby Liebig Range, especially along the north wall of the glacier leading to Mt Hutton.

Fig. 5.3. Rose Formation with red argillite south of the Dixon Glacier from a spur east of Mt Rose, east Malte Brun Range.



.

Fig. 5.4. Red argillite above green tuffaceous siltstone, typical of the Rose Formation, photographed in the Liebig Range. The rocks have been turned upside down by folding. Scale bar 5cm long.

Content: The formation consists predominantly of thin to thick-bedded (0.1 to 5m) green sandstone, with more massive bands locally up to 15m thick, rare quartzite and hyaloclasite, dense black argillite and flysch, rare basalt, and widespread red argillite with green siltstone, and dove-grey siltstone. Small cubes of pyrite (iron sulphide) may be present. The red and green band may be as thin as 0.5m, to as thick as 100m, with a double or even triple band, sometimes more, found locally. Four or five narrow bands of red argillite and a little green siltstone occur in coarse green sandstone south of the Darwin Glacier. Rarely, the red argillite is associated with basalt, massive or pillowform, and the basalt extends only for a few tens of metres as a rule and may be 1m to 5m up to 10m thick.

Fig. 5.5. Red rock and dark lava north of the old site of the Malte Brun hut, looking south towards Aoraki Mt Cook and Mt Tasman. Ice-axe 0.7m long.

North of the site of the old Malte Brun hut lies red coloured mudstone and green siltstone, persisting for about 1km. Rock in a band up to 200m wide lies between two faults, and is complexly folded with southward plunges in small folds. Red argillite beds are 0.3m thick, and green epidote and chlorite are developed in green siltstone and green sandstone, and some dense black mudstone rich in chlorite is present, arranged in thin ribbons 2cm thick. There are other rock types, including silty sandstone, varied siltstones, some beds in current-bedded lenses with laminations only 1mm thick, and three layers showing ripple crests 3cm apart. A band almost 20m thick consists of fine alternating green sandstone and black argillite up to 20cm thick, the beds arranged overall in a syncline. Hyaloclasite is present in thin bands 0.4 to 0.5m thick, and what appears to be volcanic rock is suggested by rust-coated iron-rich rock, 0.1-0.3m thick.

The thickness of the Rose Formation seems to be almost 700m for the type section[1], but there are many folds. The formation exceeds 3000m in various areas, including Liebig Range, without being able to discount duplication through low angle faults and schuppen.

Fossil content: Distinctive prismatic shell fragments of the Permian bivalve *Atomodesma* are found under Mt Hamilton near the type section[2]. Geologist Brad Field in his thesis study of Rose rocks over the middle Liebig Range described various kinds of what are called trace fossils, including burrowings[3], as well as *Torlessia*.

Depositional environment: The Rose Formation accumulated as an extensive apron fringing an igneous source. Red rocks are to be found throughout the park, eroded directly from volcanic lava formed on the sea-floor, or reworked from such sediment, and they help considerably in unravelling the structure of the Park structures. Some authorities even suggest that the red rocks were volcanic ash showers, exploded from a volcano, but the variation in number of beds suggests a sedimentary origin. Red Rocks near Wellington[4], and rocks just south of the National Park to the west of the Hopkins River, are similar. Further east, as in the Two Thumbs Range, and in the Arrowsmith Range, bands of red argillite become numerous, and may be associated with fine breccia. In the Palmer Range just south of the Rakaia River, red argillite forms numerous bands locally, notably over Mt Godley, and is closely associated with comparatively large masses of basalt and small lenses of limestone with fusuline fossils. These form a different association, called Glenfalloch Member[5].

Fig. 5.6. Eastern side of Main Divide north of Haast Glacier, looking at Forrest Ross Glacier, with Rose Formation indicated by arrowed red argillite, younging upslope. Possible Burnett Formation in foreground and to the right, younging downslope, and overturned. Note the strong fracture cleavage at angle to bedding, developed in sandstones to the left, indicated by short arrow. Photo Ray Bellringer,

Fig. 5.7. Rose Formation and red mudstone of south middle Liebig Range, in a tight fold. Photo, Ray Bellringer.

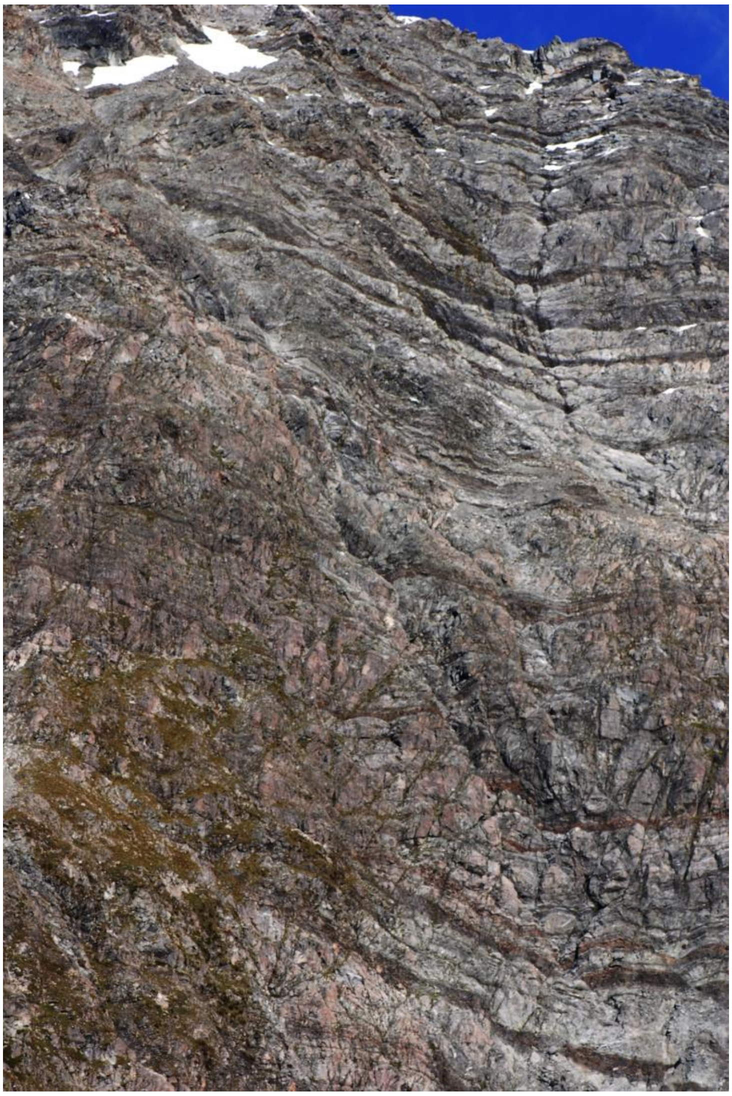


Fig. 5.8. Rose Formation with red argillite in narrow syncline, west wall of Maud Glacier.

Burnett Formation

Name: The formation was named from Burnett Glacier[1].

Type section: The type section is exposed along a low ridge leading eastwards from Mt Johnson, with further outcrop in a parallel-flowing stream, below the glacier terminus.

Content: The formation is characterised by massive and thin-bedded green sandstone alternating with beds usually 2-4m thick, or in bands 10-30m thick of argillite and flysch, totalling 400m in thickness in its type section. There are minor bands of turbidite in rhythyms up to 10-12m in thickness, with up to 30-40% as mudstone beds. Current bedding with complete catenary curves is developed in sandstone 3-5cm thick. Grey siltstone is well sorted. Argillite may be rust-coated and black, and some beds with layers 5-10cm thick in bands 2-3m thick are rich in chlorite.

Fig. 5.9. Burnett Formation looking south below old Malte Brun hut site, north of Beetham Stream, younging to the west, with Tasman Glacier below.

Fig. 5.10. Burnett Formation on Main Divide west of Rudolph Glacier. Photo Ray Bellringer.

Fig. 5.11. Folded Burnett Formation exposed north of Beetham Stream in the eastern wall of the Tasman Glacier.

Age: The formation may be mid to late Permian or even early Triassic in age.

Distribution: The formation is found widely over the Malte Brun Range and Aoraki Mt Cook and Main Divide to the north, and in the north Liebig Range, above Rose Formation.

MANNERING GROUP

Name: The Mannering Group is based on the name of Mannering Glacier[1].

Content: The Mannering Group involves the sediments deposited over the shelf and upper continental slope between the submarine deltaic fans (found further to the east on both sides of Lake Benmore and the Harper Range) and the outer slope and trough. The group is made up of quartzitic to quartzo-feldspathic clastic sediments, and lacks other than inconspicuous white or green tuffs, and has no volcanic lava, or red argillite and green siltstone, or carbonate. Evidence points to derivation chiefly from a granitic or continental terrain, as affirmed by the composition of conglomerate, found beyond the Park boundaries, which is generally dominated by clasts of quartzite or quartz-rich sandstone, with rare granitic pebbles and cobbles, although some beds have a more basic volcanic component, probably eroded locally from underlying Liebig Group.

Acolyte Formation

Name: The formation is named from The Acolyte, a peak in the south Liebig Range[6].

Type section: The type section is provided by the ridge and rock face along the eastern head of an unnamed stream flowing into the Tasman Valley: the ridge extends south of the peak called The Nuns Veil to The Acolyte, and lies immediately west of Nuns Veil Glacier.

Content: The formation is characterised by its sandstone bands 50-300m thick or more, alternating with equally thick or sometimes thinner bands of argillite or argillaceous fine

Fig. 5.12. Acolyte Formation in lower Tasman Valley, east side, with thick black argillite and pale green sandstone.

turbidite. The sandstone is often coarse and massive with bedding thick or not apparent, arkosic in composition, rarely with thin layers of black argillite or breccias. The sand grains seem remarkably fresh. The argillite and turbidite units are particularly conspicuous in aerial photographs and in the field, because they are thick, black and readily eroded. Characteristically they are made up of thin medium-fine and fine

Fig. 5.13. Sea-floor ripple-marks, some arrowed, on the base of beds of sandstone in the Acolyte Formation, southern Liebig Range, Tasman valley. The arrow is 3m long.

turbidite. The black argillite bands display sand stringers and laminae, weakly calcareous in some beds, and are coloured faintly pink after weathering, whereas the sandstone surface often turns yellow to orange on weathering. Current-bedding, ripple-marks, concretions, flute casts, and convoluted bedding, with submarine slumping, are common. The formation is apparently up to 3000m thick, but tectonic thinning and folding are widespread.

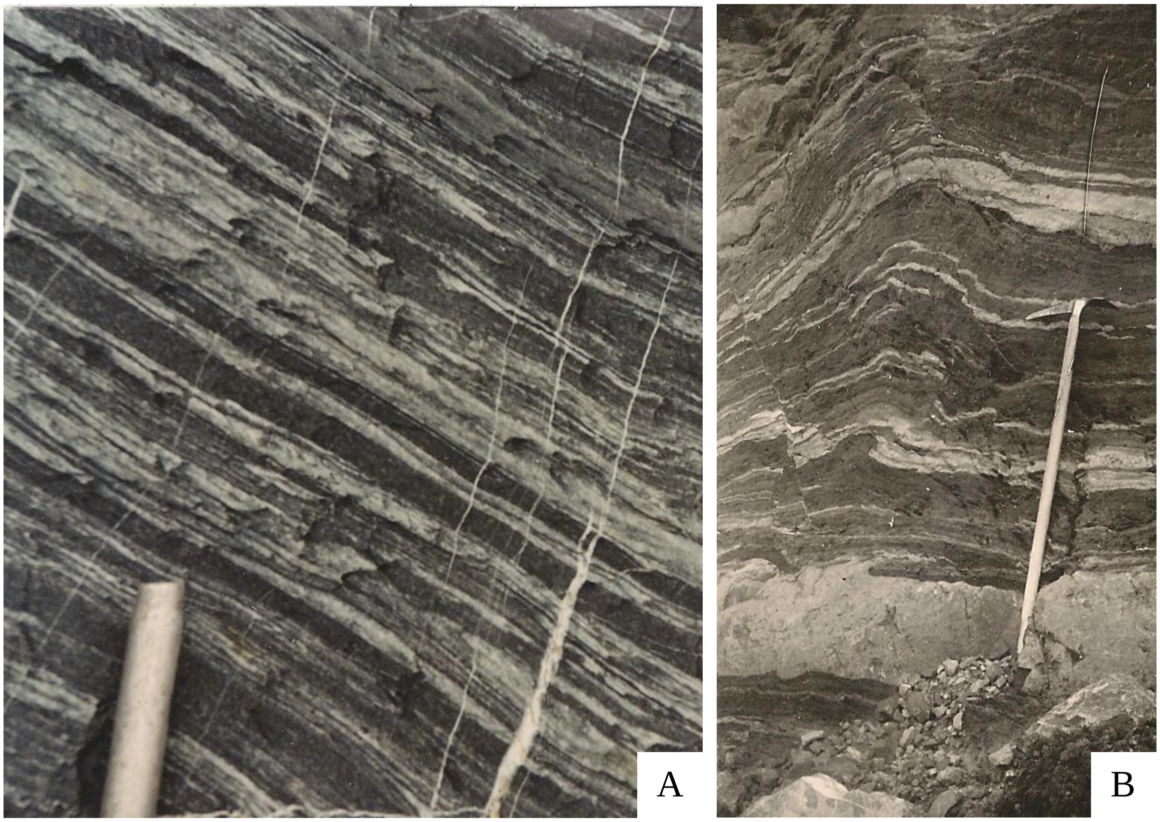


Fig. 5.14. Black mudstone with thin layers of pale sandstone, mildly metamorphosed, and shot through by veins of quartz, from lower Classen valley. The width of the pole is 2cm. B, mudstone unit with sandstone beds of the Acolyte Formation in the lower Hooker valley, west wall. The ice-axe is 1m long.

Sedimentary environment: The extensive distribution of this formation, and its likely position between rocks of the shallow-water deltaic fans to the east of the Park and trough sediments of the Malte Brun Group, indicate deposition over a broad ramp or continental shelf. Although the muddy turbidites and argillite may suggest deep water, they are here interpreted as relatively shallow water, rather than trough or slope deposits. The sandstones form a marked contrast topographically, and are so massive and thick that they might seem to have been channel-fill. But extensive mapping of excellent exposures does not support such a possibility, for the bands nowhere cross the argillites at variant strike, or visibly channel into them. Instead they represent extensive sheet deposits, and are here interpreted as representing highstand systems tracts.

Fossils: Tubes of *Terebellina* are widespread in the argillites of the formation, and there are numerous other fragmentary fossils, including leaves and burrowings. *Torlessia* and *Terebellina* are worm-like tubes, usually dated in New Zealand as Late Triassic[7], but specimens like both of these forms are found in much older Triassic, with *Torlessia* even in Permian. Some layers are rich in micro-fossils, which are yet to be systematically examined. Age determination depends on fossil brachiopods and molluscs. A tributary of Balmacaan Stream in the Harper Range[8] north of the Rangitata River has yielded Anisian fossils followed by Ladinian fossils of Middle Triassic age (see Triassic in the Glossary), as confirmed in part from the identification of the Anisian species *Daonella jadii* Campbell[9]. Species characteristic of a distinctive Ladinian brachiopod assemblage are found widely, notably at Carney's Creek in the Rangitata valley, and many other fossil localities[10]. The Acolyte sandstones yielded fossils: which I thought were distorted brachiopods in the Hooker valley, but the material, deposited in the then New Zealand Geological Survey, was not registered, and now it cannot be found. Much remains to be done over the age of the individual bands, and it would seem that the best prospects lie in resolution of micro-fossils, which include ostracods. There are at least twelve bands of sandstone and mudstone, and where the Anisian-Ladinian boundary occurs is not known.

Two units are distinguished for rocks exposed along the lower Hooker and part of the Tasman valleys. They are thick, and conceivably were once separated by mudstone, that was later squeezed out and lost.

Fig. 5.15. Unwin Member of Acolyte Formation, Black Birch Stream. Scale bar 1m long.

Unwin Member.

Named after Unwin Hut, this member is a unit dominated by thick bands of sandstone, interleaved with minor black argillite and a few turbidite bands. The type section is offered by Black Birch Stream. The unit is limited to the Hooker Valley and Tasman Valley, and is apparently part of the Acolyte Formation as mapped on the other side of the Hooker valley. The thickness is over 600m.

Sebastopol Member

Named after the peak of Sebastopol, the unit is made up of thick greenish sandstone. Microscopically, the sandstones are typified by sericitised feldspar, with some schistose structure, whereas the underlying Unwin Member is characterised by unaltered potash feldspar[11]. The unit is limited to the western side of the lower Hooker valley and lower Tasman valley on the flanks of the Mount Cook Range, and is apparently 500m thick.

Baker Formation

Name: The formation is named from the Baker Glacier, Murchison valley[1].
Type section: The type section is provided by the south wall of the Mannering Glacier.

Fig. 5.16. Base of bed of mudstone in the Baker Formation, east Malte Brun Range, showing so-called scour or flute casts (with one arrowed), left as triangular hollows scoured at the base of beds by ocean currents. Ice axe 0.7m long.

Content: Beds are well developed but rarely very thick. Sandstone is predominant in beds usually 0.5 to 2m thick, and sandstone may be finely laminated, with more than 40 layers in a sandstone bed 1m thick. Turbidite bands are widespread, varying from 0.2m to 2m thick. Mudstone weathers to a dirty brown; and may be poorly sorted. The beds display a diversity of bedding structures, including ripple marks, scour and flute casts, laminae, and current bedding. Joints may be light brown to light purple in colour.
Sedimentary environment, age: The nature of distribution, and stratigraphic position above Ladinian Acolyte Formation, suggest that the formation is of Late Triassic age, and that it developed on the shelf slope as sandy turbidites, possibly during low sea-level, or even emergent shelf.
History: Although in one study the Baker Formation was abandoned with its Onslow Member elevated to formation status[6] it is preferred for the Onslow unit to retain its member status, and the Baker Formation to be used as a full formation. This is because well bedded rhythyms of prominent sandstone alternating with argillite are widespread,

Fig. 5.17. Detail of a thick bed of Baker sandstone, containing a number of thin sandstone layers grading (leftwards) into mudstone, with thin turbidite units each side. The base of the thickest sandstone bed is at the head of the ice-axe, and the ice axe is 0.7m long. Western Malte Brun Range.

but variable in disposition of beds, and none of the constituent members, as described below, can be recognised beyond the Aoraki Mt Cook National Park. Such beds therefore are referred to an undivided Baker Formation, and occur north and east of the Aoraki Mt Cook National Park. Some of the members recognized in the Malte Brun Range are so thin that they cannot be shown on a geological map other than at a very large scale, and are therefore signified by letters and lines.

Cooper Peak Member

Name: The member was named from Cooper Peak[1].

Type section: The type section is well exposed at the south end of a small lake at the southern foot of Cooper Peak, along and above the portal of the Mannering Glacier.

Content: The member is made up of greenish sandstone in bands or beds 3-10m thick, with rare thin argillite bands 1-2m and rarely 5m thick, and exceptionally in beds 0.5m thick in bands up to 10m thick. The mafic mineral content is higher than for most units of the Mannering Group. The member is nearly 200m thick, but only 29-50m thick in the neighborhood of the Bonney Glacier. The sandstone bands include beds that are laminated, other beds that contain flecks of argillite, and beds that weather brown.

Distribution: This member has been traced through parts of the Malte Brun Range, and recognised also in the Sealy Range, and above the type section for the Acolyte Formation in the south Liebig Range.

Bonney Member

Name: The member was named from the Bonney Glacier, tributary to the Darwin Glacier[1].

Type section: The type section is exposed along the south wall of the Darwin Glacier, northeast of its junction with the Bonney Glacier.

Content: The member is characterised by thin alternating pale green sandstone 2-5cm up to 1m thick and black argillite in layers 5-30cm up to 2m thick, and the unit totals 25-70m in thickness. Bedding is frequently deformed and folded.

Distribution: This member lies above the Cooper Peak Member and is a minor unit, recognised widely in the Malte Brun Range, and above the type section of the Acolyte Formation in the south Liebig Range, as well as the Sealy Range and Wakefield ridge.

History: Initially treated as part of the Chudleigh Formation, the member was later repositioned in the Mannering Group.

Onslow Member

Name: The member was named from the Onslow Glacier[1].

Content: The member is made up of sandy and argillaceous turbidite in bands 30-50m thick, alternating with arkosic sandstones in beds up to 5m thick, in bands 50-100m thick, in all making up six bands 400m thick at the type section. Elsewhere the member may be up to 700m thick with 10 bands, and beds of sandstone, separated by thinner argillite bands, are conspicuous. Bedding structures are well developed, and chert is prominent in the member near De la Beche corner.

Steffan Member

Name: The unit was named from the Onslow (Steffan Memorial) Hut, Murchison valley[1].

Fig. 5.18. Folded Steffan Member (arrowed) on the south side of the Mannering Glacier, east side of Malte Brun Range. Beds of the Onslow Member lie to the left, and the sequence is fault-repeated to the right and left, by inclined thrusts inclined close to 45° west, as branches east of the Starvation Saddle Fault complex. Baker beds lie further to the left.

Fig. 5.19. Enlargement of view of Steffan Member, repeated by thrusts and folds, in Mannering Glacier.

Content: The member consists of units of prominent quartzose white sandstone separated by black mudstone, each unit 1-3m thick. The member is 15m thick in the type section.

Distribution: The Steffan Member is found along the east side of the Malte Brun Range, and each side of the Aida Glacier and Darwin Glacier. Because of its colour contrast, it is readily visible, and is probably a localized member, not ranging beyond the Park.

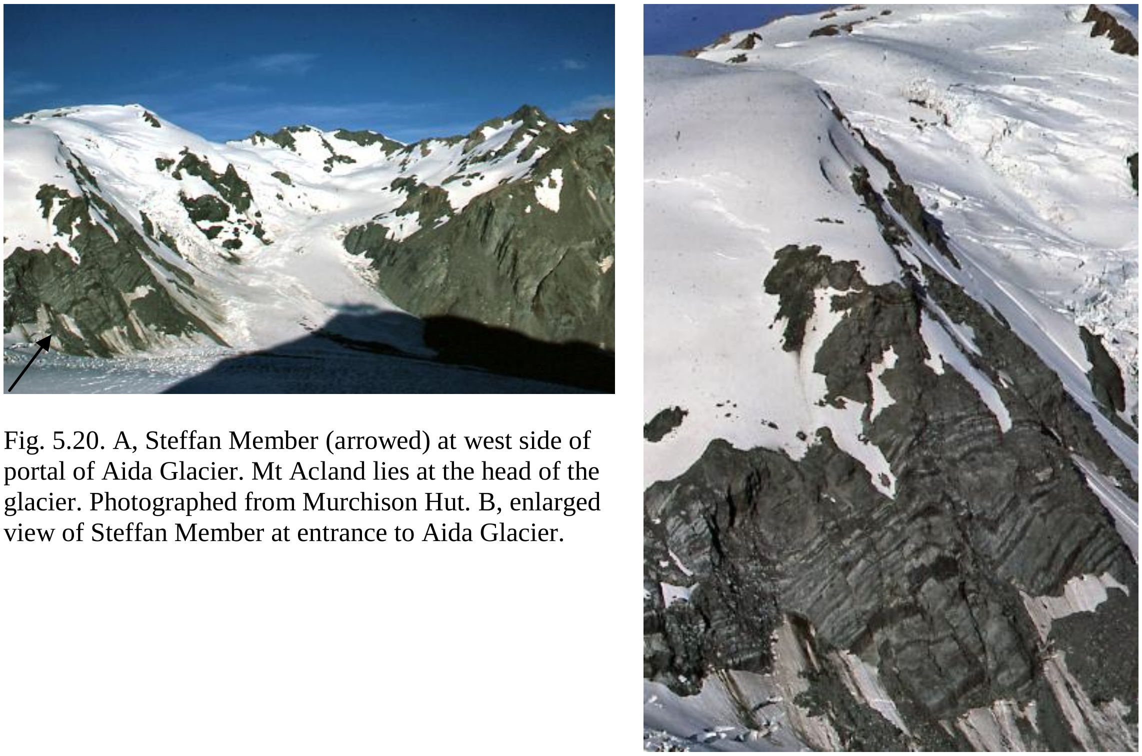


Fig. 5.20. A, Steffan Member (arrowed) at west side of portal of Aida Glacier. Mt Acland lies at the head of the glacier. Photographed from Murchison Hut. B, enlarged view of Steffan Member at entrance to Aida Glacier.

MALTE BRUN GROUP

The Malte Brun Group with its constituent formations was proposed for sediments that during Triassic time accumulated in a separate Malte Brun Sub-basin, within the Rakaia Basin ago. (See pp. 73, 124, 125 and Fig. 8.3). The name Malte Brun was taken from the range of that name[1], where outcrop is well displayed during the summer months. The rocks extend along much of the main divide of the Southern Alps, through Canterbury Province into the Travers Range of Nelson Province, and into Wellington Province (south coast, and Tararua Range), and make up part of the so-called Torlesse of New Zealand[12]. They are quartzofeldspathic, derived ultimately from plutons and quartzites, similar in composition to the sediments around Wellington[13]. Bedding is, as a rule, more strongly defined than in the Liebig Group, and folding less intense, although tight folds are locally present. There are no very thick bands of black argillite comparable to those of the Acolyte Formation, and sandstone is rarely very thick. No cherts are known, and coloured argillites are rare, and paler than those of the Rose Formation.

Novara Formation

Name: The formation was named from Novara Peak[1].

Type section: A type section is offered by the divide of the Malte Brun Range, leading northeastwards past Novara Peak to Mt Johnson. The base of the formation is not clearly exposed, outcrops towards the base of the ridge being too poor to be confident about the nature of the underlying rock, but it is likely that the formation overlies an ancient slide or tractator fault, above beds of the Burnett Formation.

Fig. 5.21. View looking east at Novara Formation towards the south end of the Malte Brun Range. The strata bend along the axis of the broad fold of the Malte Brun Anticline.

Content: The formation is made up of thick generally arkosic sandstone, well to poorly sorted, graded or massive, and thin partings of mudstone, black in colour. Scattered bands of mudstone up to 3m thick are found, together with 1-5m bands of thin alternating or graded fine sandstone and mudstone, with units only 1-3cm thick. Intraformational conglomerate is rare, and polyclast conglomerate not known. The formation seems to be at least 4000m thick in its type section if measured along the fold axis, but a truer thickness, measured from the thickness of the fold limb, is no more than 1500m, and probably less, because limbs as well as fold axes have been subject to tectonic interference. There are well developed thin argillaceous turbidites in the lower part of the formation, a thin unit of green siltstone and mauve mudstone in the upper beds, here segregated as the Malcher Member, and very thin "ribbonites", named for thin turbidites throughout the formation. The older part of the formation has more sandstone, usually in beds 1-5m thick, which weather to a pale white, sometimes with argillite flecks that give a speckled appearance, and scattered concretions appear higher in the succession. There are rare bands 0.5 to 1m thick of black mudstone, and rare 1-2m bands of current-bedded mudstone, siltstone and sandstone, some well graded, most uniform, and sometimes showing slurry marks. Higher beds have a more varied lithology, and include micro-turbidites and flasery sandstone and flecked sandstone with rare quartz fragments and grits and argillite pebbles. Quartz grit lies at the base of some sandstones. Rare chloritic mudstone and green tuff is developed, and green tuff just south of Mt Johnson represents the top of the formation.

Fossil content, age: The topmost beds have *Terebellina* as in the overlying Chudleigh Formation. Tubes are some 30mm long and 2-5mm wide, with a central lumen as thick as each wall. Grooves are not clearly developed. Distinctive very thin burrowings, of complex nature and very thin, are present widely.

Correlation: From stratigraphic position, the age would appear to be Lower Triassic.

Sedimentary environment: The formation is judged to have accumulated at the base of the continental slope, early in the development of slope and trough during Triassic time.

Fig. 5.22. Close-up view of Novara sandstone beds with bands of turbidite or ribbonite, as arrowed, characterised by thin layers of sandstone between the thin black mudstones, in southern Malte Brun Range. Scale bar 2m long.

Distribution: The formation has been recognised in the Malte Brun Range, and in the south Sealy Range, as well as to the south of the Park west of the Neumann Range and Hopkins River.

Malcher Member

Name: The Malcher Member is named from Malcher Peak, Malte Brun Range.

Type section: The divide ridge of the Malte Brun Range 1km south of Malcher Peak. The member is found in the upper Novara Formation.

Content: The lithology is outstanding for the Malte Brun Group, consisting mostly of green, mauve and pink silty beds (paler and more purple than the Rose so-called red argillites), 0.3-0.7m thick, with some sandstone, totalling some 200m thickness in all. White quartz grit and minor occasionally laminate green sandstones 0.3-1m thick are present, with some beds 2-3cm thick well graded and other beds being rippled or laminated. No fossils are known. The member is best shown on the ridge northeast of Novara Peak, the lower beds displaying exquisite mauve and green siltstone in beds 2-10cm thick, some current-bedded, and green sandstone 3-5m thick, graded and followed by black argillite, or ribbons of mudstone 1-5cm thick.

Sedimentary environment: Possibly the member with its abundance of coloured argillite has been derived from the Curraghmore Formation, found to the present west in the Otematata and Balmacaan Groups, as will be elaborated in the companion study now in preparation. It might thus provide a correlation marker, and the stratigraphic position would be consistent with the other correlations favoured herein.

Distribution: Possible correlates lie in the upper Darwin Glacier near Haeckel Peak, and on the northeast flank of that peak. No other occurrences are known.

Chudleigh Formation

Name: The formation was named from Mt Chudleigh[1].

Type section: The south wall of the Reay Glacier provides an excellent type section, reinforced by the divide crest through Mt Johnson to Mt Nathan, and also the north wall of Reay Glacier, and north and east ridges of Mt Chudleigh. The base is best exposed along the divide ridge.

Content: The formation, apparently some 1500 to 2200m thick at its type section, but no more than 1200m if allowance is made for axial thickening, is made up of 3-40m up to 200m bands of thick bedded to massive arkosic sandstone, occasionally slightly calcareous, divided by thin layers of siltstone and argillite, alternating with units 3-15m thick of mudstone and alternating fine sandstone and mudstone, with beds 0.2 to 0.5m thick. These mudstone beds are often graded, and are thicker than the individual beds in the Novara Formation. There are complex ”multiples” in which thick sandstone is followed by two up to five sandstone beds of diminishing thickness, separated by argillite which may be of increasing thickness. The sandstone beds are well defined, and persist visibly for up to 5km. They are not detectably lenticular, and are therefore interpreted as sheet deposits from slope turbidity currents that were free to spread without hindrance in deep water.

Fossil content: No well preserved fossils have been found. The fossil *Torlessia* is occasionally present, showing external linear ribs, and the tube-like *Terebellina* is also found.

Fig. 5.23. Chudleigh Formation at Bonney Glacier, beds younging west (to the right).

Fig. 5.24. Close-up view of Chudleigh sandstone, in graded layers passing up to graded thin turbidite units. (The image has been turned upside down – the ice-axe which is 0.7m long has been wedged behind a splinter to keep it from falling). The lower beds display suggestions of deposition by turbulent ocean currents. Reay valley, Malte Brun Range.

Correlation: The formation is correlated broadly with the Acolyte Formation, and is probably of Ladinian and perhaps late Anisian (Middle Triassic) age.

Sedimentary environment: The Chudleigh Formation is interpreted as having accumulated beyond the outer slope of the continental shelf as well sorted sediment in deep water at the distal end of, and probably redeposited from, the Acolyte Formation, which is made up of very thick sandstone units, alternating with thick bands of muddy turbidite and mudstone.

Distribution: The Mt Roberts Group[14] which is based on rocks in the Travers Range of southeast Nelson Province seems likely to be identical, and is treated as synonym. Many of the rocks of Wellington Province, along the south coast especially west of Wellington harbour, are comparable, and such rocks extend into the Tararua Range. In the Aoraki Mt Cook region, the formation is not known in the eastern or northern part of the Park. To the south the formation appears to be somewhat thinner than in the Malte Brun Range, where the thickness has been exaggerated by fault-drag folding.

Reay Member

Name: The member was named as a member of the Chudleigh Formation[1].

Type section: The southeast corner of the east wall of the Reay glaciated valley under Mt Johnson.

Content: The member is made up of massive sandstone 125m thick, weathering in patches to an orange rusty colour, somewhat less quartz-rich than other sandstones, and containing a few layers 1cm thick and stringers 0.5-0.1 thick of black argillite. No fossils are known.

Sedimentary environment: The member is exceptional for the Chudleigh Formation, and is interpreted as channel-fill, rather than a tectonic insertion.

Distribution: To the southwest, somewhat volcaniclastic sandstone is found along the south wall of the upper Mueller Glacier, east of Barron Saddle Hut, and appears like the Reay unit to be channel fill.

Walpole Formation

Name, type section: This formation, named from the Walpole Glacier[1], has its type section along the crest of the Malte Brun Range south of the summit of Mt Nathan to the top of the Chudleigh Formation. Other outcrops are found widely.

Content: The Walpole Formation is dominated by black argillite, in bands 3-10m thick, and sandstone and argillite turbidites, with scour casts, ripple bedding, and grading. Some small channel-fills are evident, 1-3m deep and up to 5m wide. Thin calcareous layers and small calcareous concretions are developed. In the Malte Brun Range, the formation is up to 200m thick. Layers split easily, and the mudstone is closely fractured, making for sharp edges to the rock. Conglomerate is present in units 0.4m thick.

Fossil content: Small tubes and *Terebellina* are found in the type area, and speculatively and from stratigraphic position, the age may be Carnian (Late Triassic). Fossils of this age are found nearby in the Southern Alps, and the Carnian-Norian bivalve *Hokonuia* has been reported from rocks of similar lithology at Otira Gorge[15].

Sedimentary environment: The turbiditic nature suggests deep water deposition beyond the reach of thick clastics, in a trough beyond the continental slope.

Distribution: This formation is developed widely, including the north Malte Brun Range, and over the Sealy and Neumann and other ranges of the main alpine divide.

Similar lithologies are found to the west as far as the Alpine Fault, where the beds have become schistose.

Fig. 5.25. Mt Sefton from the east, showing schistose turbidites of the Walpole Formation. Beds at the summit seem to have been overturned, and are arranged in tight small and large elongate folds.

Barkley Formation

Name: This formation was named from the Barkley Glacier[1].

Type section: The type section is offered by the divide of the Malte Brun Range, mostly just north of the summit of Mt Nathan.

Content: The formation is named for thick sandstone intervening between two argillaceous turbidite units called the Aiguilles Rouges and Walpole Formations. The sandstone is arkosic in beds 1-5m thick, and there are two or three 5m thick argillite-rich flyschoid units with thin sandstone layers. A few thin conglomerate beds are present, up to 0.4m thick.

Fig. 5.26. The base of a bed in the Barkley Formation in the Walpole Glacier, showing a regular pattern of scouring by ocean currents. The ice-axe is 0.8m long. Photo D. L. Homer.

Sedimentary environment: The formation represents a short-lived deposit, possibly developed near the outlet of a submarine canyon, given its position between deeper water turbidite deposits.
Distribution: The formation has been mapped mostly in the Aoraki Mt Cook region. It is 250m thick in the type section, as judged from the drag-fold-extended crest of the Malte Brun Range, but is less than 70m thick to the southwest in the Hopkins Valley.

Aiguilles Rouges Formation

Name: The name comes from Mt Aiguilles Rouges[1].
Type section: The type section is exposed along Barkley Glacier.
Content: Alternating sandstone and mud-dominated turbidite with subcalcareous beds, small-scale slumping, and sandstone channels characterise this formation. It is some 350m thick at the type section, with three sandy units, but six sand-dominated units lie along the divide, becoming coarser upwards in grain size. Gnarls on the west wall of the Barkley Glacier represent small distribution channels (Fig. 5.28). Megaripples, rare load casts and exquisite current bedding are developed. Some mudstone is limonitic.
Fossil content: Very similar beds have been described from Arthurs Pass to the north[16], where beds contain the Late Triassic (Norian) fossil bivalve *Monotis*. Further north the Travers Formation in the St Arnaud Range of southeast Nelson[14] is identical lithologically, and contains rare specimens of the same bivalve.

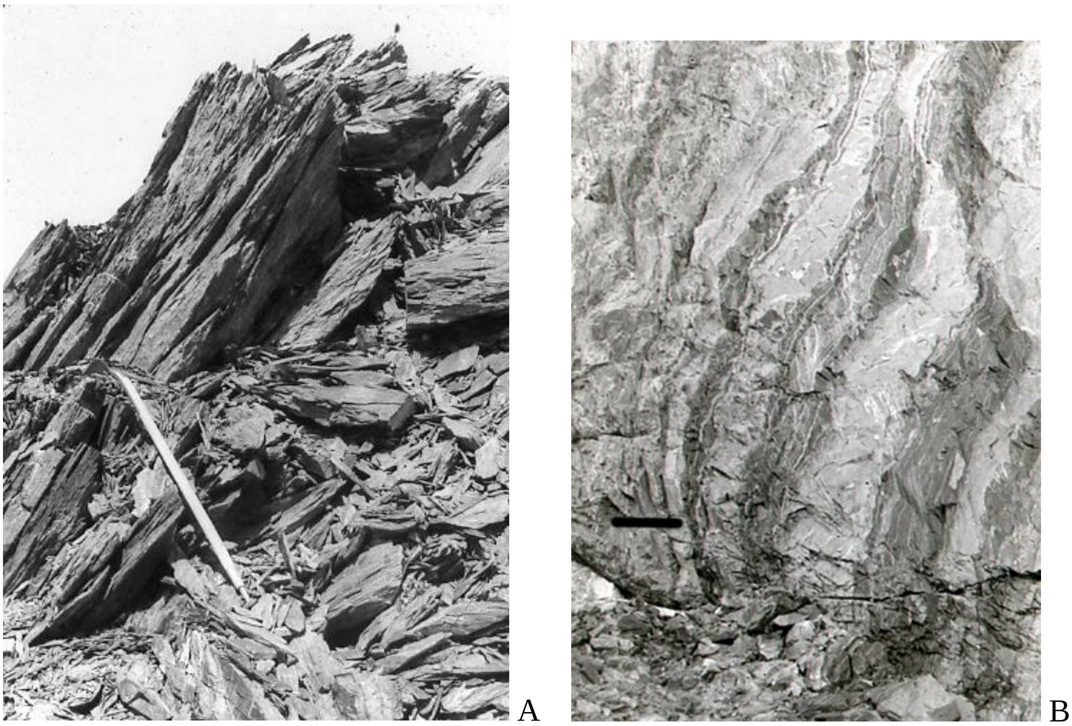


Fig. 5.27. A, Cleaved black mudstone in Aiguilles Rouges Fomation, with some sandstone beds at the . Langdale Glacier. B, turbidites of the Aiguilles Rouges Formation, Langdale Glacier. Ice axe 80cm long and scale bar in B 15cm long.

Sedimentary environment: This formation is regarded as trough infill, like the Walpole Formation.
Distribution: The formation becomes thicker towards the Alpine Fault, and probably

merges with the Walpole Formation. It contributed substantially to the schistose rocks (Haast Schist), which make up much of the Main Divide south of Mt Hicks.

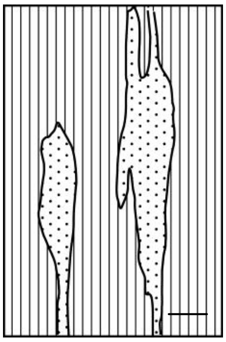


Fig. 5.28. Diagram of channels of sandstone forming gnarls in the argillaceous turbidites of the Aiguilles Rouges Formation, type section in Barkley Glacier, Scale bar 0.5m.

Fig. 5.29. Main Divide and Mt Brunner, with formations of the Malte Brun Group, now rendered schistose, viewed across the Mount Cook Range.

Frind Formation

Name: This formation was named from Frind Peak, Malte Brun Range[1].

Type section: The type section commences just south of the Aiguilles Rouges Peak, and continues north of the peak as far as the upper Beetham Glacier[17].

Content: The formation is characterised by arkosic, quartzitic, and muddy sandstone in beds 3-6m thick, alternating with intervals 5-20m thick of argillite and fine sandstone beds 0.1-0.3m thick. There is much dirty sandstone, thanks to mud intermixed with the sand grains and the sandstone-argillite may form multiples. No argillite layers are as thin as the ribbonites of the Novara Formation.

Sedimentary environment: The development of the Malte Brun Group involved a steady increase in depth and maturation of sediment, culminating in the Aiguilles Rouges Formation. The overlying Frind Formation marked a shallowing of the trough and increase in coarse clastic sedimentation, often with dirty sandstones containing a large clay component, presumably heralding the end of subsidence and commencement of shallowing that led to Jurassic emergence. No formation has been found to stratigraphically overlie the Frind Formation.

Age: The age is tentatively suggested as Rhaetian, latest Triassic, but no age data has been determined.

Distribution: The formation is limited in distribution to the Malte Brun Range and south and west of the Mueller Glacier.

SCHIST

When sediments are subject to shear strain or directed squeezing by faulting and folding, new minerals develop, as a rule along the planes of least pressure, so that the appearance and nature of the rock changes, in terms of new minerals aligned along planes of weakness. The rock becomes fissile, splitting readily along the weakest planes of new minerals. The rocks of the Southern Alps have been subject to great pressures, under the accumulation of overlying sediment, and under two major mountain building episodes, called Rangitata and Kaikoura Orogenies. Signs of burial alteration have been detected for Late Permian-Early Triassic (255-235 million years ago) and Late Triassic-early Jurassic (215-195 million years ago)[18]. It is believed that schist developed at various times, starting widely in the Jurassic, roughly 140 and up to 177 million years ago, succeeded by uplift and cooling in the mid-Cretaceous, about 100 million years ago, and resuming in the late Cenozoic, related to continued movement along the Alpine Fault, which began 38 million years ago[19].

The lowest grades of pre-schist alteration are assessed by authorities from the presence of zeolites[20], and at overlapping grades of alteration, zones of chlorite are recognized[21]. Many rocks in the Aorangi Mt Cook National Park belong to zone Chlorite 1 and 2, which also contain the zeolites called phrenite and pumpellyite. Rocks altered to Chlorite 3 and Chlorite 4 are more restricted in distribution. In their lower textural grades, schists are only weakly cleaved, with sedimentary features still preserved. At higher textural levels, bedding has been largely destroyed and replaced by transposition – that is movement of minerals into new layers that mimic beds, but not of original formation, and not deposited in that form on the sea floor. In addition there may be several episodes of refolding and segregation of minerals. Even so, the broad aspects of the rock betray their parent lithology at least to Chlorite 3, and so allow the rocks to be traced to their origins.

In the upper Murchison Glacier, near the Alpine Club hut, schist is well developed and readily accessible. The schist has developed in a complex shear and intensely folded zone around Starvation Saddle. A fault runs from above the hut down the snowfield, with another fault converging from the south. Movement along the fault has folded rather than caused the schist, arguably through dextral movement because synclines plunge northwest, and offsets of rock and geomorphic features suggest right lateral (dextral) movement north of the hut.

Under increasing pressure, rock may become more and more buckled, and there is a complicated system of fold-analysis by geologists that unravels the sequence of responses to pressure to point to the history of folding, and therefore mountain building. Near the Murchison hut, the symbol F1 may be applied to sedimentary slumping, and F2 to now east-west oriented and minor folds, verging (facing) east. Metamorphic lineations seem to be parallel, but not always. F3 signifies the main folding and development of lineations with axial plane cleavage. F4 involves intense local folding, across lineations and along limb axes. In the ridge below the Murchison hut, sandstones 5-10m thick are metamorphosed, and mudstone up to 2.5m thick has been squeezed into lens, and in some examples, apparently squeezed out of existence. The bands are now highly contorted. Schist is well developed over the ridge leading to Mt Cooper south of the hut, but schist comes and goes over the south Cooper ridge. One of the complexities in mapping the degree of alteration into schist is the way the grade changes along strike in these mountains of the Park, especially east of the Main Divide., so that accurate mapping of schist entails a great deal of careful work, if massive extrapolation is to be avoided.

Over the Sealy Range, above the prominent and massive green sandstones immediately above The Hermitage, formations up to and beyond the crest of the ridge are metamorphosed to Chlorite 2 and rarely Chlorite 3, with an overlying band of greenschist[11]. Further west the formations are less metamorphosed. Where schists are widespread, and well understood, they are mapped as formations, as in the Mt Ida area south of the Waitaki River[22]. In the Aoraki Mt Cook National Park, it is considered that to map beds as schistose is to conceal their affinities and origins, and the stratigraphy is clear enough, with obfuscation – assuming the goal is to clarify origins - unnecessary. In so far as metamorphism is concerned with post-stratigraphic alteration, metamorphic maps should arguably be divorced from stratigraphic maps, or better still, superimposed on stratigraphic maps.

Schist is widespread along the Main Divide, from the southern border of the Park near Barron Saddle, to Harper Saddle west of Mt Hicks, belonging to Chlorite 3 and above, and the rocks can be attributed to formations despite a high degree of deformation and alteration by their overall appearance, including colour, aided by contiguity with identifiable formations above and below and along strike.

Chapter 6

ANCIENT FAULTS

Recent faulting may reactivate old faults – and even reverse the direction of movement. Some authorities seem to claim, in discussing recent earthquakes, that faults can only act along a pre-existing fault, but this is nonsense, and seems to imply that all structures were laid down in Genesis One. The truth is that under steadily changing direction of earth pressure, new deformations can develop, some of which are faults. But it may be difficult to distinguish old faults, worn down so that no fault scarp is apparent, from really ancient faults, tens of millions of years older, which were initiated when the mountain-building first took place over the Southern Alps. It is complicated enough to unravel relatively recent and active faults, developed under the present sea-floor spreading regime and closely related to the Alpine Fault, so it may prove difficult to establish whether a fault which cuts across rock at a high angle, but leaves no surface scar, is ancient or modern. But it is even harder to determine the presence of a fault that lies parallel to the beds. Yet these play an important role in controlling the distribution of beds and formations. There are a number of faults, here termed ancient, that lie parallel to the beds, and which may be called bedding-plane faults and are indicated by the removal of formations. The complete succession for older rocks in the Park involves the Malte Brun Group, and time equivalent Mannering Group, which overlies the Liebig Group. If some of the groups or some of their formations are missing, or if they lie in an unusual relationship, then a fault may be suspected. Moreover these particular faults are somewhat unusual for New Zealand, because the faults lie parallel to the bedding, and strata and formations of quite different ages may lie next to another in parallel, and in many instances, older strata lie on top of younger strata, which is the reverse of normal stratigraphic succession. It is possible to explain this by an elaborate series of vertical fault movements and rotations, but the simplest explanation is often – not inevitably – best. And this is that rocks were either thrust subhorizontally, not vertically, or as an alternative, slid down a gentle slope, under the sea probably, in what are called nappes. Such nappes are common in major mountain ranges of the world, such as the Alps of Europe, Rocky and Appalachian Mountains of North America, and Himalayas of the Indian subcontinent. I have worked for many years in the Rocky Mountains and in the Himalaya, as well as travelling through the Alps and Appalachians, and am satisfied that the Southern Alps of New Zealand also have a similar basic structure, that arose in the Mesozoic Era, and was later disrupted by Alpine Fault strike-slip movement, with steeply inclined faulting. In this latter respect, the Southern Alps are unusual, but deformation and growth of the original Southern Alps began just like many other mountain ranges, with the development of huge submarine slides. Some geologists, brought up in New Zealand and persuaded by the strong and prevailing emphasis on strike-slip lateral faulting and considerable vertical displacements, do not like this model. One even pronounced that there were no nappes in New Zealand, because there were no terminal folds and heaps of rock at the front of nappe slides. But such are found only in Europe in one small area. In other regions, including much of the Alps, Appalachians, Rocky Mountains and Himalaya, such occurrences have been destroyed by erosion, or, as may be the case for New Zealand, destroyed by later mountain building and subduction. It has also been stated that “strong mylonitic fabric should be developed at the base of recumbent folds” but this is dubious[1].

Persuasive evidence for ancient faulting is demonstrated in the southern Liebig Range, where layers of Permian Rose Formation lie above layers of much younger mid-Triassic Acolyte Formation: there is faulted contact between them, and some faults are parallel rather than steeply inclined to the bedding. Such suggests nappes or low angle thrust faulting, also called slide-faults. Near Mt Misery, east of the Park borders, there are actually six such layers, Rose Formation alternating with Acolyte Formation, to form schuppen. The bedding-plane faults were related to the first mountain building phase of the late Jurassic and early Cretaceous Periods, starting more than 170 million years ago, called the Rangitata Orogeny. Later such faults were folded and refaulted, during the younger and ongoing mountain-building phase, called the Kaikoura Orogeny. It would be possible to achieve a much more complicated explanation that avoided the need to propose low angle faulting or sliding, but such explanations are not based on geological evidence.

ANCIENT AND POSSIBLE ANCIENT FAULTS (Fig. 6.1, Fig. 6.3)

Sealy Range and divide west of Mueller and Hooker Glaciers

Ancient fault 1. Looking first at the southern areas, and starting in the west, beyond the Park boundary, metamorphosed green volcanic rock (greenschist) of the Liebig Group, with fossil evidence for a Permian age, lies over Frind Formation of the upper Malte Brun Group. This is an unnatural relationship: Permian volcanic rock, metamorphosed into metavolcanics, lying above upper Triassic Frind Formation. Ancient faulting has placed the Liebig rocks over the Upper Triassic Frind Formation. Possibly the rocks and structures curve into or near the Park boundaries in the upper Tasman Glacier (see pp. 118-119).

Ancient fault 2. The Malte Brun Group lies above the Liebig Group, and the Mannering Group has been lost, destroyed by slide-faulting.

Ancient fault 3. On the east face of the Sealy Range, the fault- or slide-thinned Permian Liebig Group is separated from the Mannering Group below by a fault, and the Mannering Group consists of Onslow and Cooper Peak Members and Baker Formation, and Sebastopol and Unwin Members of the Acolyte Formation. This fault extends as far as Harper Saddle on the west side of Mt Hicks.

Ancient faults in the south and west Park

Ancient fault in Ben Ohau Range? The geology of the upper reaches of Birch Hill Stream at the southern boundary of the National Park is like that of the Ben Ohau Range, and consideration is left for study of that range in the companion study.

Ancient fault 4. The geology seems to get more complicated in the Mount Cook Range, south of Aoraki Mt Cook and east of the Mueller and Hooker Glaciers, because ancient fault 4, dividing the Mannering Group (Triassic) from the overlying but older Liebig Formation (Permian), has itself been strongly folded by later distortion, at least partly relating to the phase of mountain building during the Kaikoura Orogeny. Possible vestiges of the ancient fault cross the Hicks – Dampier ridge, Earle Ridge and near Pudding Rock, but much later faulting cannot be ruled out. The fault is more completely exposed over the Mount Cook Range, emerging on to the Tasman valley south of Ball Glacier. From north of Ball Pass in the Mount Cook Range to as far as the Main Divide north of the Rudolph Glacier, most of the rocks belong to bands of Burnett and Rose Formation, partly in stratigraphic contact, partly in faulted contact, and there is no clear evidence for any ancient fault. The Rose and Burnett reach considerable thickness, as if the tract to which they belong has been greatly swollen by probable Quaternary faulting.

Ancient fault 5. On the east side of the Rudolph Glacier at the southern end of the De la Beche ridge, beds of the Mannering Group appear to underlie beds of the Burnett and Rose Formations. As discussed shortly, this could be a northern extension of ancient fault 4, with the continuation of that fault largely covered by the Tasman Glacier.

Possible and likely ancient faults in the Malte Brun Range

Ancient fault 6. It seems probable that an ancient fault separates Burnett Formation of the Liebig Group from Mannering Group (Steffan, Onslow and Cooper Peak Members and Baker Formation). The Burnett is closely folded, and on the whole seems likely to have overlain Onslow Member, and is separated from that formation by a fault.

Ancient faults 7, 8. Fault 7 divides Mannering from Liebig and mostly Malte Brun Group, and fault 8 divides Liebig from Malte Brun Group. The two have been partly revived and partly destroyed by recent activity along the Beetham Fault, which has merged the two over much of its course. The rocks each side of the Beetham Fault are not parallel, and so not like those of several of the other ancient faults itemised in this account. They may have once been parallel and later altered by further distortion. A fault also passes through the Malte Brun Pass. The suggestion of a sinuous outline might suggest great age – but folding of fault lines is not unknown, as discussed below, and it is therefore regarded as a fault of the Kaikoura Orogeny.

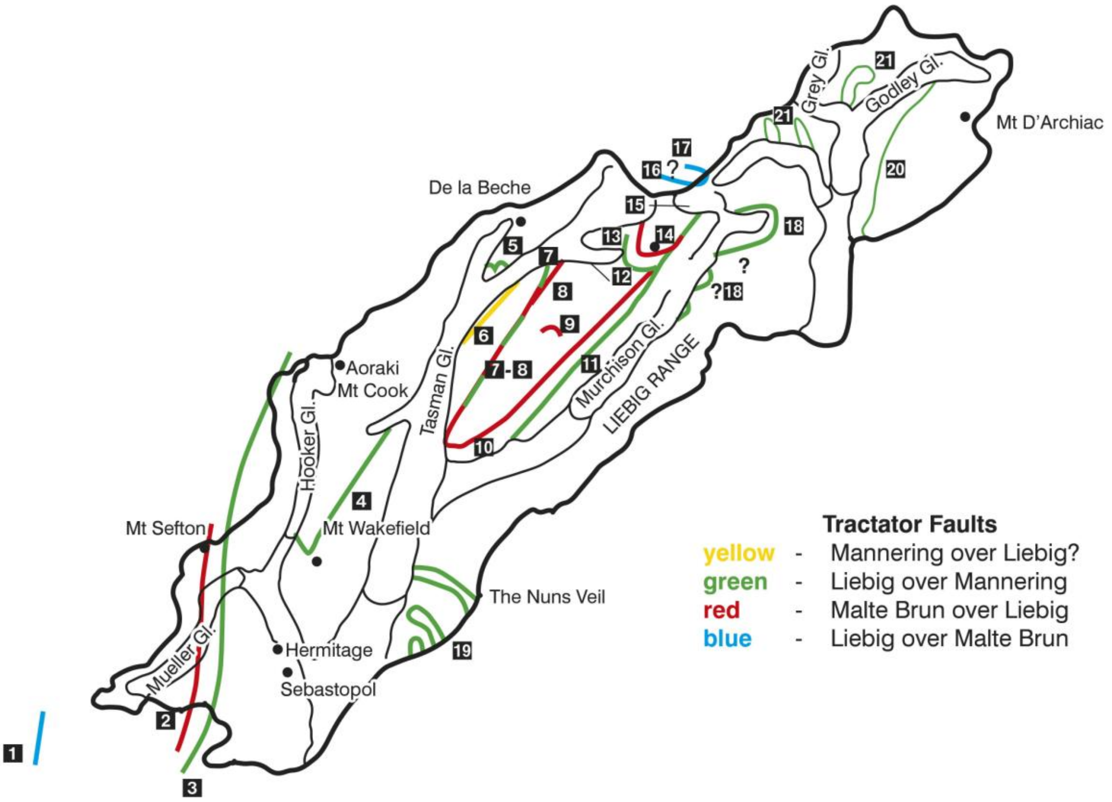


Fig. 6.1. Sketch map of Aoraki Mt Cook National Park, outlining faults which are likely to be ancient faults – that is tractator faults, coded by number as discussed in the text, and by colour as signifying correlative tractator faults. Some faults shown as a plain black line (eg. 12, 15) are deemed to be of more recent origin. Doubt attaches to Faults 16 and 17.

Ancient fault 9. This fault separates Liebig (Rose Formation) from Malte Brun Group (Chudleigh Formation) on the southern face of Mt Malte Brun.

Ancient fault 10. Fault 10 along the eastern side of the Malte Brun Range separates Triassic Malte Brun Group from mostly Permian Liebig Group.

Ancient fault 11. Another fault close by separates Liebig Group from Mannering Group. Both faults 10 and 11 have been reactivated during the Kaikoura Orogeny, and so the strata each side of the present fault are no longer always parallel to each other, and as well have become partly merged.

Further ancient faults are associated with the Haeckel Syncline in the northern Malte Brun Range.

Fault 12. Fault 12 lies between Malte Brun Triassic and Mannering Triassic. If it ever was an ancient fault, it has been rejuvenated by Kaikoura faulting, to bring Onslow and Steffan beds of the Baker Formation of the Mannering Group into contact with the Chudleigh Formation of the Malte Brun Group, so that a number of Malte Brun Formations are missing, and have been faulted out. Were the contact indicative of an ancient fault, it would imply that the Malte Brun tract was overlain by a repeat succession of tractator faults and tracts found in the Sealy Range and south Malte Brun Range. But it seems more likely that the succession is repeated by Kaikoura faulting, rather than by development of Rangitata slide sheets.

Ancient fault 13. The The Mannering Group lies in juxtaposition with Permian Liebig Group.

Ancient fault 14. The Liebig Group lies below Malte Brun Triassic.

Upper Tasman Glacier

Fault 15. Limited outcrops near Tasman Saddle and Kelman Huts, between the Liebig and Malte Brun Groups, suggest a fault between strata that belong to the Burnett Formation to the north and Chudleigh or other Malte Brun Group units to the south. Probably the fault belongs to the Kaikoura Orogeny: and it has been recently active, as indicated by the rocks along the divide between the Tasman and Murchison Glaciers rocks a little to the north of Kelman Hut. The fault and the rocks either side are of very limited outcrop, so that it is difficult to determine the nature of the fault.

?Ancient faults 16, 17. It is possible, but uncertain, that the Malte Brun Group exposed over the Main Divide, and involving Graceful and Brodrick Peaks, is separated from older Liebig Group and possible Mannering Group by faults. Possibly these belong to one fault that bordered the southerly and northerly margins, and was later folded. But the area was obscured by fog when examined, and the affinities of the rocks insecure.

Liebig Range

Ancient fault 18. Complex possibilities lie in the structural arrangement of the rocks between Mt Cooper and Coopers Mate, each side of the Murchison Glacier, involving the Mannering and Liebig Groups. The Mannering beds dip below Liebig sediments around the Aida Glacier, but only a small area of Liebig remains across the Murchison Glacier north of Mt Cooper. One fault is recognised, but there might be two. Outcrops of possible Acolyte sandstone (or sandstone of Cooper Peak Member) along the Murchison valley seem to be faulted against Rose Formation, and might have been part of the same fault, or developed much later as a Kaikoura fault.

Ancient fault. Only traces of an ancient fault are suggested north and south of the Classen Glacier, between Acolyte or Baker deposits of the Mannering Group, and older Rose Formation. Evidence for the nature of the fault is best provided further south along the west side of the Godley valley, beyond the Park boundary, and analysis is deferred.

Ancient fault 19. In the southern Liebig Range, involving the peaks of Biretta, The Nuns Veil and Armchair, as well as Botanical Spur and Gorilla Stream, extensive deposits of Rose Formation are separated by a fault from Acolyte and subsidiary components of the Mannering Group. This fault and rocks either side have been gently folded in large open folds in comparatively recent times. Some underlying rocks belonging to the Mannering Group are not parallel to Rose rocks, but lie at high angles, as if a nappe traversed highly folded rocks.

Upper Godley valley

Ancient faults 20,21. Rose Formation lies in narrow strips (21), as illustrated in Fig. 49, 50, 52, pp. 110-113, and in great accumulations (20) over Acolyte Formation, and sometimes Burnett Formation around the Godley valley and subsidiary glaciers.

The development of Tracts of sediment and Tractator Faults (= ancient faults)

During the Permian and Triassic Periods, from almost 300 million years ago to almost 200 million years ago, the rocks of the Aoraki Mt Cook National Park were laid down over sea-floor of the Rakaia Basin, the Wheeler, Rose and Burnett Formations of the Permian Liebig Group, followed by the Acolyte and Baker Formations of the Triassic Mannering Group. In another part of the sedimentary basin, called Malte Brun Sub-basin, rocks of the Novara, Chudleigh, Walpole, Barkley, Aiguilles Rouges and Frind Formations were deposited, to form the Malte Brun Group. There were phases of disturbance by earthquake, sea-floor shifting and submarine slumping during the Permian Period, in which rocks are folded more than the younger sediments, followed by major disturbance after the Triassic, and during the Jurassic Period, when dry land emerged[3] to the east, to be colonised by land-plants, as around the Clent Hills near the Ashburton River in central south Canterbury. Major mountain building, as the Rangitata Orogeny, became vigorous during the middle to late Mesozoic Era, and the deep-water and submarine continental shelf deposits began to rise, and slide as nappes, or be thrust as fault bound tracts over tractator faults.

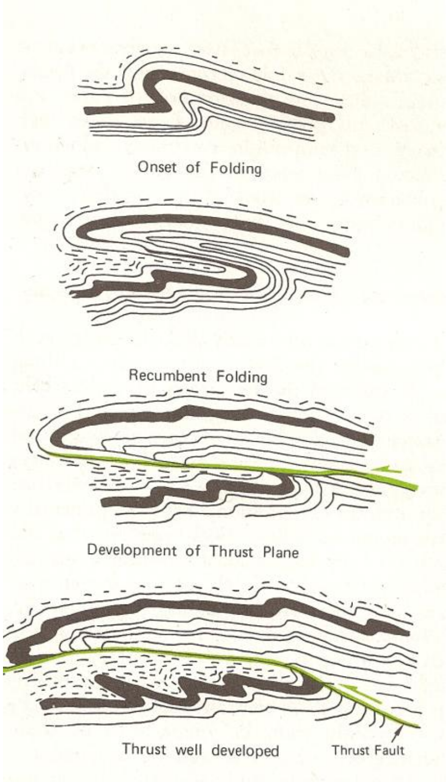


Fig. 6.2. A standard representation of the development of low angle thrust sheets, shown as cross-sections of a fold growing in the rock, and breaking along its lower limb[2]. The difficulty comes from trying to understand what is impelling the growth of the fold and fault. A different interpretation visualizes the fold and fault as growing under gravity. According to this interpretation, the fold, and later the fault develop as sediments are sliding downslope, impelled by gravity. The sediment on the sea-floor has been lifted up, and so the folds grow because the sediments have been tipped over and have spilled out.

It should be realised that there was both a piling up of tracts, to form mountains, and a spreading out of some tracts far from their original position, in present terms eastwards, so that a term such as accretion, though commonly used with reference to the Rangitata Orogeny, does not do justice to this particular orogeny. Accretion has been envisaged as sediments being carried on sea-floor that acted like a conveyor-belt, moving towards a subduction zone. Such did not apply to the alpine sediments that underwent the first major orogeny in the Southern Alps, where there was a great deal of spreading, sediments sliding many tens of kilometres from the original position[4]. The rocks of the National Park do not show any sign of accretion: the term has been misapplied to them, from a misunderstanding, or more likely a general unawareness, of their geology, by geologists anxious to apply a model, or extrapolate from postulations made elsewhere in the globe.

In the schistose rocks to the west and south of the Park, huge recumbent folds or nappes are well developed[5]. These are allied to the tracts of the Park, but appear to have developed at depth under a pile of overlying sediment.

The Aoraki Mt Cook National Park is too small an area to amply interpret the nature of the Rangitata Orogeny, so the nature and age of rocks of a much larger area between the Rakaia and Waitaki Rivers are considered in discussing the orogeny in Chapter 7.

INTERRELATIONSHIPS BETWEEN THE ANCIENT FAULTS

An important question concerns how these ancient or tractator faults interrelate, in order to construct a succession for the tracts and their tractator faults, whilst making due allowance for interference and modification during the Kaikoura Orogeny.

Main Divide from Barron Saddle to Elie de Beaumont, including Sealy and Mount Cook Ranges

The Hopkins-Sealy-Mueller-Hooker succession is made up of four tracts, dominated in turn by Liebig, Malte Brun, Liebig and Mannering sediments, separated by ancient or tractator faults 1, 2 and 3. The intervening tracts may be termed A, for the Malte Brun sediments between tractator faults 1 and 2, tract B for the Liebig sediments between faults 2 and 3, and tract C for Mannering sediments below tractator fault 3.

A degree of interpretation is necessary to unravel the relationship to ancient fault 4, which separates Mannering from Liebig Group in the Mount Cook Range. It is apparently identical with ancient fault 3, and if so, carries implications for the overlying tract of Liebig Group, which is of thin to moderate thickness over the Sealy Range and Main Divide north of Mt Sefton, and increases to great thickness over Aoraki Mt Cook and northwards beyond the Rudolph Glacier, as far as Mt Elie de Beaumont. This increase may reflect in part a change in the thickness of the tract that developed during the Rangitata Orogeny, but also reflects Kaikoura insertion through faulting of additional fault- or fold-controlled packages of Burnett and Rose Formations. Ancient fault 5 at De la Beche corner is the same as ancient fault segments 3 and 4. This being so, it is possible to suggest a comparatively simple major outline of tracts and tractator faults for the rocks of the Park for much of the southwest and middle segments (Fig. 6.3, p. 76). They have been folded in a major Wakefield Syncline, and the rocks of the Sealy Range and much of the surrounds of the Hooker Glacier belong to a west dipping limb, implying an anticlinal axis west of the Wakefield Syncline. No axis is preserved, and has been possibly faulted out, but more likely concealed by closely spaced folding as over Aoraki Mt Cook. The western limb of the Wakefield Syncline north of Ball Glacier is also ill-defined. If it did persist, it has been masked by folding, because eastward younging sediments that would be part of such a limb are common along the eastern slopes of the Main Divide north of the Ball Glacier and as far as the Rudolph Glacier. The obscuring of putative fold limbs or axes by this degree of folding explains the thickening of the tract, through insertion of additional Rose and Burnett Formations of the Liebig Group from Aoraki Mt Cook and northwards.

Malte Brun Range

The arrangement in the Malte Brun Range is complex, and considerably disturbed by Kaikoura faulting. To some extent, questions remain. Simplistically, the range is traversed from north to south by two major tractator faults on each side of the range, numbered 7, 8, 10 and 11. But the tracts and tractator faults have been strongly affected by renewed faulting during the Kaikoura Orogeny. On the western side, there are two small fault-bound slivers of Rose and Wheeler Formation next to the Mannering Group sediments, which appear to be remnants of the Liebig tract B above tractator fault 2 (= 4 and 5). It would seem likely that much of the Liebig tract has been removed by the Beetham Fault, to bring much of the Mannering Group and its underlying tractator fault 8 against Malte Brun Group. On the eastern side of the range, faults 10 and 11 match faults 7 and 8 next to the western Liebig outcrops, and fit with tractator faults 2 and 3 in the Sealy Range. They are better preserved than along the western side of the range, but have been reactivated to varying degree in more recent time. Ancient fault 9, separating Rose from Malte Brun sediments on the south face of Malte Brun peak, clearly matches ancient fault 2 = 7 in part, and 10.

On the western side of the range, it is possible that a tract lying above ancient fault 6, and involving much folded Burnett Formation, formerly was part of tract B, and that it later was folded in a small fold, before substantial faulting. But other possibilities cannot be ruled out, and no reconstruction can be definitely established. Any distinction from or equation between fault 6 with faults 3 and 4 can be no more than conjectural, and the fault itself has by now been largely modified by recent activity. The belt of Mannering Group that is exposed at De la Beche corner, and below ancient fault 5, could be presumed to curl across and underneath the Tasman Glacier into the belt of Mannering Group along the western Malte Brun Range, younging westwards as if on the eastern limb of a major syncline. At present it is not possible to determine if fault 6 is the same as fault 5 – if so, it forms part of the overall simple succession. But if fault 6 was separate, it may indicate a fresh tract D, underlying the Mannering Group, and it is coded provisionally as separate in Fig. 6.3.

At first sight, the tracts and tractator faults of the Haeckel Syncline appear to fall within the same arrangement, with tractator faults 13 and 14 matching faults 2 and 3, and the tracts moderately close to their counterparts to the south and west. The significant fault is number 12, between Malte Brun Group apparently below, and Mannering Group above. Overall, the geometry implies that fault 12 is a Kaikoura fault, upthrown to the east. To regard it as a tractator fault would mean that for this area, the Malte Brun Group was followed by further tracts of Mannering, Liebig and Malte Brun Groups, and that step is difficult to sustain, in view of the nature of the fault.

Head of Tasman Glacier, Liebig Range

The poorly exposed fault 15 south of Tasman Saddle Hut and near Kelman Hut seems to be a recent fault. It could have revived an ancient fault, as a continuation and modification of the fault 13 and/or 14, but that remains unproven. Little can be said of faults 16 and 17 which border the turbidites at the head of the Murchison Glacier, exposed in the peaks of Graceful and Brodrick. As suggested on p. 70, they might even match ancient fault 1, known from the Hopkins River area, but could be of much less significance, or even non-existent.

Tractator fault 18 in the neighbourhood of Mt Cooper and Coopers Mate separates Liebig Group above Mannering around the Aida Glacier, suggestive of ancient fault 3, and probably a modified continuation of fault 10. Some outcrops mapped as Wheeler Formation of the Liebig Group lie north of Mt Cooper, to be interpreted as either infaulted, and/or an offline remnant of the Liebig rocks to the south. Apparently the Baker beds underlie Rose Formation, consistent with tractator fault 3, but to the south of Coopers Mate, Rose could underlie Baker, and the relationships are uncertain in this area. Possibly the rocks belonged to an underlying tract of Liebig Formation, below a tract of Mannering Group, and possibly tractator fault 18 is the oldest in the Park. But more study is needed, and provisionally the Baker beds are regarded as enclosed by one tractator fault, which is regarded as extending south along the east wall of the Murchison Glacier to delineate some outcrops which are provisionally assigned to Acolyte sandstone, though they also resemble Cooper Peak beds.

Tractator fault 19 in the southeast part of the Park between Rose and mostly Acolyte Formation matches fault 3 and 4 of the Sealy and Mount Cook Range. Tractator fault 20, between Mannering and Liebig Groups, matches tractator fault 3 of the Sealy Range.

This summary covers a limited area, and it will be possible to elaborate on the extent of the tracts and the nature of the tractator faults in the companion volume. In the Aoraki Mt Cook National Park, tracts largely consist of only one group, Liebig, Mannering or Malte Brun, but elsewhere tracts often involve both Liebig and Mannering Groups, whereas the Malte Brun Group is always in a tract of its own.

MAJOR FOLDS

Wakefield Syncline and possible anticline to the west

Beds of the Sealy Range and Mueller and Hooker Glaciers young west, and so suggest the west limb of an anticline, opposing the eastward younging beds of the

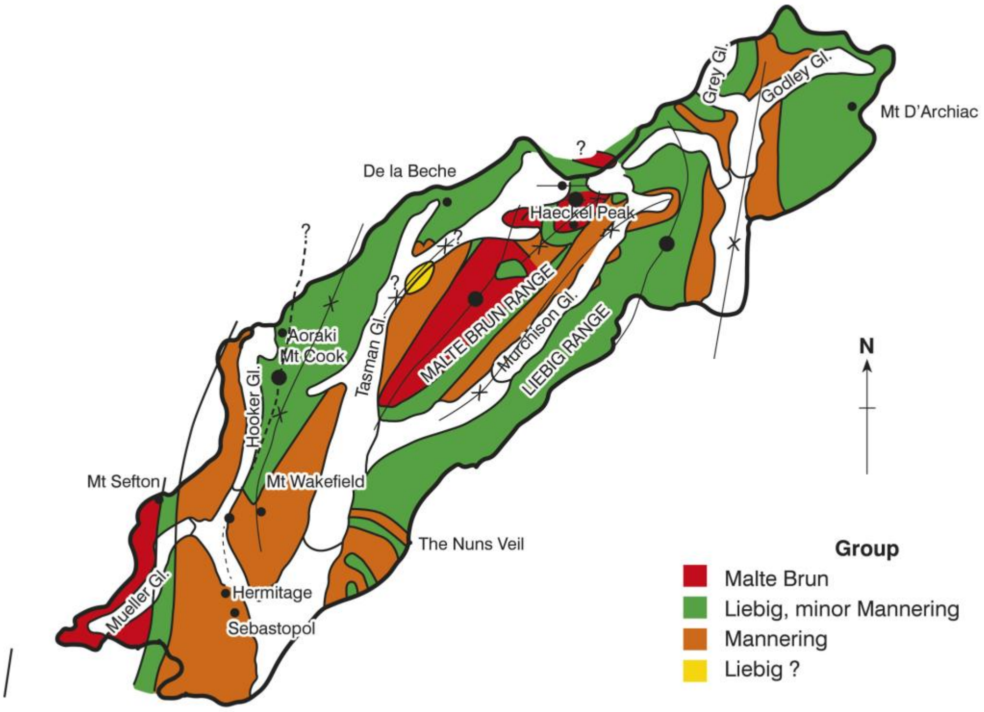


Fig. 6. 3. Map of Aoraki Mt Cook National Park showing the distribution of tracts and only some of the major folds in the Aoraki Mt Cook National Park. The dashed line on the left shows a putative anticlinal axis west of the Wakefield Syncline. and the synclinal axis west of the Malte Brun anticline is highly speculative. The Annan Anticline shown (not named) north of Haeckel Peak possibly was bent round from the Malte Brun Anticline which traverses the Malte Brun Range.

southern Mount Cook Range in the Wakefield Syncline. The axis of such a fold is not known: it may lie concealed within the folds over either the western or eastern flanks of Aoraki Mt Cook, or even both flanks, or have been lost within a fault, perhaps for only part of its extent, south of Pudding Rock, concealed by the Hooker Glacier. The northern extent of the Wakefield syncline is also obscure. Attention will be drawn to the complexity of the fold in the Ball Glacier (Fig. 7.10, Fig. 7.11, p. 87) and folds are found west of the Tasman Glacier, below the Main Divide, masking any major synclinal axis. Certainly many beds young east, as in the Wakefield Syncline further south.

Malte Brun Anticline and minor associated folds

The Burnett beds along the westerly side of the Malte Brun Range can be interpreted in different ways. They could represent Liebig Group, underlying Mannering Group, to suggest the presence of a minor fold, largely hidden by the Tasman Glacier. But recent faulting, or duplication of the Liebig/Mannering tractator fault offer alternative explanations.

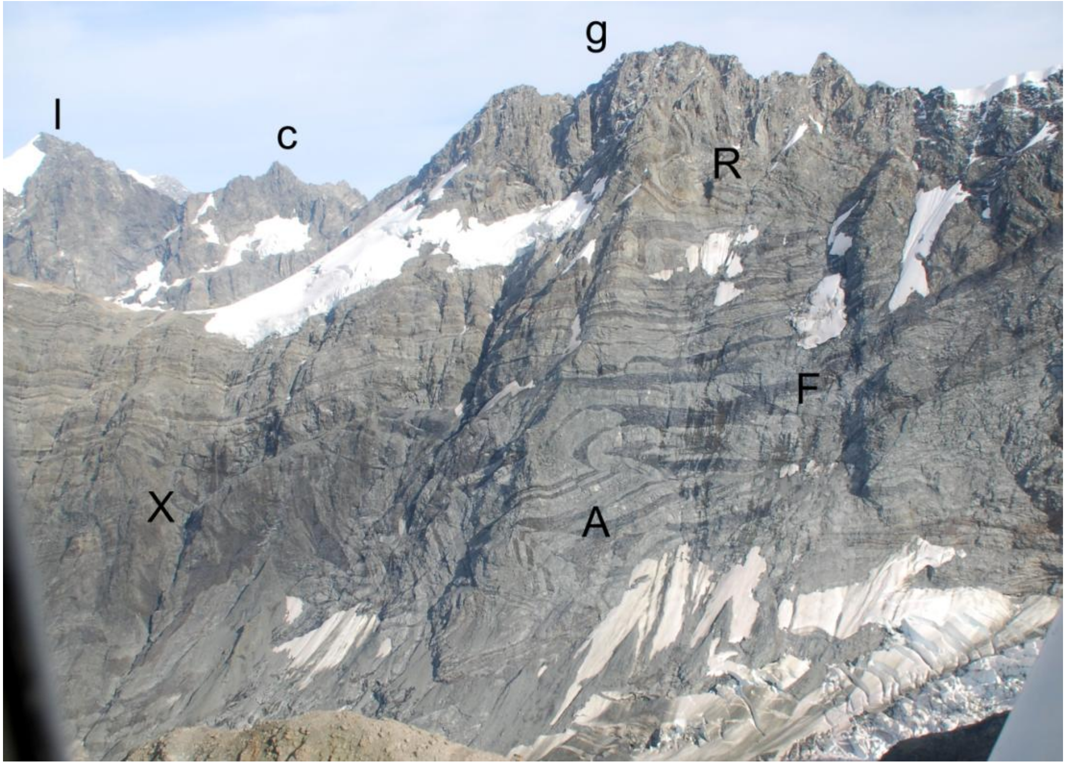


Fig. 6.4. The western wall of the Maud Glacier, below Mt Fletcher (g), made up of rocks of the Rose (R), Burnett and Acolyte (A) Formations, which have slumped southeastwards in folds. Small thrust faults (F) and chaos breccia (X) have also developed during the sliding. Mt Cassino (c) and Mt Livingstone (l) in the background, west of Grey Glacier.

The Malte Brun Anticline involves two substantial tractator faults and three tracts. The westerly band of Liebig and Mannering Groups suggest a former anticlinal axis, since destroyed by the Beetham Fault complex, or substantially uplifted Liebig – Mannering that formerly underlay Malte Brun. The adjoining Malte Brun Anticline, composed mostly of Malte Brun Group, underlain by Liebig Group as shown by the south face of Malte Brun, could have originally been flat-lying beds or folded in a syncline by the end of the Rangitata Orogeny, and then subsequently everted and squeezed to a steeply plunging anticline, but a syncline seems unlikely due the presence of the nearby Haeckel Syncline. The Malte Brun fold persists as far as the upper Tasman Glacier, and does not appear further north, judged from outcrops at the head of the Whymper Glacier. Possibly the axis bends sharply from an approximately northern trend into an east-west trend, as represented by the Annan Anticline, a distorted anticline along the Annan-Darwin ridge. Such bending would have developed at the time of uparching and apparent westward stepping of the rocks, as discussed on p. 119. A broad shallow syncline, the Burnett Syncline, lies east of the anticlinal axis and probably resulted from Kaikoura deformation.

The arrangement of Mannering sediments at Cooper Peak and across the Murchison Glacier in the vicinity of the Aida Glacier suggests an anticlinal arch. Further north, the arrangement of mostly Acolyte Formation of the Mannering Group and Rose and Burnett Formations of the Liebig Group suggest a large and weakly defined, folded and faulted syncline, with complex axis largely along the Godley valley, overlain by Rose Formation.

Chapter 7

GEOLOGY THROUGHOUT THE PARK

In this chapter, aspects of the geology are summarized for the different areas in the Aoraki Mt Cook National Park.

MUELLER GLACIER, SEALY RANGE

The Mueller Glacier lies between the Sealy Range and Main Divide with Mt Sefton and other peaks. A variety of rocks and formations, belonging to the Mannering and Liebig Groups, crosses the Sealy Range, together with a lengthy array of Malte Brun Group to the south and west. The rocks are extensively faulted, and bear moderately well developed folds[1], but they are not major folds, and usually are contained within single formations and units over the Sealy Range. The Sebastopol and Unwin Members of the Acolyte Formation uphold the lower slopes of the Sealy Range along the Hooker valley, and are succeeded by moderately thick Baker and Onslow Formations, which have been metamorphosed into Chlorite 2 schist, locally verging on Chlorite 3. Conglomerate is present in beds 0.7 to 3m thick. A narrow strip of Bonney black shale extends above the Cooper Peak beds, to show that the upper Baker Formation is not markedly folded north of the Hoophorn spur. The Great Groove Fault[1] is contained in this formation, and is not stratigraphically very significant. Just south of the Park boundary along Birch Hill Stream, a branch fault indicates right lateral strike slip. At the southern boundary in Birch Hill Stream, Rose Formation with red argillite, and possible Wheeler Formation are enclosed by faults, and noted as an exotic fault sliver[2]. The rocks between Jamieson Saddle and Birch Hill Stream relate better to those of the Ben Ohau Range to the south, and this narrow area has been

Fig. 7.1. West wall of the Mueller Glacier, showing small faults and folds in the schistose rock below Mt Sefton, enhanced to bring out structure. Note the reverse S-curve (arrowed) and attenuated anticlines arching eastwards and separated by small thrust planes or tight synclines.

left out of the map, to be discussed in the companion volume. The Permian rocks in the band traversing the upper eastern face of the Sealy Range have been metamorphosed into greenschist. The Green Rock Fault[1], a rather dispersed fault, involves thin Wheeler and Rose Formations of the Liebig Group, as a major and ancient fault, possibly rejuvenated to a minor extent during Pleistocene time. The Liebig Group is cut off by an obscure but important fault from overlying Triassic beds of the Malte Brun Group, which is repeated as two major bands, divided by a fault. The easterly strip is best exposed by headwaters of the Dobson valley, south

Fig. 7.2. Greenschist, two of many blocks used to make up the stone walls around the petrol pump near The Hermitage, showing the rock in cross-section (above) and in surface view (below). Scale bar 10cm approx. The rocks were brought in from the Wanaka area and are judged to be sedimentary in origin.

of the peaks of Sealy and Jean. It commences with Chudleigh Formation, but Novara Formation is found south of the Park, and overlying argillite-dominated turbidites are well developed. The southern and eastern wall of the Mueller Glacier, below the crest of the Sealy Range, has a number of faults which cross the formations with comparatively little affect, and display only minor displacements. The Kitchener Anticline extending along the crest of the Sealy Range, and a fold to the west under the Metelille Glacier seem to have been somewhat flattened by overthrusting from the west, and broken by small

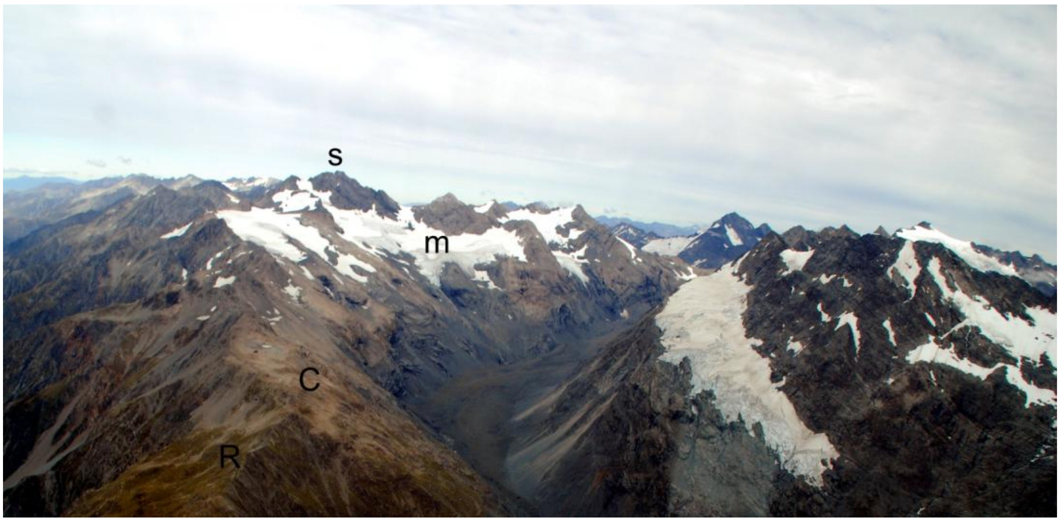


Fig. 7.3. East end of the Sealy Range, with Rose Formation (R) and Chudleigh Formation (C), above the Mueller Glacier, with Main Divide southwest of Mt Sefton to the right. Mt Sealy (s) and Metelille Glacier (m) lie in the background.

Fig. 7.4. View southwards up the Mueller Glacier, Sealy Range to left and foreground, with Chudleigh Formation indicated by C, lying above and to the right of Aiguilles Rouges turbidite (A), and Walpole turbidites (L) below the Metelille Glacier. More Chudleigh Formation lies in the foreground. The dark rock of the Main Divide is more schistose.

overthrusts. The second and major band of Malte Brun Group is developed further west, and is much more schistose. Perhaps the most intriguing outcrop is provided by green sandstone 200m thick close to Barron Saddle near the hut, in the basal Chudleigh Formation. It appears to have been a sandstone channel, like that of the Reay Member exposed by the Reay Glacier near the base of the Chudleigh Formation. On the eastern side of the Main Divide the schists have been closely faulted, often by small upwardly concave shears, and attenuate folds are well developed, as well shown in Fig. 7.1, mostly within single rock units.

-

Fig. 7.5. Sefton ridge with Frind Glacier below Mts Brunner and Sefton. The rock is mostly schistose, composed of Malte Brun Group, with some Liebig Group to the lower right.

HOOKER GLACIER, WEST WALL AND HEAD

The western wall of the Hooker Glacier is composed mostly of Mannering Group, with Acolyte Formation along the lower and western side of the glacier, continuing north from the Sebastopol and Unwin Members, and overlain by Baker Formation, including Onslow Member, slightly and not very schistose. The Main Divide curves westwards along the upper Hooker Glacier, to take in highly schistose Liebig Group and Malte Brun Group.

The steep southern face of Mt Hicks is composed mostly of sandstone with thinner argillite bands. Comparatively fine bedding, even within the sandstone on the western part of the south face, suggests Baker Formation, and possibly some Onslow Member, but the thicker units further east indicate Acolyte Formation, like that exposed on the western wall of the Hooker Glacier south of Pudding Rock (see aerial photograph SN 8595 L 16), and the northern side of Mt Hicks (aerial photograph SN 8595 L 18) shows similar massive bands of sandstone and thin argillite. Pudding Rock is notable for the development of concretions in layers and beds. Further along the main divide towards Mt Dampier, the rocks are Burnett Formation, with thick bands of sandstone and black mudstone, and Mt Dampier exposes Burnett Formation, judged from the amount of argillite.

Much of the western face of Aoraki Mt Cook possibly consists of Rose sandstones and thin argillite, with minor folds, including north-plunging synclines.

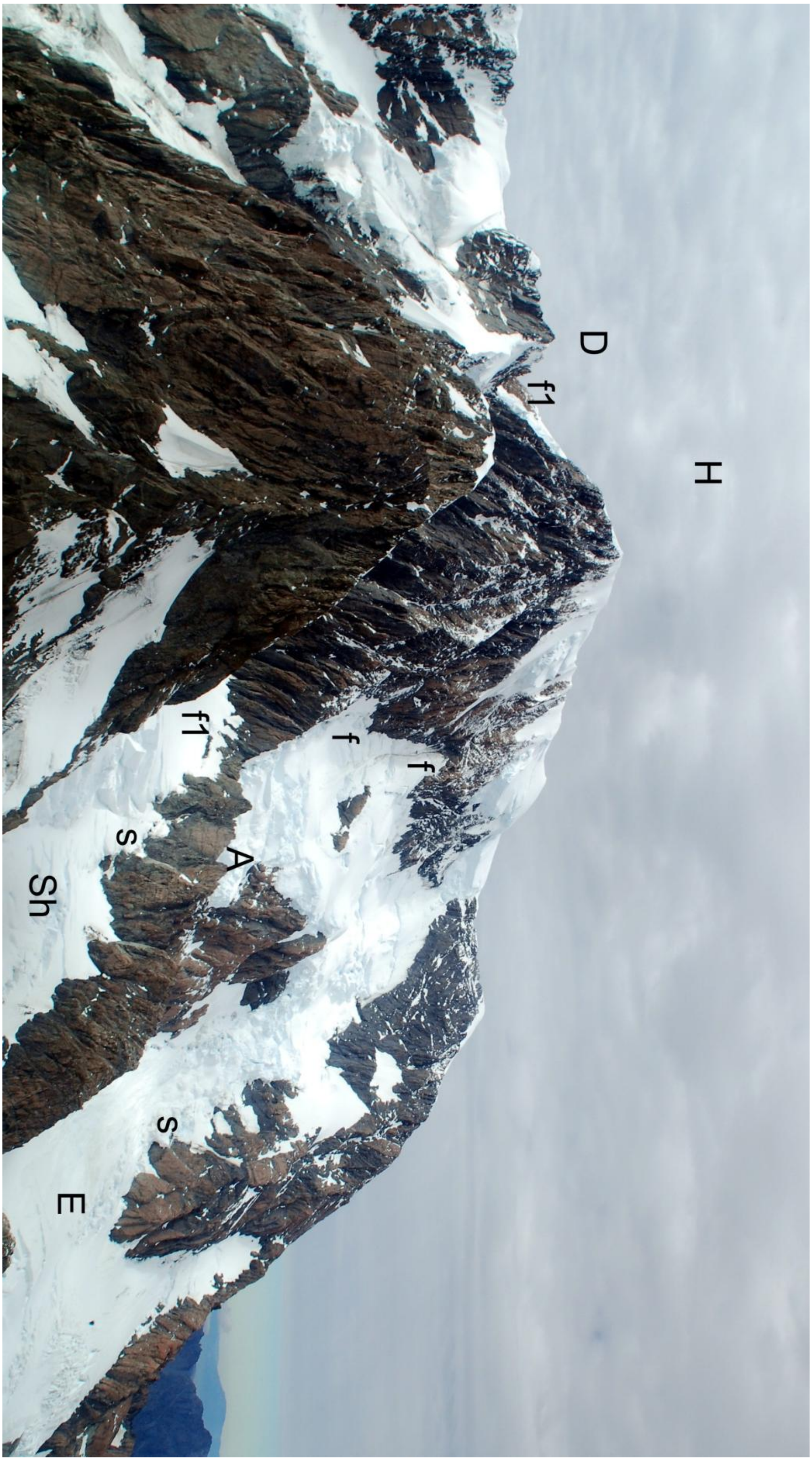
Yet no red Rose argillite has been observed, and the western face needs closer study to rule out the possibility – perhaps even likelihood - that the beds belong to the Burnett Formation. A well defined fault is indicated through Green Saddle, near the narrow runnel at the foot of Aoraki Mt Cook, and other faults are visible over the western face of Cook, none of major dimensions. Attitudes in bedding vary to indicate shifts in strike and some broad folding, stronger than shown in a published form-line map[3], and several photographs suggest an anticline at the western end of Earle Ridge, near Empress hut[4]. A number of observations have been provided in a study of the rocks around the Hooker Glacier[3]. The figures provided herein show beds that conform in strike with the general attitude of beds through the Hicks – Dampier ridge, and the eastern side of Aoraki Mt Cook, but the tightly folded and rather dark beds further north, looming over Green Saddle and its narrow runnel below, seem to lie differently, fault-isolated perhaps, or possibly the faulted nose segment of a largely destroyed fold. The view of Aoraki Mt Cook from a slight different angle in Fig. 7.7 confirms this variation in strike, with large slabby exposures of rock towards the base of Earle Ridge striking at an angle to the Green Saddle and runnel exposures, and parallel to the general trend.

Fig. 7. 6. Mt Dampier (D) and Aoraki Mt Cook, separated by Green Saddle and Sheila Glacier (S), showing tight slender folds over the northwest ridge (Earle Ridge) leading to the high peak of Aoraki Mt Cook. Beds below r strike at an angle to the beds and folds closer to the Sheila Glacier.

MOUNT COOK RANGE, AORAKI MT COOK EAST

Mount Cook Range, Mt Wakefield to Ball Glacier, and Anzac Peaks

The Mount Cook Range consists mostly of Liebig and Mannering Group, folded in a very large syncline, first recognized by Professor Lillie[4]. The Sebastopol and Unwin Members and ordinary Acolyte rocks underpin the eastern side of the


H
D
f1
f
f
A
f1
s
s
E
Sh

[Opposite page] Fig. 7.7. View from the west of Mt Dampier (D) with Mt Hicks (H) in front, and Aoraki Mt Cook, above the Sheila Glacier (Sh) and Empress Glacier (E). The narrow runnel leading to Green Saddle. seems the locus of a fault (f1 – f1). Note the small tight folds of possible Rose Formation over Aoraki Mt Cook and the indications of moderate faults (f), oriented eastnortheast. The slabby appearance of rock on Mt Hicks and lower right of Aoraki Mt Cook (s) on Earle Ridge (A), shows that the beds are seen in lateral view, indicating the beds curve round to lie parallel to those on the eastern face of Aoraki Mt Cook.

Mount Cook Range, and these together with the Wakefield Syncline superficially indicate a major structure like a major drag fold, although the connection to the rocks of the Sealy Range lies buried by Pleistocene and Recent sediment below the Hooker valley, and in fact the main divide rocks do not bend into those of the west limb of the Ball Syncline. The Acolyte beds are followed by younger formations of the Mannering Group, and then by an ancient tractator fault and thick Permian rocks of the Liebig Group.

Along the east limb of the syncline, the formations of the tract are exposed by the west wall of the lower Tasman Glacier and east side of the Mount Cook

Fig. 7.8. The Wheeler Formation along the south side of the Ball Glacier, the colour differences due to weathering. The Ball fold is arrowed with Rose Formation, as discussed for Fig. 7.10.

Range, and just south of the Ball Glacier curve gently towards the Tasman Glacier, with the Wheeler Formation bordering the south side of the Ball Glacier. Rose Formation exposed in the core of a fold assigned to a Ball Anticline by Professor. Lillie[5], although the relationship to Wheeler implies a syncline, and it lies almost on line with the Wakefield Syncline, plunging northeast. The fold simulates an upside-down anticline, or more likely introclinal fault-drag fold (see pp. 30, 31, Fig. 3.8). In the fold, a number of beds young outwards, as if anticlinal, as also argued by Professor Lillie. Other beds young inwards, offering contradictory evidence as to whether it is a syncline or an anticline. Or is it both, with rocks complexly interfolded? Are there two tracts involved, or has there been very attenuated multiple folding? To answer these questions, closer inspection of Fig. 7.10 and 7 11 is invited. A smaller fold appears to be shown at the lower left of the larger fold, and plunges south The lower left part of the main fold seems to indicate a double anticline separated by a syncline, and other small scale folds are present. Such complexity suggests that the fault, marked by an ice- filled fissure, has compressed the strata to its south into tight folds. Clearly any interpretation of the major folds, whether anticlinal or synclinal, becomes moot

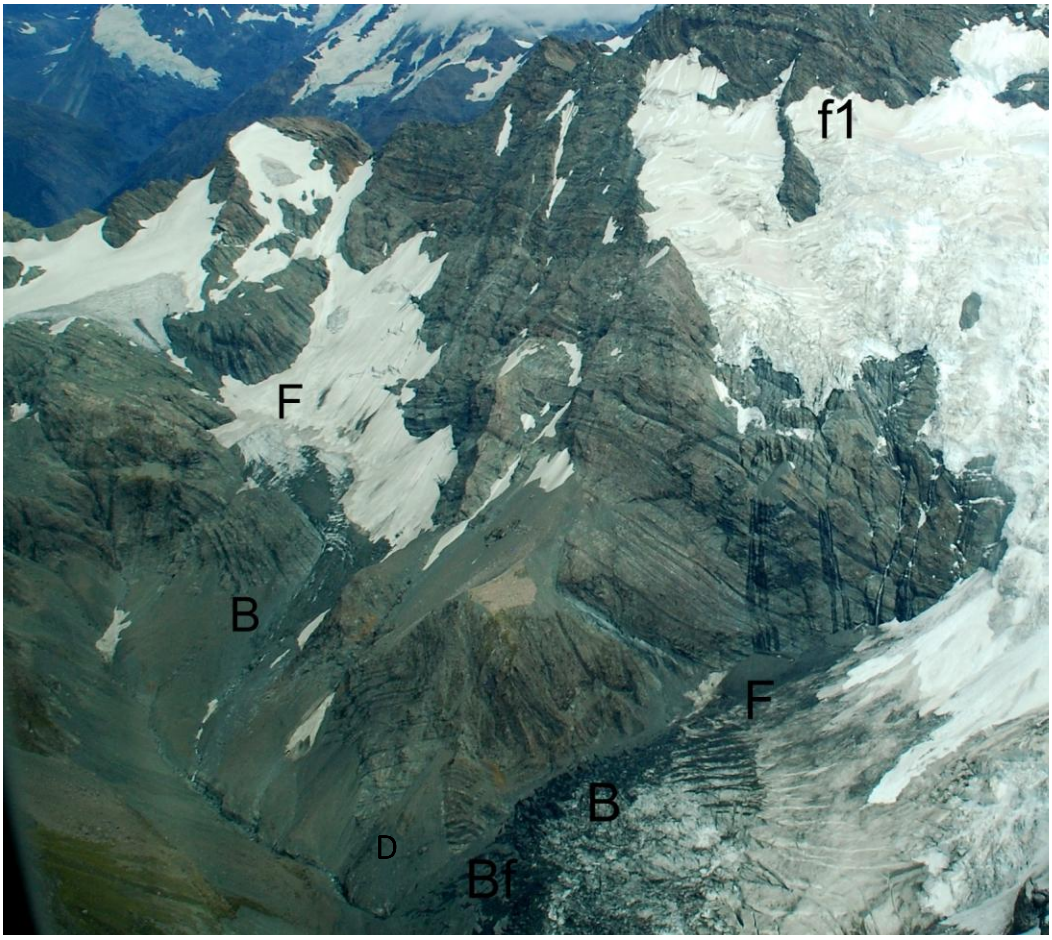


Fig. 7.9. A general view of the Ball Glacier and Mount Cook Range near Mt Pibrac, showing the relationship between the Ball fold B B with its ancillary fold to the left (D - Bf), and the Pibrac Nazomi fold (f1), separated by a well defined fault F F in between.

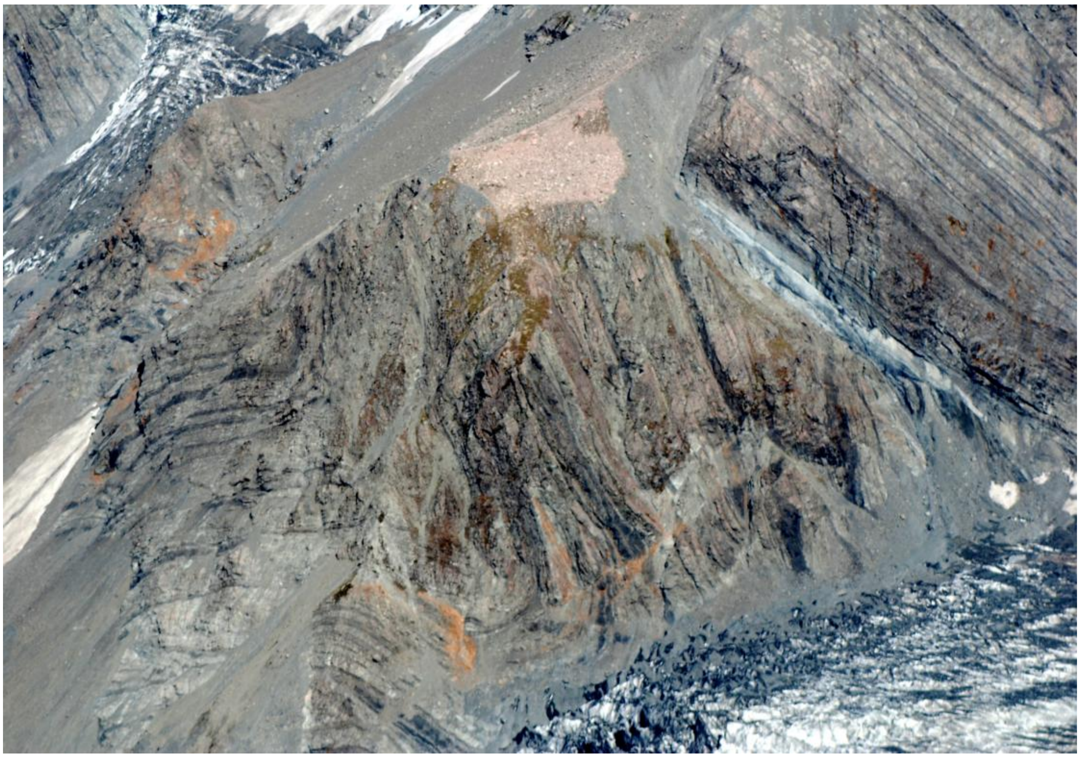


Fig. 7 10. Ball Glacier and fold in the Rose Formation. As shown in the following figure, the beds on the left side of the fold form closely packed elongate folds, caught up in the folding. These small folds are somewhat like distorted enterolithic folds illustrated for the Chudleigh Formation in the Malte Brun Range[6], and for folds near the Mannering Glacier (Fig. 1.21, p. 17).

Fig. 7.11. Lines traced along beds in some of the tight folds that make up the fold of the preceeding figure, rather conservatively, for folds seem to be more complete than shown. Clearly, younging directions taken to indicate an anticline are of dubious value. The folds and major fold close north, and may be an introcline caused by drag-folding. The fault to the right is drawn along the ice-filled fissure. The tight small-scale folds indicate distorted enterolithic folds[6], which are found widely in the Park, in the Chudleigh and Rose Formations, and especially in the Acolyte Formation. Unlike beds of the Wakefield Syncline to the south, closure is to the north, and may be slightly off-line from the axis of that major fold.

and highly fraught. The presence of Rose Formation next to the Wheeler Formation allows a syncline, in a stratigraphic sense, so that alignment with the Wakefield Syncline seems acceptable, but complexity has arisen through strike slip movement along the fault just to the north, inverting the folds into an introcline, and different closure implies change in plunge**.** Or the fold is new, arising well north of Mt Wakefield, subparallel with the trend of the Wakefiled Syncline.

Pibrac – Nazomi folds

Along the main divide towards Aoraki Mt Cook well displayed folds of moderate size in Burnett Formation as figured[7].

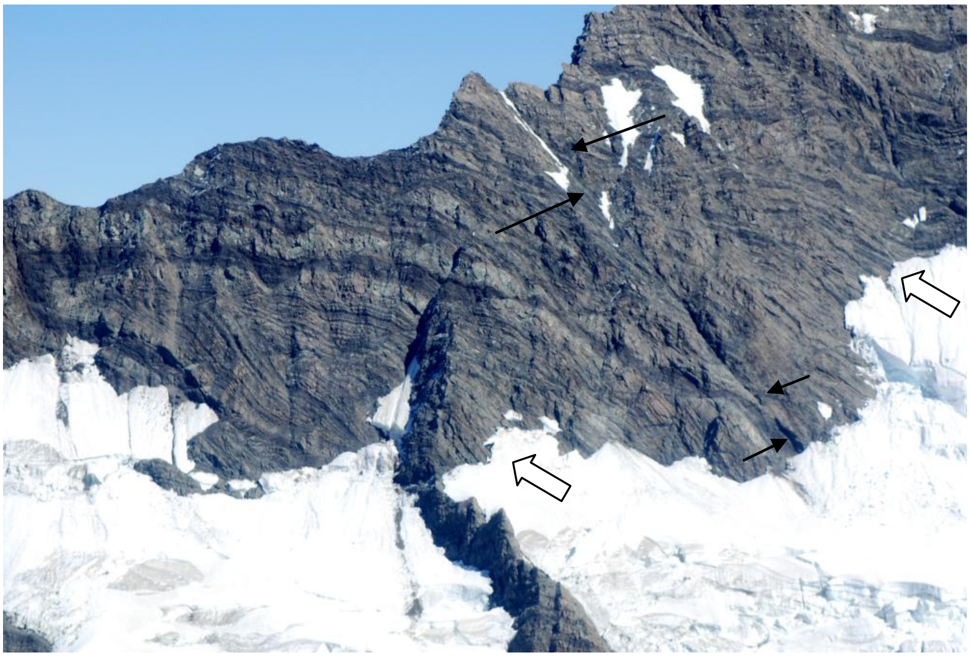


Fig. 7.12. Folds south of Mt Nazomi[7], two indicated by broad arrows, a likely syncline plunging northeast on Mt Pibrac signalled by the lower broad arrow, with a fold just above (second broad arrow), plunging southwest, with confused bedding above, induced either through tectonism or slumping. A well defined left lateral fault divides the two folds, only a minor fault because it lies in the same formation, and upthrow is to the right, as you can see if you trace the beds, and note the displacements indicated by the short and long arrows either side of the fault. There appear to be other tighter, less complete folds as well, closing in the same sense, as though cryptic faults had removed intervening counter folds.

Aoraki Mt Cook massif (east side), Anzac Peaks

The Aoraki Mt Cook rocks belong to the Rose and Burnett Formations, the Rose distinguished by firm well bedded greenish sandstone with partings of mudstone and rare red mudstone, the Burnett by thick and thin sandstone weakened by the interleaving of often thick black mudstone. The Burnett Formation is well exemplified by the rocks exposed on the main ridge between the high and middle peaks, and the Rose by the firm rocks with subsidiary folds and an apparent anticlinal axis as exposed on the Caroline face, passing into the Zurbriggen ridge. This band possibly continues into the hypothecated Rose rocks on the west side of the mountain, but this connection has not been confirmed. Easterly bands of Burnett and Rose Formations continue north from the rocks of the Mount Cook

Range. Unfortunately, there is insufficient information to determine major fold axes and possible faults. Two bands of thick black argillite on the eastern side of the Anzac Peaks above the Burnett Formation are folded in a syncline to suggest a narrow strip of Acolyte Formation, above complexly folded Burnett.

Fig. 7 13. South ridge and southeast or Caroline face of Aoraki Mt Cook. Beds of Rose (R) Formation, with tight folds as arrowed low on the face and along an anticlinal core, and Burnett Formation (B). A thin strip of Burnett (B1) lies between the two Rose bands.

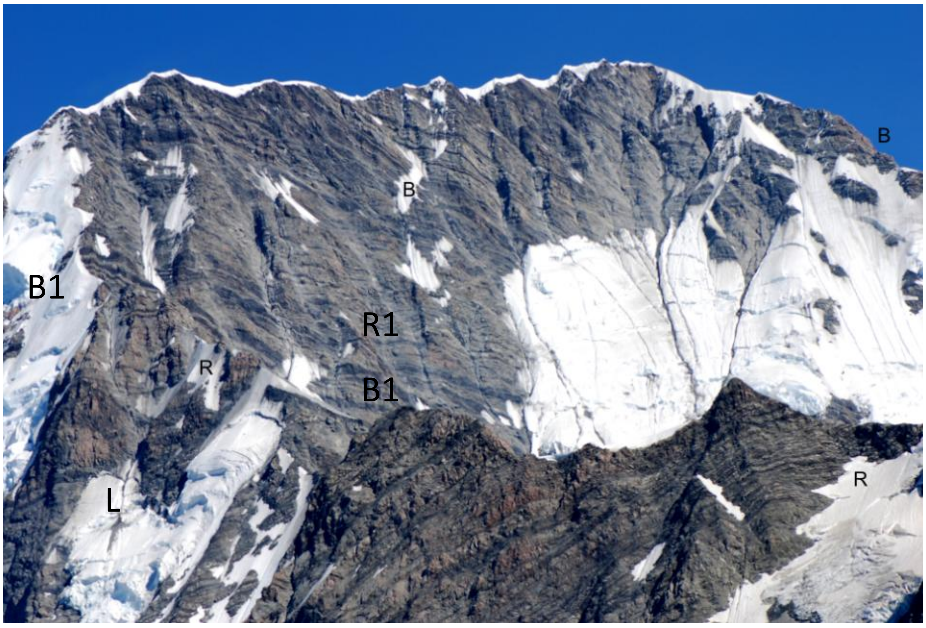


Fig. 7.14. East face of Aoraki Mt Cook and ridge leading to the Anzac Peaks to the right. B is Burnett Formation, and R the Rose Formation. R1 and B1 form thinner bands, R1 seemingly an anticline, with slender folds in B1. Note the apparently boulder outcrop (above L), possibly signaling a disruption (faulting?) zone.

Fig. 7.15. Anzacs in the foreground, and Grand Plateau rocks beyond, with Zurbriggen Ridge (z). The Rose Formation (R) passes into the Hochstetter icefall (h), and Burnett Formation (B) to right of Malaspina (m) youngs upwards and westwards. The Linda Glacier is signaled by s.

Fig. 7.16. Mt Dampier from the east, above the Linda Glacier, and the peak of Malaspina (m). Most of the rock, with abundant layers of black argillite, belongs to the Burnett Formation.

Fig. 7.17. Mt Tasman with Mt Silberhorn to the left, and Plateau Hut (arrowed). Glimpses of rock between the ice[8] suggest Burnett Formation. Note bouldery outcrops on face of foreground ridge, probably due to weathering of closely fractured rock.

Fig. 7.18. Mt Lendenfeldt and Mt Dixon, masking Mt Haast. Plateau Hut arrowed. Engineer Col left of Lendenfeldt. Note the syncline, indicated by lower arrow above the Hochstetter Glacier.

A moderately prominent scarp signifying a recently active fault crosses the Caroline face of Aorangi Mt Cook and passes into the Grand Plateau, and is upthrown on the northwest side. The Burnett Formation has much mudstone, and so is prone to rock-fall.

MAIN DIVIDE NORTH OF AORAKI MT COOK

From Grand Plateau to Rudolph Glacier

The rocks along the western wall of the Tasman Glacier gained attention in a publication by Professor James Park (father of Air Vice-Marshall Sir Keith Park of Battle of Britain fame), when he illustrated some of the large folds[9]. Rose and Burnett rocks are to be seen on peaks around the Grand Plateau, but there is so much ice that uncertainties remain. There are folds which possibly are arranged en echelon, but rather seem to be changing in pitch along their length. What is clear is that Burnett Formation is well exposed over peaks along much but not all of the Main Divide, and also along the lower slopes bordering the Tasman and Rudolph Glaciers.

Fig. 7.19. Burnett Formation, east side of Main Divide north of Mt Haidinger. Rocks just below the divide are overturned, younging downslope, and an obscure synclinal axis is arrowed. Rocks to lower left Rose Formation. Photo Ray Bellringer.

Fig. 7.20. Rose Formation (R) including red argillites (arrowed) arranged in slender folds, and Burnett Formation (B) below the Main Divide above the Tasman Glacier. Photo Ray Bellringer.

Fig. 7.21. Rose Formation near Forrest Ross Glacier. Red argillite in anticlinal arch and other outcrops arrowed. Photo Kerry Bellringer.

Rudolph Glacier to Elie de Beaumont, west side upper Tasman Glacier

Few rocks are exposed along this section, and they are poorly known – I simply have not done enough study on the ground of these outcrops. The lower De la Beche ridge between the Rudolph and Tasman Glaciers displays Onslow Form-

Fig. 7.22. The divide rocks north of the Rudolph Glacier are largely concealed by ice, but continue from the Haidinger and other peaks south of the glacier, which expose Burnett and Rose Formations. A few fold axes are visible in the rocks[9]. Strong rock ribs uphold the West Peak (P) of Elie de Beaumont (E). Also showing Coronet (C), Green (G), and west side of Hochstetter Dome (H), behind the west ridge of Mt Darwin, in the foreground. Photo H. P. Barcham.

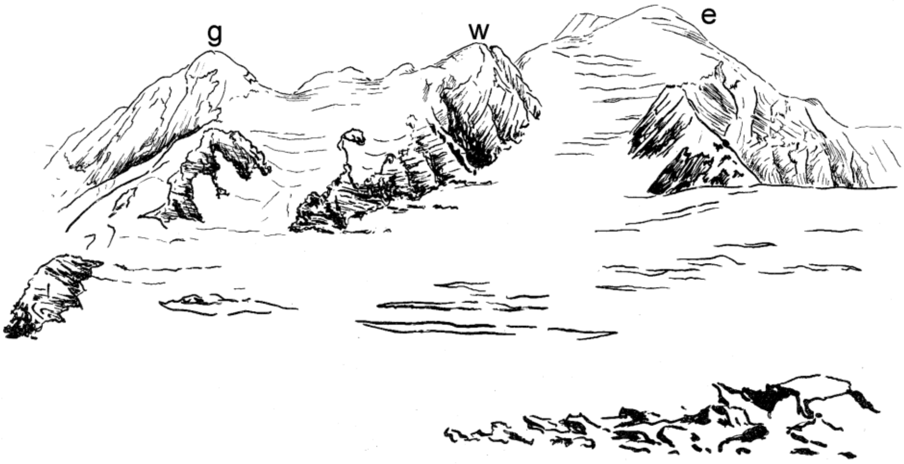


Fig. 7 23. Field sketch of Mts Green (g), Walter (w) and Elie de Beaumont (e) from upper Tasman Glacier, showing curvatures in bedding.

-ation rocks with Steffan Member and outcrops of silica or chert (see Fig. 1.14, p. 11). Burnett and Rose beds cross the Rudolph Glacier, but otherwise the area is little understood. Folds are visible below the peaks of Green and Walter[10], and although the formation may be Burnett, this is yet to be confirmed. These folds, together with a syncline on the north side of Coronet, plunge southwards. Although the summit of Elie de Beaumont shows no rock, there are very steep

Fig. 7.24. The south side of Mt Green (in the right foreground), Elie de Beaumont and West Peak, with Climbers Col in the foreground, photographed from Coronet. The development of slabs is marked, suggesting Burnett Formation, but possibly Baker or Rose Formation. Photo H. P. Barcham.

exposures on both sides of the ridge to West Peak, and the rocks dip steeply west at close to 60°, with thick well-bedded sandstones, and much less mudstone in thin layers. The appearance is somewhat like that of the south wall of Mt Hicks, but closer examination is needed. On the map, the rocks are shown largely as Burnett Formation, as continuing on from south of the Rudolph Glacier, and red argillite typical of the Rose Formation has not been seen. Published photographs show the slabby nature of the rock[11], and there are strong oblique fractures to the lower right in one photograph, due to cleavage, as if a fault extended up the right hand gully.

MALTE BRUN RANGE

Although the rocks of this range have been examined in some detail, obscure areas remain. The south end of the ridge leading from Novara has poorly exposed and broken rock. The rocks mapped as Frind Formation north of Beetham Stream include five black turbidite bands (see aerial photograph SN 8595 A 12), comparatively thin compared with bands of well bedded arkosic sandstone. There are recent faults and minor folding, and the turbidite rocks are interpreted as being too thin to be typical of the Walpole or Aiguilles Rouges turbidites, and so belong to the upper Chudleigh, separated by faults from the Frind Formation. Alternatively, at least the major band in the middle of the five could be mapped as Walpole Formation, reduced by faulting, above the Chudleigh Formation. More complex scenarios cannot be ruled out without further study.

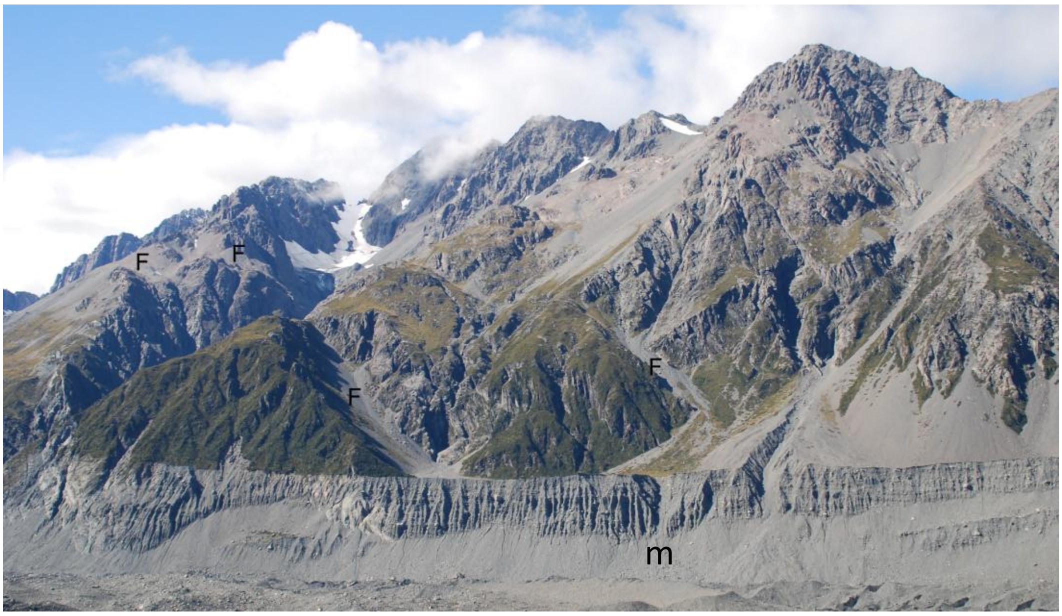


Fig. 7.25. Southwest end of the Malte Brun Range, including Malcher and Novara Peaks to the right of mist-clad Mt Johnson. The range is made up of the Malte Brun and Mannering Groups, with prominent fault lines F-F, including the Beetham Fault, as the one on the left. Note the moraine collapse (above m) in line with the main Beetham Fault.

Many figures have been provided to illustrate the geology of this range, especially in the section on the stratigraphy of the Malte Brun Group (pp. 59-67), as well as Beetham Fault (pp 12-13, 20-21) and Haeckel Syncline (pp. 13-15, 33-

34). Only some of the small structures are noted on the geological Map 2 – there are a great many irregularities, and complexities have had to be omitted. On the

Fig. 2.26. The well bedded Malte Brun Group (Novara and Chudleigh Formations), with the peaks of Johnston (J), Malcher (M) and Novara (N) at the south end of the Malte Brun Range, above softer greener rock of the Liebig Formation, looking across the Murchison valley.

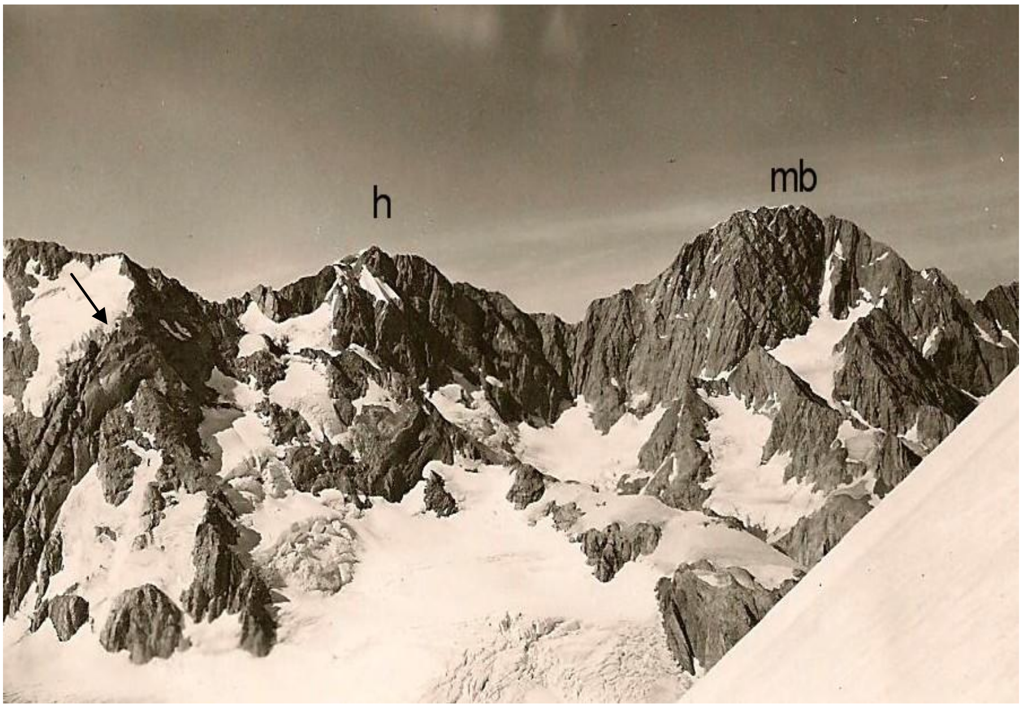


Fig. 7.27. The northern Malte Brun Range from Mt Green, showing Mt Malte Brun (mb) and Mt Hamilton (h), looking over the ridge west of Mt Darwin. Note the smoothly rounded crest of fold on this ridge, as pointed out by an arrow. This is apparently the base of an upsidedown syncline, where the western end of the Haeckel Syncline steepens and rolls skywards. Photo H. P. Barcham.

southerly leading ridge from Mt Johnson there are three levels with notable submarine slumping. A fold was recognized by Professor Lillie as the Burnett Syncline, east of the Malte Brun Anticline, and best preserved near the Burnett Glacier, east of Mt Johnson. This is a shallow fold, and, accompanied by further folds, may be traced along the east side of the Malte Brun Group as far as the Cascade Glacier. It appears unlikely that it was other than a Kaikoura deformation, passing into the much older and more complex Haeckel Syncline.

The rocks along the south wall of the upper Tasman Glacier, involving the peaks of Abel, Annan and Darwin, are very well exposed, and the geology is complex, involving various units of the Malte Brun Group, with folding and some faulting, from just west of Darwin peak eastwards beyond the head of the Tasman Glacier, with rocks moderately metamorphosed, up to Chlorite 2. West of Darwin peak, the rocks belong to the Liebig and Mannering Groups, in tight northward plunging folds, at least some of which seem to be genuinely upside down, marking the oversteepened core of the Haeckel Syncline. At the extreme west, Frind (?) beds on the northern end of the Malte Brun Anticline are closely folded, with a south plunging anticline and syncline on the southwest face, near several other closely spaced folds. The robust sandstone beds making up the peak of Annan indicate Chudleigh Formation, which curl at the foot of the peak in meeting the Tasman Glacier to indicate an anticline (Fig. 7.28) and the tower mid-way between Mts Annan and Darwin has sandstone beds like those of the Barkley Sandstone. The thick turbidites of the Darwin buttress below the peak of Darwin belong to the Aiguilles Rouges Formation, which is in abrupt faulted contact with Permian Liebig Group to the west. There are thin black argillites and argillite-dominated turbidites between the Chudleigh sandstones of Mt Annan and the Barkley sandstones of the tower, and these increase greatly in thickness to the base of the ridge and edge of the Tasman Glacier, and belong to the Walpole Formation.

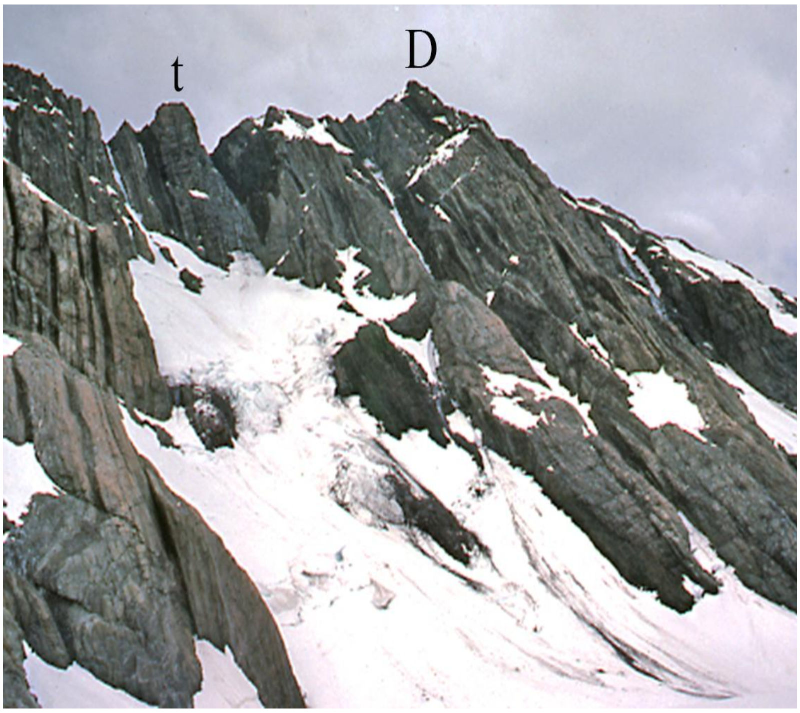


Fig. 7.28. Showing the anticline in Chudleigh Formation to lower right, at the base of Mt Annan (to left, out of sight). To right along the ridge crest lies a narrow strip of Walpole Formation, which appears to broaden substantially towards the base of the ridge above the Tasman Glacier. The Barkley Formation in the tower (t) follows to the right, and then comes the Aiguilles Rouges Formation, and Mt Darwin (D).

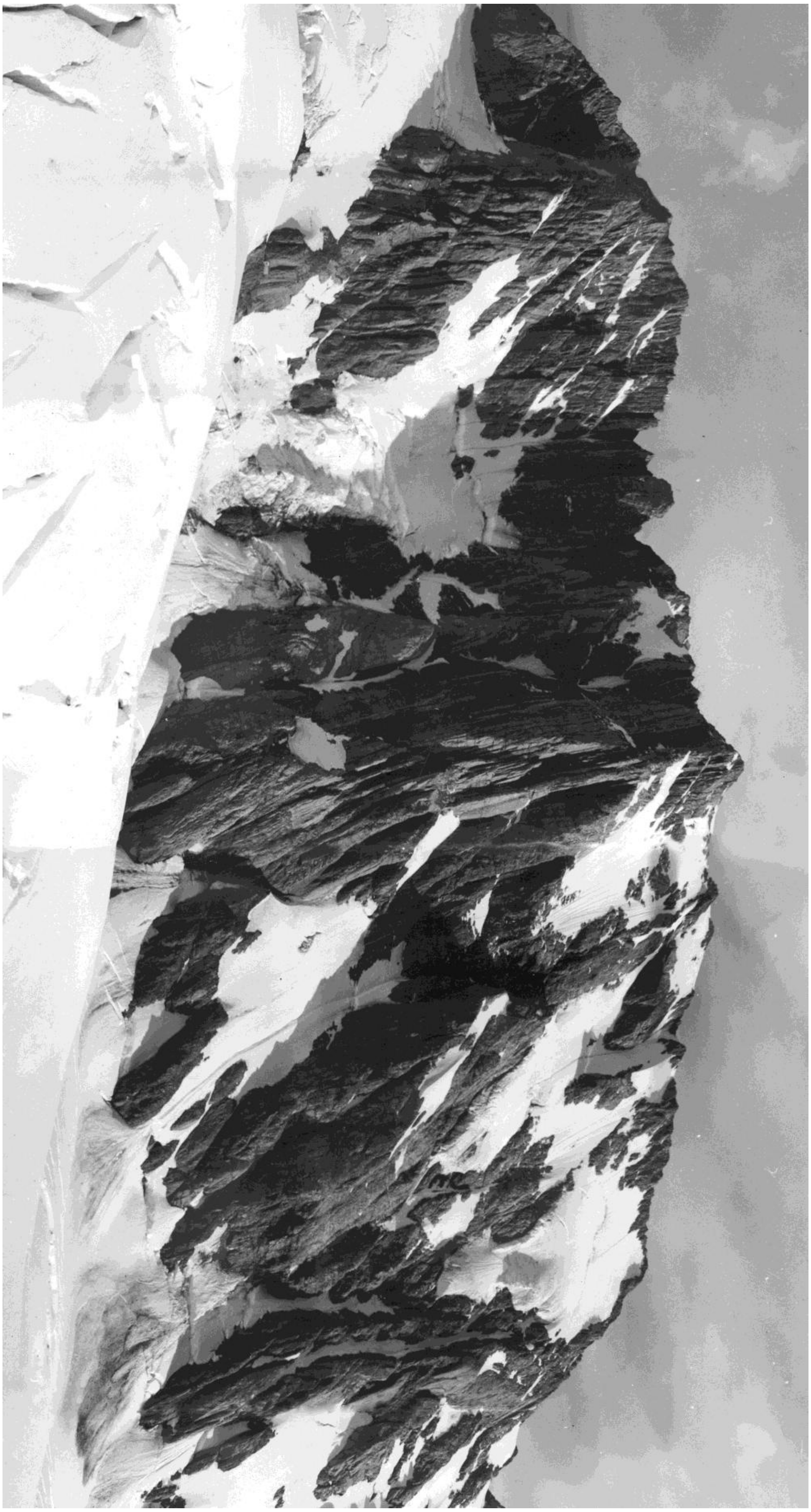
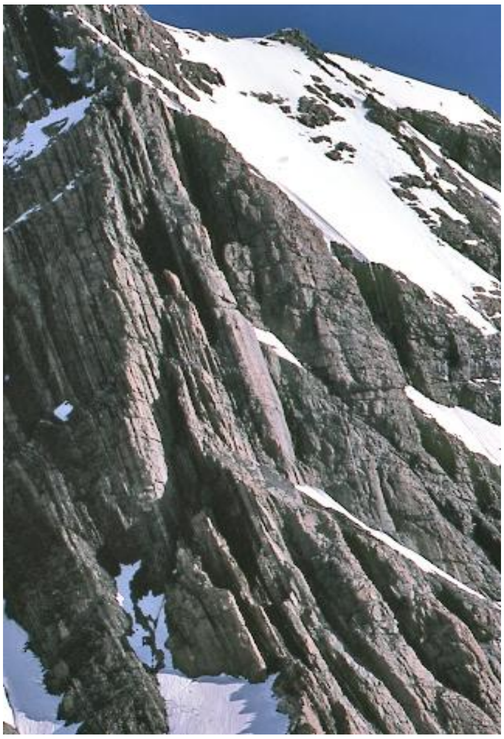


Fig. 7.29. [facing page] Northern face of the Annan to Darwin ridge, viewed from near Tasman Saddle Hut. See large fold-out photograph in New Zealand Alpine Journal.[12] Photo S. N. Beatus.

A

B



C

Fig. 7. 30. A, view from Tasman Glacier of the tower (T) of Barkley Formation with Aiguilles Rouges Formation to the right and part of narrow outcrops of Walpole turbidites to the left along ridge crest. Minor folds visible. B, view from north-east of Darwin Peak and turbidites, with prominent syncline, arrowed. C, lower part of so-called Darwin buttress north of the peak, made up largely of sandy turbidites of Aiguilles Rouges Formation.

Minor folds lie between the Annan flanks and the Darwin buttress, and overall the structure has been called the Annan Anticline[6].

Further folds, turbidites and sandstone units are exposed in the eastward continuation of the Darwin-Annan ridge through Mt Abel and further peaks as far as Starvation Saddle. There is a well developed synform exposed over the northeast face of Mt Abel (Fig. 7.32), which appears to be the northeastern extension of the Haeckel Syncline. This megafold as mapped displays an extra-

Fig. 7.31. Peak at eastern end of the Annan-Abel ridge at head of Murchison Glacier, northwest of Murchison Hut, suggestive of Walpole Formation. The rocks to the left strike a little differently from those to the right, and a syncline and anticline are developed on the northern side, not seen in this photo.

Fig. 7.32. Upper Murchison Glacier, with Tasman Saddle to right, Starvation Saddle out of sight to left. Mt Tasman visible in distance at right, and Haeckel in centre background. Mt Abel is concealed by the wing-strut, and to the left is a prominent synform, possibly the eastward extension of the Haeckel Syncline. Beds to the left young to the left and are weakly overturned and include a faulted anticline, with beds to the left overturned and younging left.

ordinary triangular shape, and it is the northwest corner of the triangle that is particularly exceptional, both in plan and in the nature of the fold, and its subsidiary folds that appear to be overturned.

Some uncertainty pertains to the correlation of the rocks in the saddle between Annan and Haeckel peaks, and it is suspected that there are some infaulted turbidites of either the Aiguilles Rouges or Walpole Formations[13]. As shown in Fig. 3.11, p. 33, slender anticlines are well defined on the flank of Mt Haeckel, next to the major syncline, and it is likely that formations are crowded into the Annan-Haeckel gap, folded and faulted, and partly concealed by ice.

HEAD OF TASMAN AND MURCHISON GLACIERS

There is so much ice and so little exposed rock that it is difficult to unravel many aspects of the solid rock geology in this area. The most conspicuous geology is provided by the peaks of Graceful and Brodrick, in which turbidites are prominent, dipping southwest, possibly Aiguilles Rouges and Walpole Formations, with Barkley Formation represented by thick sandstone, but conceivably Burnett. All the beds are metamorphosed to Chlorite 3. Thick sandstone beds, poorly known, and possibly like those of the Burnett or even Chudleigh Formation, lie in scattered outcrops in the upper Murchison nevé. It is one of those areas which needs more study.

The head of the Whymper Glacier, west of the Park boundary, exposes more of the rocks making up Mt Elie de Beaumont and the Maximillian Range, but was examined under unfavourable conditions of heavy fog. Much of the weakly schistose rock belongs to the Rose Formation, with some red argillite and is folded in a large syncline (Fig. 7.34) that appears to continue under the north face of Hochstetter Dome, with indications of an anticline to the west below Hochstetter, and closer to the peak. A thick band of black turbidite is like those

Fig. 7.33. Schistose rocks on north side of Mts Brodrick and Graceful at the head of the Classen Glacier, above Rose Formation in the foreground. One affect of schistosity is to gentle the angularity of fractures common in the Malte Brun turbidites. The rocks of Mt Aylmer further along the ridge look like Rose Formation, yet to be verified.

of the turbidite in the upper Rose Formation of the northern Liebig Range. No contact with the Malte Brun Group rocks along the Brodrick – Graceful ridge was seen, and it assumed that the Hochstetter and Aylmer rocks are divided from the Brodrick and Graceful rocks by a fault. The key to resolution of the geology for Mt Aylmer and Hochstetter Dome lies beyond the Park boundary.

Fig. 7.34. The northeast side of the Maximillian Range just north of Mt Elie de Beaumont from above the basin of the Whymper Glacier near Hochstetter Dome. The rocks delineate a southsoutheast plunging syncline in the Rose Formation, of subschistose Chlorite 2, and appear to lie in faulted contact with darker Chorite 3 schist of the Acolyte Formation to the east[13].

LIEBIG RANGE

Rocks of the Liebig Range are less deformed that those of the Sealy and Mount Cook Ranges or Mt Sefton, and show some open folds. There is little schist, and only low grade metamorphism. The rocks belong to the Liebig and Mannering Groups, and geology is moderately well exposed.

Northern Liebig Range

Fig. 7.35. Aida Glacier to left, with peaks named Coopers Mate (CM), Richmond (R) and Anthill (A). Lake Tekapo in background. Photo Kerry Bellringer.

Fig. 7.36. Mt Acland (A) to Mt Conrad (C) along the northern Liebig Range, above the Murchison Glacier. Mts D’Archiac (a) and Sibbald (s) lie in the background.

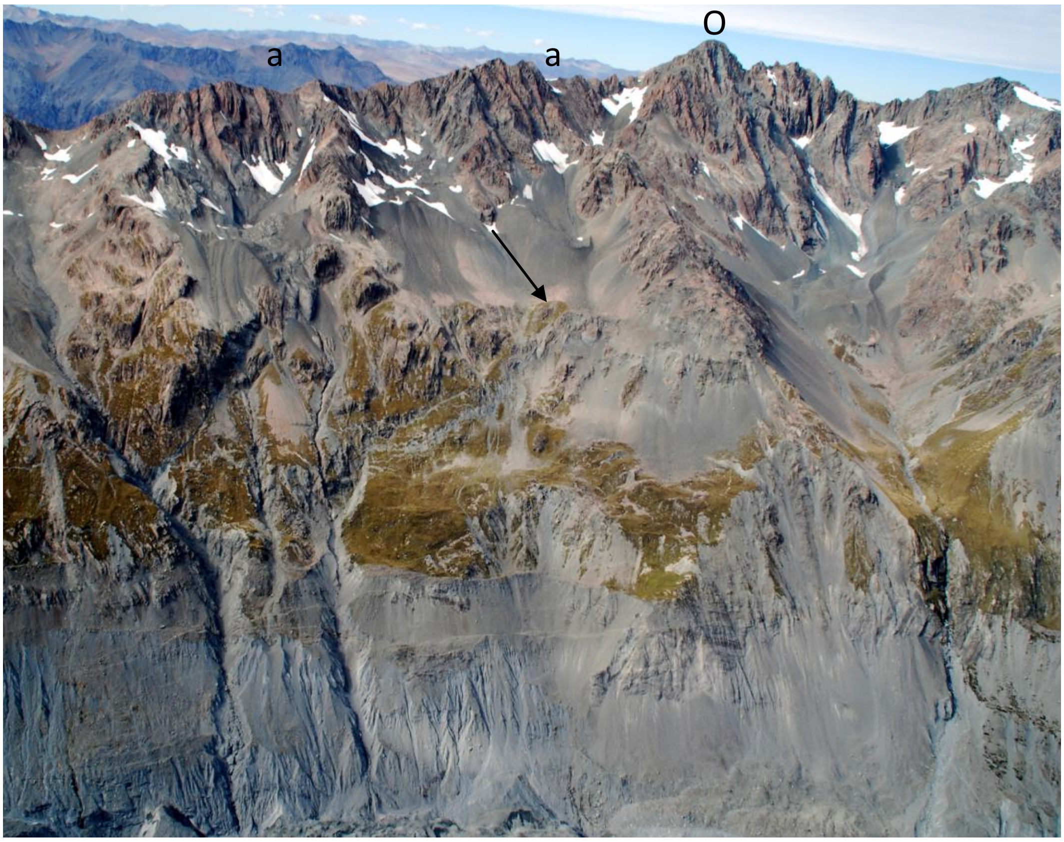


Fig. 7.37. Northwest side of Liebig Range showing Rose Formation south of Mt Conrad to the start of the cluster of peaks named Olaf (O), Kenneth and Ronald Adair, above the Murchison Glacier. Prominent bands of argillite at a and a. Note the gentle folding into anticlines, with one arrowed.

South of the Aida Glacier, rocks of Coopers Mate extend across the Murchison Glacier to Mt Cooper, and delineate the nose of a large anticline with mostly Baker Formation at the core, and a few medium-sized anticlines, plunging variously both north and south. At the base of the range, close to the Murchison Glacier, there are three massive greenish sandstone outcrops, assigned to Acolyte on Maps 2 and 3, but possibly belonging to the Cooper Peak Member of the Baker Formation. Other than in these small areas, Rose Formation is predominant. Rose rocks cross the range between Mts Acland and Hutton, and display broad not very deep folds, some increasing northwards in complexity, with petalloid folding, caulifowering into a number of smaller folds northwards.

Fig. 7.38. Rose Formation on the south side of Mts Olaf, Kenneth and Ronald Adair, just north of Mt Hutton, in the Liebig Range**.**

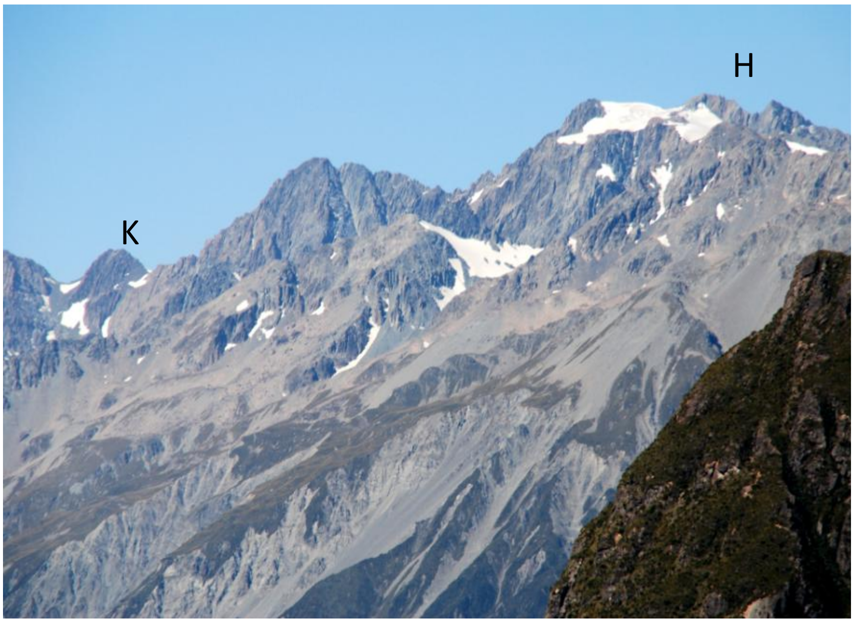


Fig. 7.39. Peaks of the middle Liebig Range, dominated by Mt Hutton (H), in Rose Formation, viewed from ridge south of Ball Glacier. Mts Ronald Adair, Olaf and Kenneth (K) lie to left.

Within the Rose Formation north of Mt Olaf, a band up to 150m thick of well bedded turbidite approaches rocks of the Aiguilles Rouges and Walpole turbidites of the Malte Brun Group. Similar bands cross the divide at several places, and have been disrupted by minor faulting and repeated in part by folding. Possibly the band is represented in the Whymper Glacier headwall to the north, and as far south as Mt Blackburn south of the Park border.

The peaks of Olaf, Kenneth, Ronald Adair and Hutton are composed of Rose Formation, and offer particularly enjoyable if easy climbing. Folding is not as tight nor as pervasive as in the Malte Brun Range.

Northeast Liebig Range

In the northeast corner of the Liebig Range north of the southern branch of Rutherford Stream, rocks belong chiefly to the Rose and Acolyte Formations, and pass southwards into well defined tractator faults beyond the Park boundary to the south of Rankin Stream and in the Hall Range as far as Mistake Peak along the western side of the Godley Valley.

Mid-Liebig Range

The mid-Liebig Range is low with little rock worth climbing, Mt Abbott being the most interesting peak. Here there are large gently flexed folds which refold earlier folds. The prominent fold that is displayed upvalley from the terminus of the Murchison Glacier extends towards the crest of the range well south of Mt Tamaki, and is broken by minor faults and small folds (Fig. 3.2, p. 27), some of a clearly older generation.

Fig. 7.40. Rose Formation at Mt Abbott and Ailsa Pass in the Liebig Range, east of Aoraki Mt Cook.

South Liebig Range

A few minor peaks emerge to the south of the Liebig Range, such as Monastery, Biretta and The Nuns Veil. The Rose Formation remains prominent, and is separated from underlying but younger Mannering Group by an ancient tractator fault, which has been gently folded.

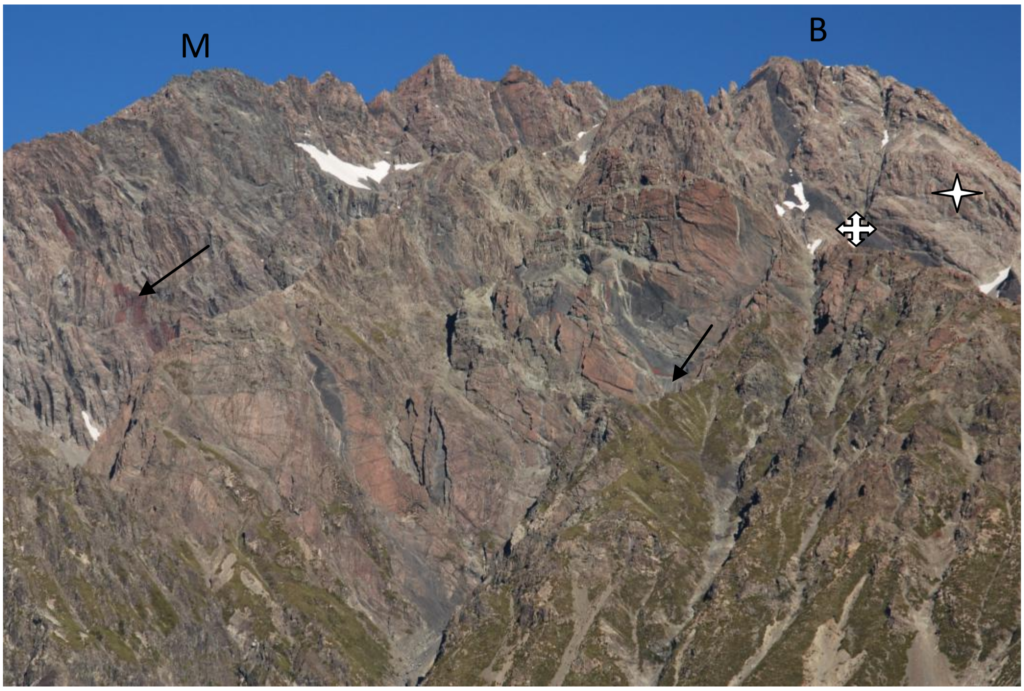


Fig. 7.41. Monastery (M) and Biretta (B) Peaks from west, showing red mudstone (arrowed) of Rose Formation, with Bonney shale Member (with cross) and Cooper Peak Member (as starred) to south (right). The base of a sandstone bed in the foreground is shown as a smooth slab. Note the long fracture just right of the star that passes from Biretta Peak through to the foreground. Ray Bellringer, photo.

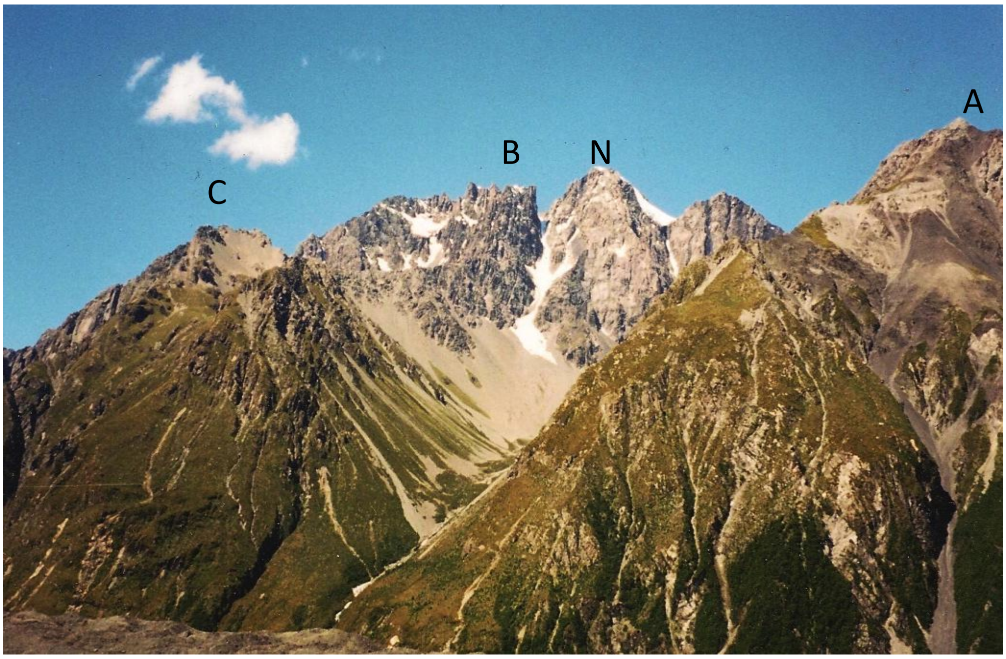


Fig. 7.42. Biretta (B), The Nuns Veil (N) and Botanical Spur of The Acolyte (A) peaks of southern Liebig Range, viewed across the Tasman Glacier, with The Armchair (C) to the left. The angular and frenetic relationships of black mudstone and sandstone of the Acolyte Formation are shown to the upper right. An incomplete anticline is indicated in the thick sandstone band of The Nuns Veil, also indicated in Fig. 1.11, p. 9.

Fig. 7.43. Complexly interrelated black mudstone and pale (green) sandstone of Acolyte Formation on Botanical Spur of The Acolyte, south Liebig Range. Under severe pressure of folding, the thick sandstone units have broken into large blocks, surrounded by more mobile mudstone. Photo Merrin Waterhouse.

CLASSEN GLACIER, TASMAN SADDLE TO MT MOFFATT, NORTH LIEBIG RANGE

Classen Glacier and surrounding peaks[14]

The Classen Glacier occupies a formidable chasm with steep walls in its lower reaches before opening into a recently formed lake that is even more tedious to circumnavigate than moraine. To the south, at the northern end of the Liebig Range, the peak of Acland is formed from an anticline of Rose Formation, with minor folds, including small synclines at a high angle to the trend of the major anticline. This is overlain by Burnett Formation with a number of narrow folds, and the lower mountain slopes of Acland to the east above the floor of the Godley valley have thick Acolyte Formation, dominated by black mudstone, with less sandstone than usual. This formation also has a few folds, and might seem to pass stratigraphically upwards into Burnett, but younging directions and fold axes indicate that the succession is overturned, suggesting a hidden fault or fold axis. The northern wall of the lower Classen Glacier bears small glaciers – smaller indeed than shown on the Map 3, because of recent melting - and the rocks from Mt Mannering to east of Mt Panorama show several tight folds, with the largest over the face of Mt Mannering. The rocks between the Easter and Sustins Glaciers along the north side of the Classen Glacier include some thick quartzose sandstone approaching in some respects the Steffan and Cooper Peak Members of the Baker Formation, though this is yet to be confirmed and the rocks have not been mapped as such. To the west the Rose Formation continues into the Whymper Glacier, and to the north, the Rose, Burnett and Acolyte rocks continue into the complex area of the Grey, Maud, Ruth and Godley Glaciers.

Fig. 7.44. Southwest wall of proglacial or terminal lake in the Godley valley below Classen Glacier, exposing Acolyte Formation. Note the beds seem little disturbed, compared with those nearby adjoining the Grey and Maud Glaciers just to the north.

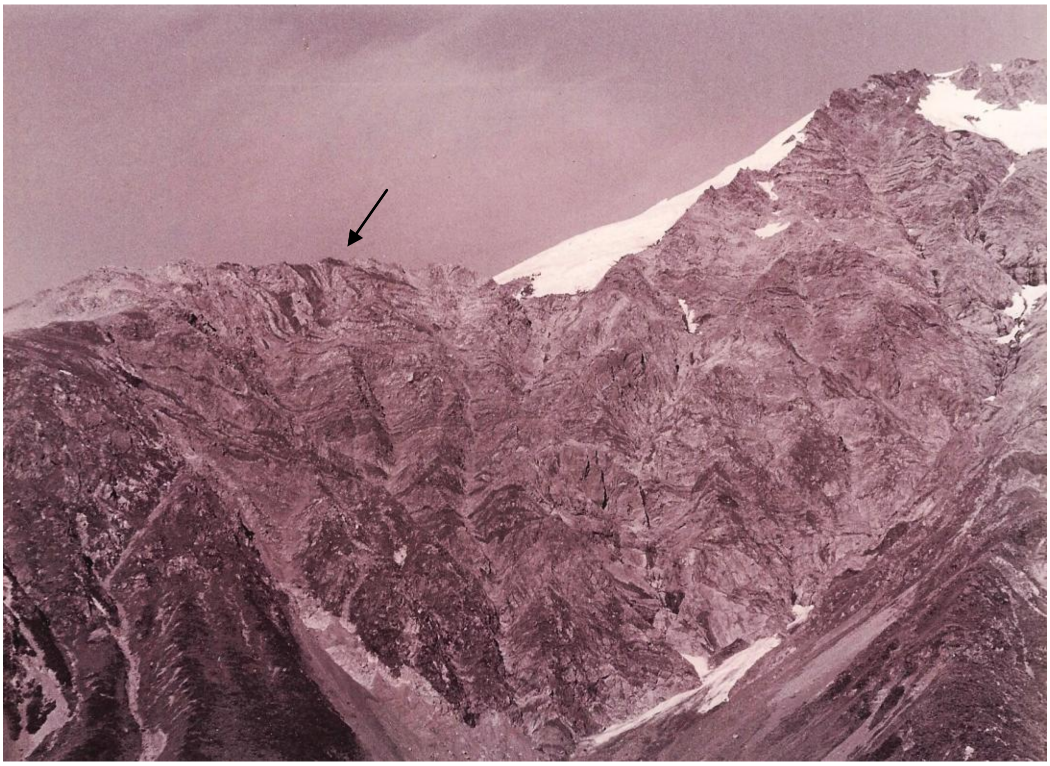


Fig. 7.45. Southeast face of Mt Acland, mostly Rose and Burnett Formations, with synclinal axis arrowed, adjoining the anticline over Mt Acland.

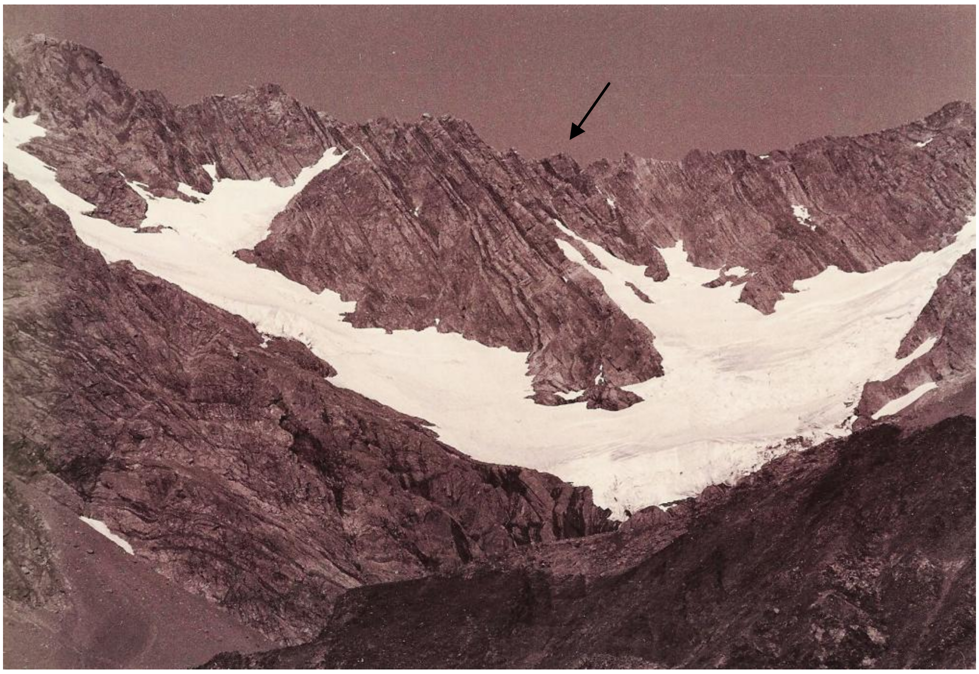


Fig. 7.46. Ridge north of Mt Acland, showing anticline in Rose Formation. Beds young north and outwards, and include a minor (arrowed) anticline, with further folds visible. Acolyte Formation in foreground.

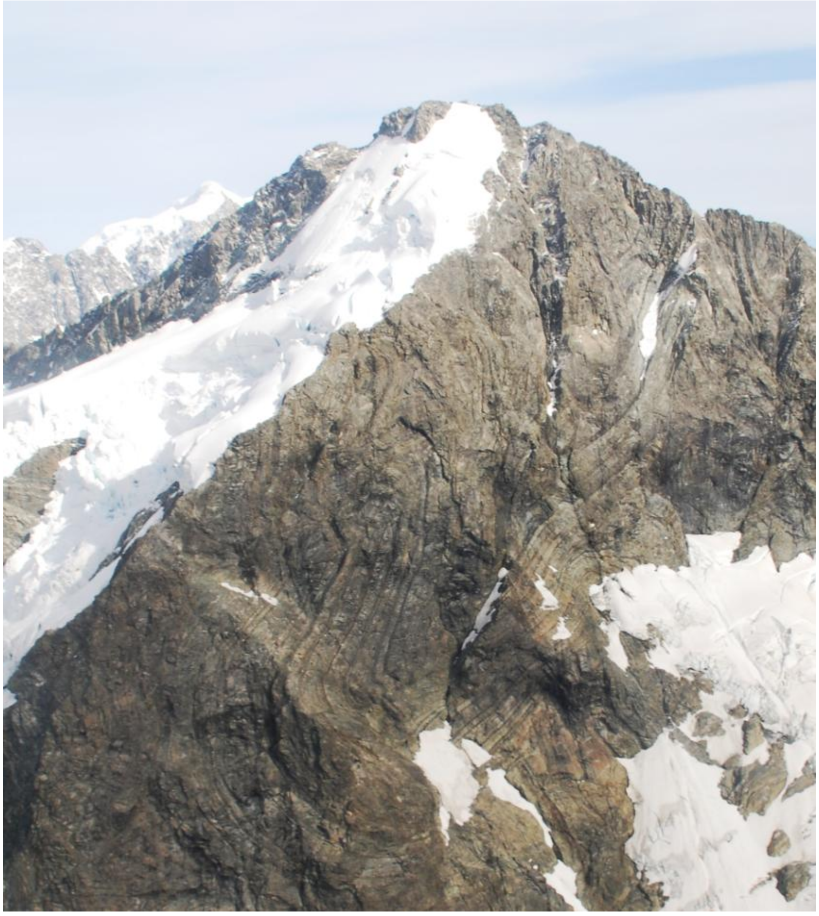


Fig. 7.47. The complex north-plunging syncline in Rose Formation over the east face of Mt Mannering, above the Classen Glacier. Mt Elie de Beaumont lies in the background to the left. Photo Kerry Bellringer.

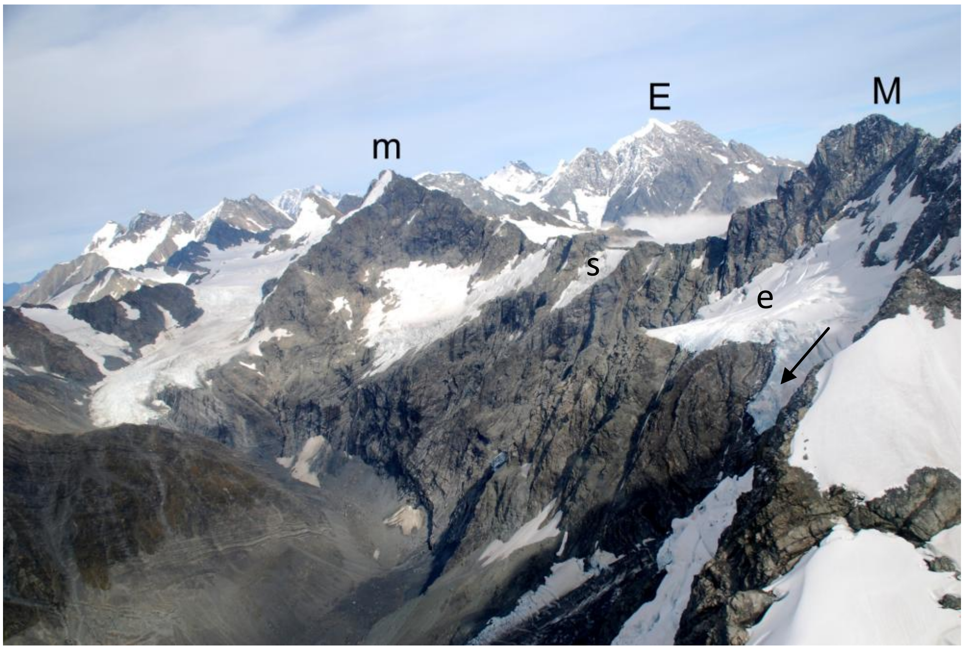
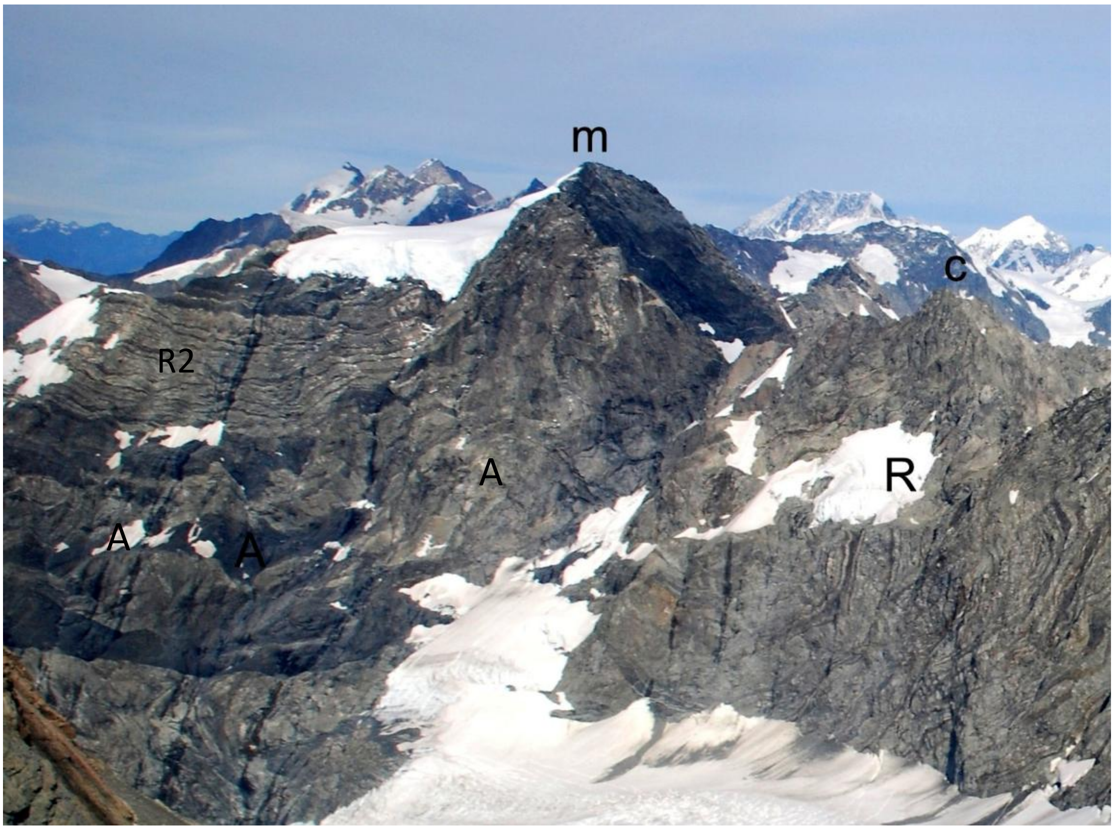


Fig. 7.48. North side above Classen Glacier, showing Mt Mannering (m) and remnants of Sustins Glacier (s), and nearer, the Easter Glacier, (e) below Mt Huss (M). Mt Elie de Beaumont (E) in background. Syncline arrowed below Mt Moffat, (which is out of sight to right).

Grey, Maud, Ruth and lower Godley Glaciers, Neish Plateau

From a geological perspective, this area is superbly interesting. It is home to a number of lowly but ice-clad peaks and deeply channeled glaciers, now suffering the growth of several large glacial lakes, and its geology is complicated, with many folds and

Fig. 7.49. Continued on facing page, and see for caption.



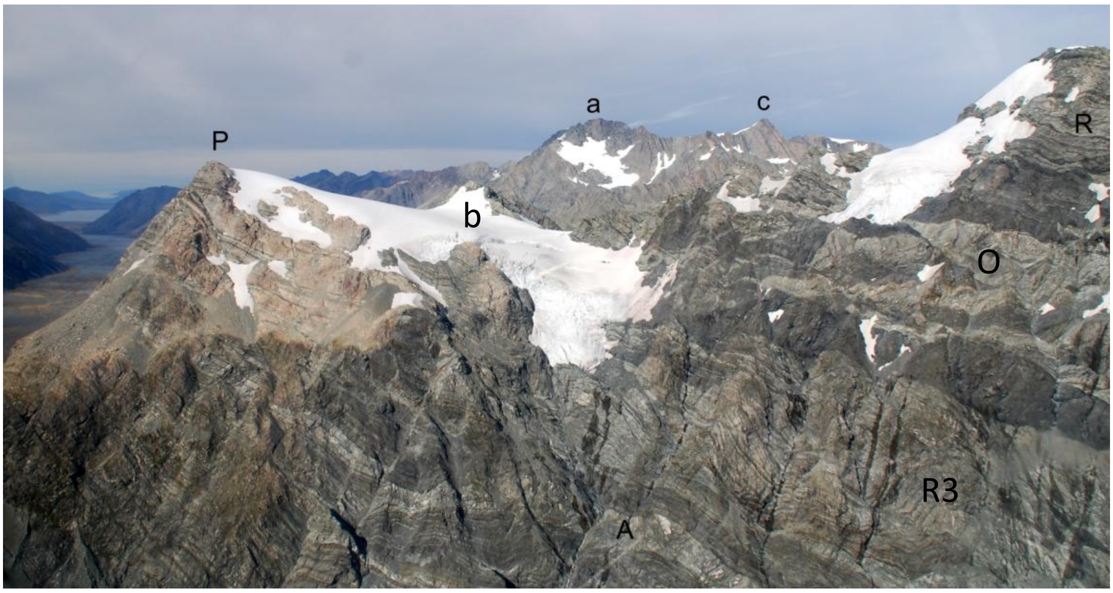


Fig. 7.50. Mt Panorama (p), Mt Bruce Murray (b) and lower portal south of Grey Glacier in foreground, showing Rose Formation (R = R2 in Fig. 7.49), with a possible second band (R3) below, and Acolyte (A) beds. Mt Acland (a) and Mt Conrad (c) and Lake Tekapo lie in the background. Note the number of small-scale folds and short overthrust faults (left of O).

Fig. 7.49. [Continued from facing page]. Panorama of west wall of Grey Glacier, from Mt Livingstone (m) through peaks of Cassino (c), Alamein (a) and Takrouna Peak (t), showing Rose (beds around R), Burnett (B) and Acolyte (A, A) Formations, indicative of massive deformation and submarine slumping, which occurred during initial phases of the development of tracts and tractator faults. A large slab of Rose Formation (R2) lies left (east) of Mt Mannering.

short overthrusts apparently due to massive submarine slumping, demonstrating an early phase of tract development, with folding and faulting that has intimately associated Rose Formation with green sandstones and thick black argillite of the Burnett and Acolyte Formations. It is not always easy to distinguish the Burnett Formation from Acolyte Formation with its thicker bands of sandstone and mudstone. The two developed in stratigraphic succession, Acolyte above Burnett. The geology is much simplified in the geological map, with the complexity of outcrops exposed on steep rock walls difficult to map at a feasible scale, but the photographs demonstrate well the intricacies that are revealed by good and clear outcrop, the difference due to the advantages of an oblique view as opposed to an aerial perspective.

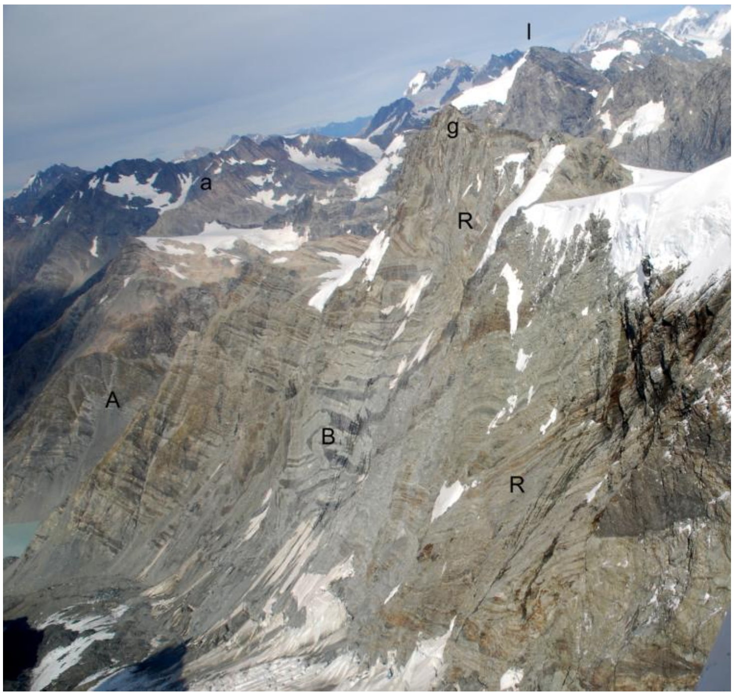


Fig. 7.51. Lower west wall of Maud Glacier with Mt Fletcher (g), showing Rose (R) and Burnett (B) Formations, Acolyte (A) also represented to south of Grey glacial valley. Mt Livingstone (l) lies above Grey Glacier, with part of terminal glacial lake visible. Distant peaks of Aoraki Mt Cook and Tasman lie to upper right. The north-plunging Acland Anticline (a) is also visible.

The most interesting of all outcrops lies along the east wall of the upper Grey Glacier, north of the peak of Takrouna, where beds are arranged in several large and tightly packed folds. A little to the south, east of Mt Livingstone, thick sandstone blocks are interspersed with thick mudstone, where a layer has disaggregated under the stress of submarine slumping, or slurching, a word which conveys lurching and sliding under gravity and probably aided by the presence of water. It appears that huge blocks became detached and slid downslope, to leave the stratigraphic succession confused and complex, in what is called chaos breccia.

Fig. 7.52. [Opposite page] The lower west wall of the Ruth Glacier. Note the weird shapes of the green-tinged sandstone, and the large block of Rose Formation (R) with curled end at right, set amidst extensive and overturned Acolyte Formation (A). It matches a similar band (R2) south of Mt Livingstone (see Fig. 7.49 and 7.50). The large irregular exposures of Acolyte sandstone illustrate chaos breccia (x) at lower left. Beyond lies the west wall of the Maud Glacier with Mt Fletcher (g), succeeded by the west and south wall of Grey Glacier below Mt Livingstone (v), showing Rose Formation and Acolyte Formation, and Mt Loughnan (l) beyond.


R2
x
v
g
R
I
A

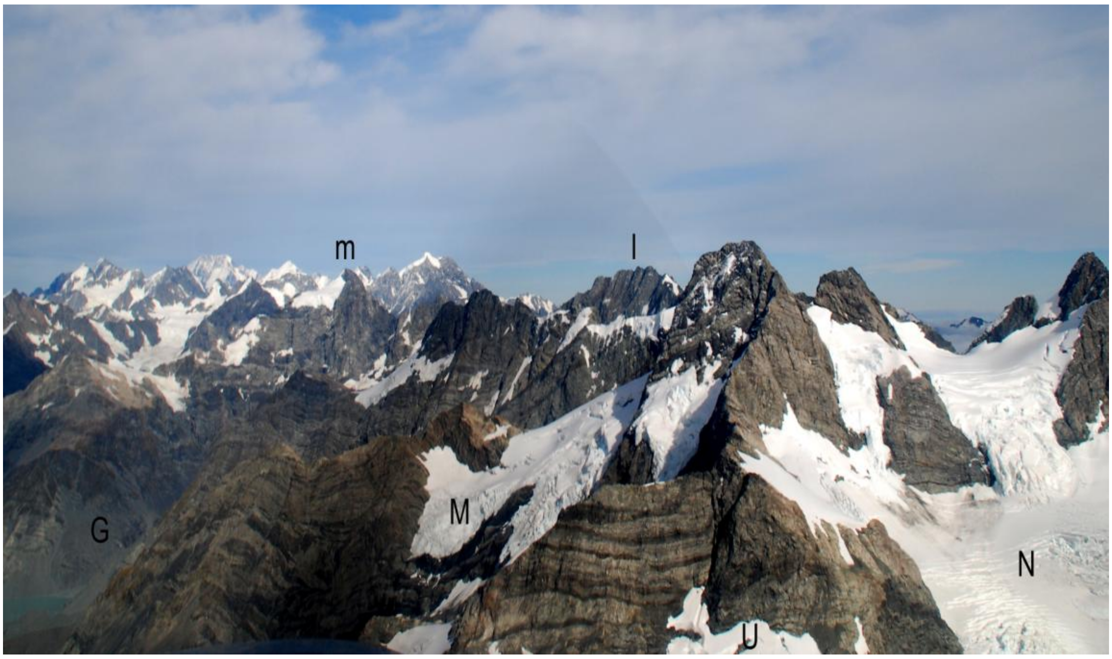


Fig. 7.53. Neish Glacier (N) and lower western wall of Ruth Glacier (U), followed by the western walls of the largely concealed Maud (M) and Grey Glaciers (G). The Acolyte Formation is somewhat disaggregated on wall of Maud Glacier. In the distance, well known high peaks of the Park are visible along the sky-line, beyond Mt Loughnan (l) and Mt Mannering (m).

These two figures illustrate the varying nature of Acolyte outcrops, some of which seem little disturbed, whereas others show disaggregation, thickening or thinning, and folding.

Fig. 7.54. The upper Neish Glacier, with Acolyte Formation, overlain by ? Rose Formation (R), or possibly Burnett Formation, apparently reflexed into folds. To judge from grading of beds and direction of younging, the ?Rose Formation underlies the beds assigned to Acolyte Formation. Mt Loughnan (L) visible to south.

THE D’ARCHIAC MASSIF AND UPPER GODLEY GLACIER

Fig. 7.55. Mt D’Archiac with mostly Rose Formation. looking west from Maud Glacier.

Fig. 7.56. Ridge north of Mt D’Archiac, and at the head of the Godley Glacier, looking east. A band of alternating mudstone and sandstone, signified informally as Rb, looks like Burnett Formation, but is regarded as intra-Rose, with Rose Formation each side, south of Mt Pyramus (P), and shown as Rb in Fig. 7.58. There are several faults, F showing a mineralized zone, and f, with limited displacement.

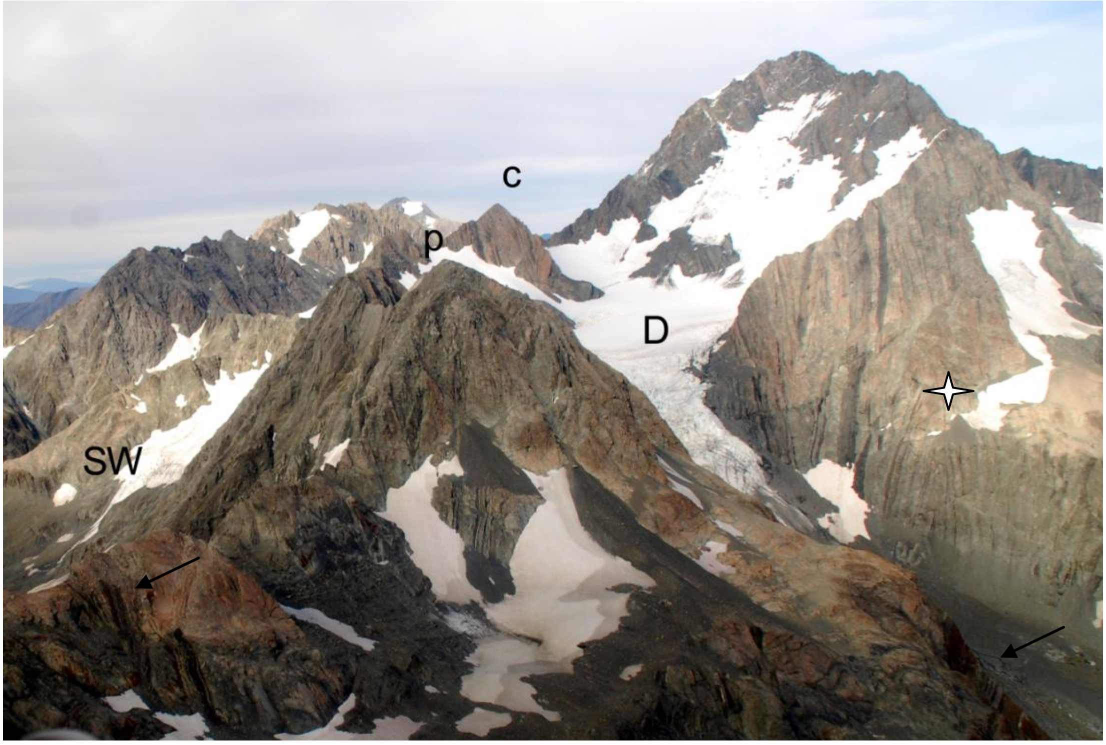


Fig. 7.57. View southsouthwest to Mt D'Archiac and Dennistoun Glacier (D), with red argillite bands, as arrowed. Mt Dennistoun (c), Mt Pyramus (p) and Saint Winifreds valley (SW) are indicated. An antiform on the flank of Mt D'Archiac is starred, and several other folds are visible.

The rocks are well exposed over the massif of Mt D'Archiac, and consist of Rose, Burnett, Acolyte and Baker Formations (including segments beyond the Park boundary). A large strip of rock between McKinnon Stream and Godley Glacier to the north is chiefly of Acolyte bands, with possible Burnett. There is a band of alternating thick argillite and sandstone "Rb" which extends from south of Mt Pyramus at the head of the Godley Glacier, as shown in Fig. 7.56 and 7.58. This could be Burnett, and might be separated from a fault on one or other side – probably the northern side, from Rose Formation, but it is treated as a band within the Rose Formation, because the unit is nowhere as thick as characteristic Burnett Formation. To the east and beyond the borders of the Aoraki Mt Cook National Park, Rose Formation is exposed north of the Forbes River and South Forbes Glacier. Most of the peak itself consists of Rose Formation, with outcrops of red argillite exposed in the low peaks and saddles at the head of the Godley Glacier, as well as further south well above the Godley valley.

A large but not very deep syncline is well exposed along the western wall of the upper Godley Glacier, and another is figured with similar orientation on the flank of Mt D'Archiac along the lower wall of the Dennistoun Glacier, and other folds are developed, as shown in Fig. 7.57. Further folds are present in the Rose Formation over Malthus and Dennistoun Peaks, and also southwest of D'Archiac, but faults and folds are few.

SUMMARY

Three exceptional aspects call for summary. The first and most significant is the recognition of what are here called tracts, separated by tractator faults, which are broadly equivalent to nappes or recumbent folds, or low angle thrusts. The presence of

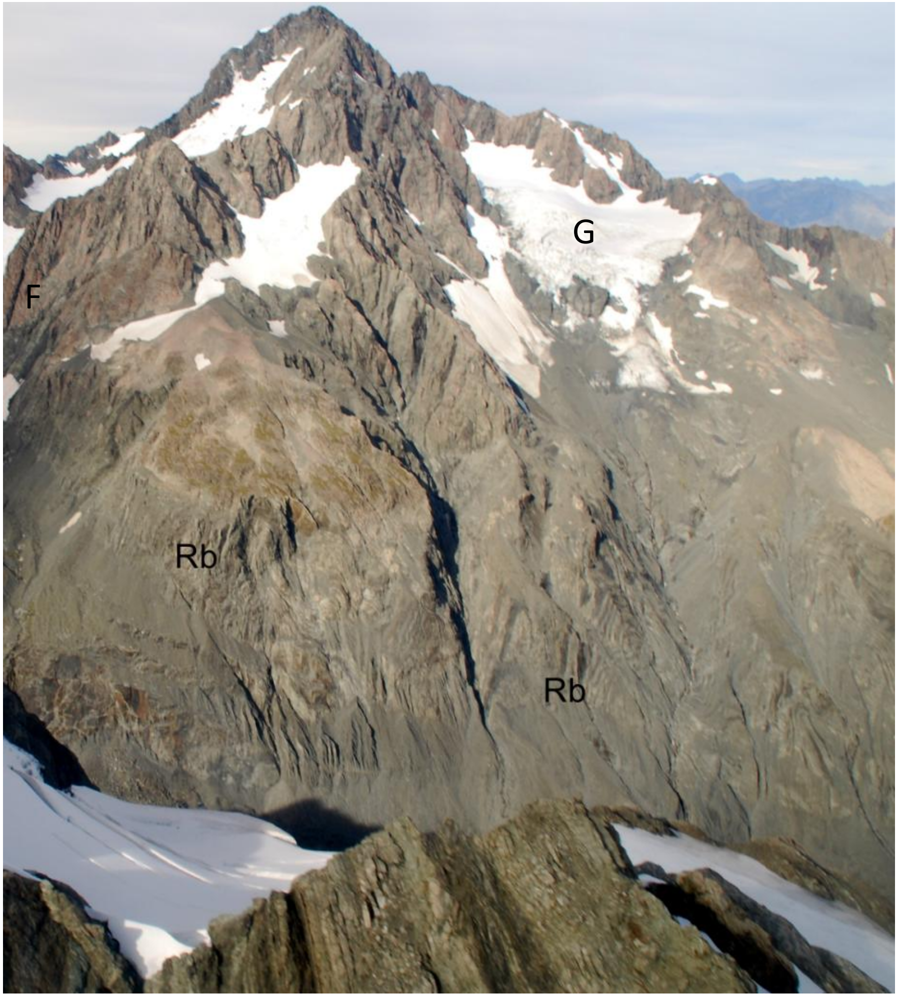


Fig. 7.58. Mt D’Archiac and FitzGerald Glacier (G) looking across the upper Godley Glacier. Rb turbidites as in Fig. 7.56, and fault (F) on extreme left. Viewed from west of D’Árchiac.

these tracts shows that during the major mountain building during the later Mesozoic Era, called the Rangitata Orogeny, the Southern Alps underwent much the same processes that built the Himalayas of south Asia, the Alps of Europe, which globally are aligned with the Southern Alps of New Zealand, lying between Gondwana and Laurasia.

There are additional aspects. The exceptional height of Aoraki Mt Cook appears to be due to exceptionally thick Rose and Burnett Formations, compared with rocks to the south, the increased thickness ascribable to additional folds and possibly duplicated fault-bound slabs.

A further intriguing point lies in the differing natures between the rocks south of Mt Elie de Beaumont, and those to the north. In the south, the westerly rocks well beyond the Park borders are made up of a band of Liebig Group with a few metavolcanics, informally called the Hopkins band (see Fig. 7.60, p. 119). These overlie thick Malte Brun Group as exposed on Mts Sefton and La Perouse, followed to the east by Liebig and Mannering Groups, considerably reduced in thickness by faulting in the region of the Hooker Glacier. These groups are trending more northerly than the Main

Divide, which crosses the belts of rocks progressively. From Mt Dampier to the Rudolph Glacier, the divide passes along rocks of mostly the Rose and especially the Burnett Formations. Further east lies the Malte Brun Range, with thick outcrops of Malte Brun Group.

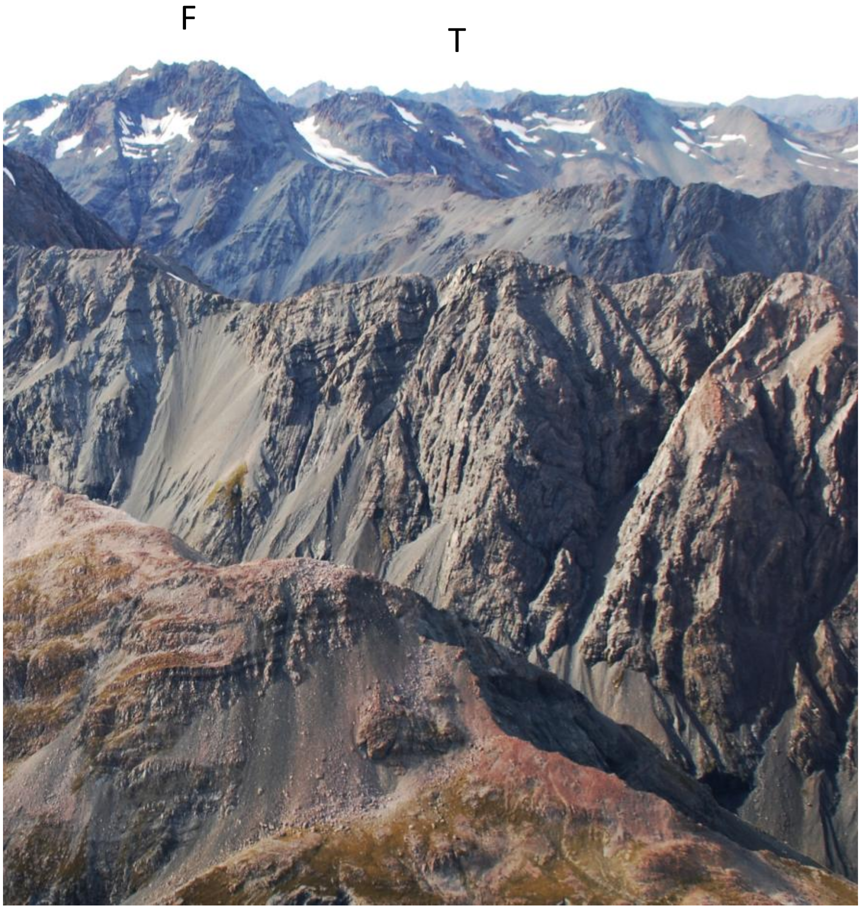


Fig. 7.59. South-plunging anticline and recent fault in Rose Formation south of FitzGerald Stream, southwest of Mt D’Archiac. Mt Forbes (F) in background, and beyond that Two Thumbs peak (T) is visible on the skyline.

North of Mt Elie de Beaumont to beyond Mt Mannering beside the Classen Glacier, the rocks of the Main Divide are more metamorphosed, and it appears that the entire belt of Malte Brun Group of Mt Sefton, as questionably represented by the turbidites of Mt Brodrick and Graceful Peak, has been severely diminished. The westerly rocks appear to have moved east, as a strong eastward stepping, but the stepping does not appear to be caused by a single and recent fault. The rocks on the northeast side of the Rudolph Glacier strike slightly differently, by 10°, as if pulled eastwards by the stepping, and the strikes and fold axes are consistent for the length of the divide peaks, from the Rudolph Glacier to the southwest face of Mt Elie de Beaumont. Then the changes start. Part of the Maximillian Range displays green Rose Formation, with some outcrops of red argillite, trending roughly east-west, and extending into the head of the Whymper Glacier, and this is also shown in a study of greenschist[15], all in similar sharp contrast from different rocks to the south. It seems feasible to regard this band of Liebig Group, Rose Formation, as the same as either the Sealy Range band east of Mt Sefton, or the Hopkins Range band west of the Malte Brun

Group in the neighborhood of the Hopkins valley. The Hopkins correlation is deemed more likely, because further west down the Whataroa River, rocks are like those west of the Hopkins band, not the Sealy band. Moreover the Hopkins band adjoins Malte Brun Group, which is possibly represented in the Brodrick-Graceful peaks around the head of the Whymper, Tasman, and Murchison Glaciers, whereas the Sealy Permian adjoins Mannering Group to the east[16]. But this aspect remains contentious.

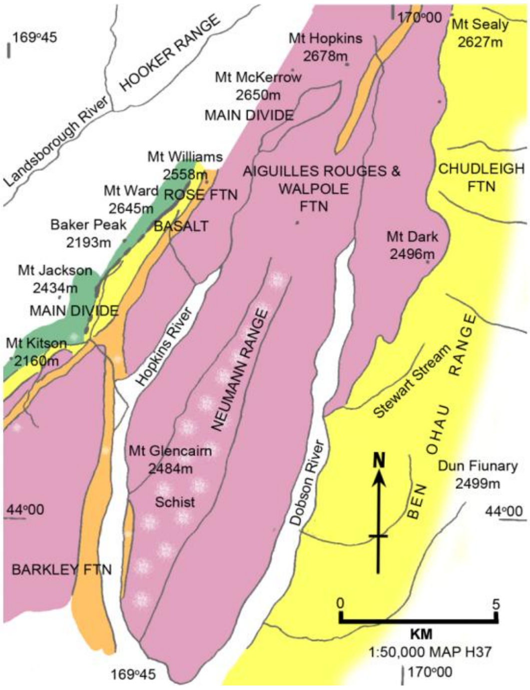


Fig. 7.60. Distribution of formations, showing the presence of a belt of Permian (green) Rose Formation, beyond the southwest borders of the Aoraki Mt Cook National Park, and informally called the Hopkins band for purposes of this text. Basalt is present, with Permian conodont fossils. Possibly this belt enters the Park just north of Mt Elie de Beaumont. The broad belt of Aiguilles Rouges and Walpole Formations (Ftn) involves repeated bands, and limited outcrops of Novara Formation are present within the yellow “Chudleigh” Formation (Ftn). Figure based on 1:50 000 map H37.

At the head of the Tasman Glacier, faults and folds extend roughly east - west, and the peaks of Darwin and Annan expose further rocks of the Malte Brun Group, complexly folded in an Annan Anticline, which has been faulted and distorted so that it is not clear whether the fold axis lies roughly east-west, or northwest-southeast. It could even represent a former continuation of the Malte Brun Anticline, bent around the Haeckel Syncline. The large Haeckel Syncline is also deformed. Much of the fold is oriented northnortheast-southsouthwest, but the western end of the axis has been stretched and oversteepened, showing that the stepping occurred after the initial development of the fold. This belt of roughly east-west trending rocks and structures extends no further than the Starvation Saddle Fault where it intersects the Murchison Glacier. The rocks of the Mannering Group west of the Murchison Hut arch round in an anticlinal nose into the peak called Coopers Mate.

On the more northerly side of the upper Whymper Glacier, the rocks consist of schistose (Chlorite 3) to subschistose Mannering Group, and these pass into the rocks of much of the Classen Glacier, from west of Mt Mannering. The lower and eastern Classen rocks resume the Park-predominant trend of northnortheast-southsouthwest, and are mostly of Acolyte and Baker Formations, and also Rose and Burnett Formations in the Liebig Group. They extend far north, beyond the boundaries of the Park. There is no Malte Brun Group.

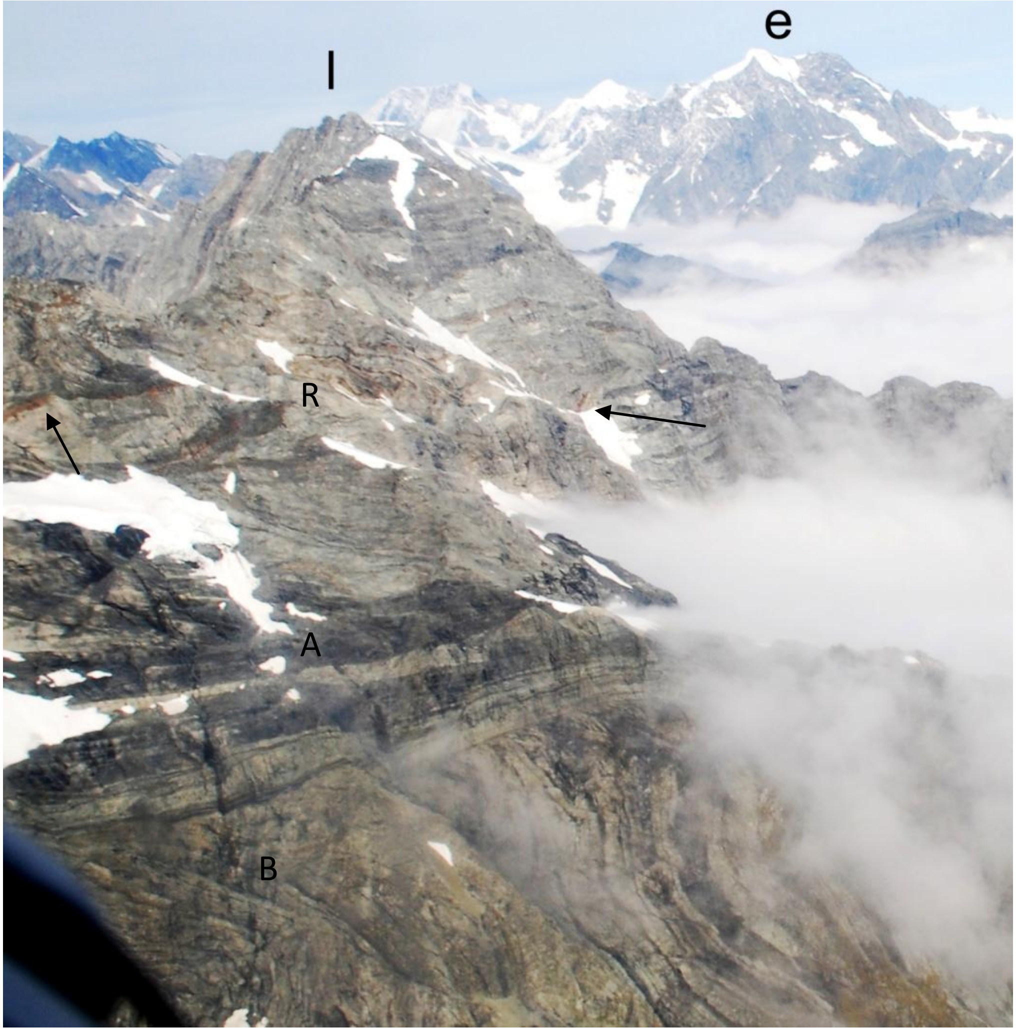


Fig. 7.61. Rocks just west of Mt Seymour on the Main Divide to the multi-peaked Mt Loughnan (l), and on to Elie de Beaumont (e), with Rose (R), Burnett (B) and Acolyte (A) Formations, including a marked change in strike in the foreground, suggestive of a faulted syncline. Two of the red argillite bands are arrowed.

Attention has been drawn to the presence of schist near Murchison Hut, and the likelihood that a high and now vanished massif existed over the heads of the Tasman, Whymper, Classen and Murchison Glaciers, that acted as the spawning ground for the development of the glaciers. Let me suggest it be called Mt Phantomia, or Old Hochstetter. The massif may have included a considerable thickness of Malte Brun Group, piled up over the rocks now exposed by the present glaciers. In so far as the massif dated from the Pleistocene glacial ages, it would seem that the warping, thrusting and stepping may have dated from an early phase of the Kaikoura Orogeny, conceivably after earliest Pleistocene.

Warping along the Alpine Fault

The overall disposition and stepping of the rocks north and south of the Whymper-Classen Glaciers suggests the likelihood of uparching along the Alpine Fault. According to this explanation, a large buckle developed along the eastern side of the Alpine Fault, analagous to buckles along the east side of the Wellington Fault, where down-warping has depressed the Wellington Harbour and the now infilled Hutt Valley, followed to the south by upwarping over Brooklyn and other southern Wellington suburbs[17]. For the Aoraki Mt Cook National Park, the equivalent on a larger scale may be the southerly downwarp that has allowed preservation of Malte Brun Group above Liebig and Mannering Groups, and a northerly upwarp that has pushed up rocks that underlie the southerly exposures. The Malte Brun rocks were formerly present in the northerly area, but have been lifted high and eroded away. Consequently the northerly rocks are more schistose, and rocks of the Malte Brun Group are lacking. The warping has not been simple, involving some folding, some faulting, and boundaries are not clear-cut. If the northerly rocks had been thrust eastwards by major fault stepping, there would be much more clearly defined faults, but such do not appear to have been developed. Stratigraphic mapping of the rocks along the Alpine Fault may yield information on major deformation due to the fault, a matter not addressed in previous work. Whether the upwarping is due to uparching asthenosphere, or emplacement of additional thrust material, requires geophysical study, or closer analysis of rock facies. Nor is it clear if the upwarping extended as far west as the Alpine Fault itself.

Chapter 8

REGIONAL SETTING FOR HARD ROCK GEOLOGY OF AORAKI MT COOK NATIONAL PARK

The Aoraki Mt Cook National Park covers too small an area for its relationships to the rest of even just the South Island to be interpreted, so a brief summary is provided to outline its relationship to some of the geological features in nearby regions, with emphasis on the original disposition of rocks and their sedimentary sources, and aspects of the Rangitata Orogeny of upper Mesozoic age, and comments on the deformation of rocks to the east during the present and ongoing Kaikoura Orogeny.

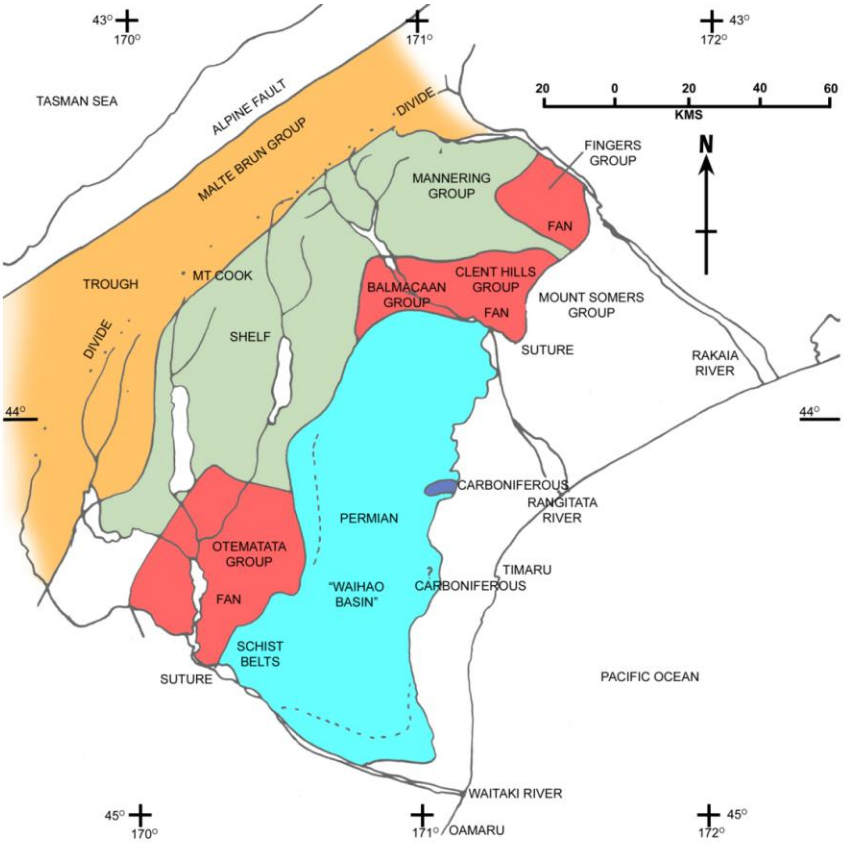


Fig. 8.1. Broad outline of distribution of Mesozoic rocks of the Rakaia Basin in the central part of the South Island, New Zealand, shown as trough and shelf. Most belong to the Triassic. The Permian-Triassic with some Carboniferous rocks of the "Waihoa Basin" to the east are now sharply cut off by a major fault complex or geosuture from rocks of the same age, but different facies, to the west. This is clearly demonstrated by the three huge assemblages of deltaic fan deposits, shown in red. These accumulated at the mouth of three major rivers of Mesozoic age, which drained a land that has now disappeared. The mid-northerly one includes the Clent Hills Group, of Jurassic age. The Fingers Group, Balmacaan Group and much of the Otematata Group overlie the fan deposits. They grade westwards into the Mannering Group, which accumulated over a continental shelf in front of the fans, and Malte Brun Group accumulated in deeper waters at the same time, actually further west than where shown on the map, for they have moved eastwards during the Rangitata Orogeny. Thus the present distribution is complicated by the sliding of tracts of sediment during the Rangitata Orogeny from the trough eastwards in part over the sedimentary fans, and the original disposition of accumulation is better conveyed in Fig. 8.3. The "Waihao Basin" seems likely to be the southern extension of the Pahau Basin, recognised further north in Canterbury and extending through the east coast of the North Island.

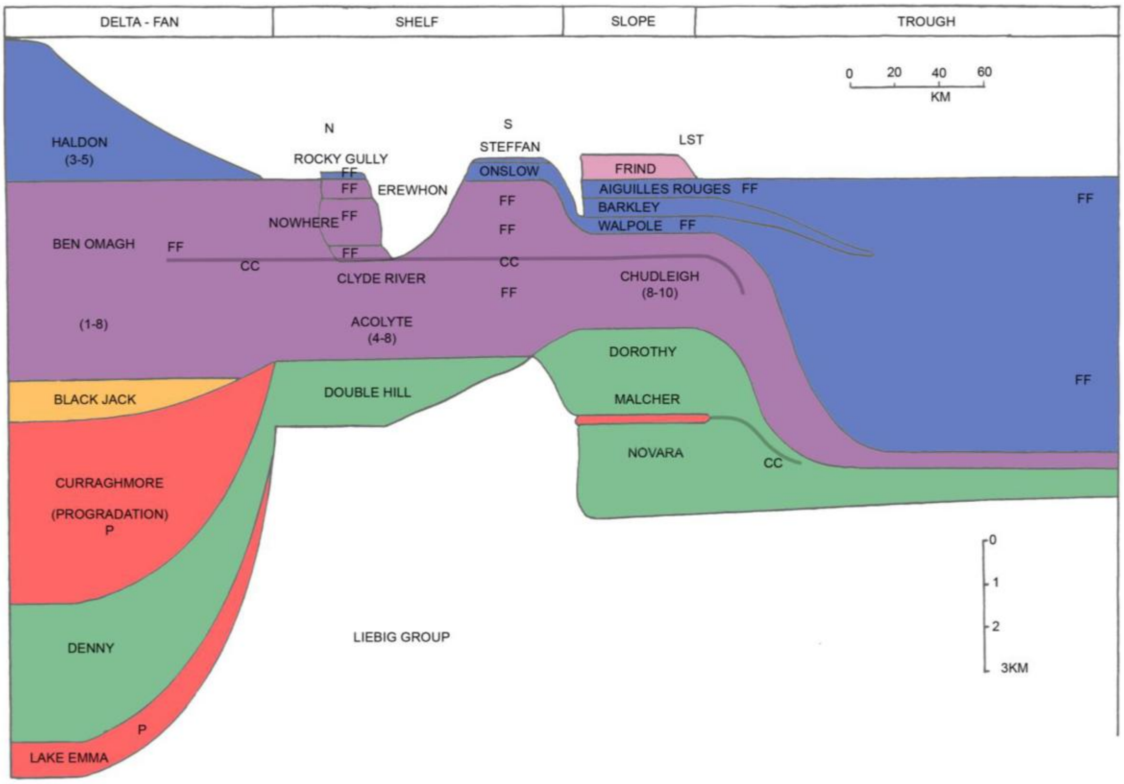


Fig. 8.2. Chart or cross-section showing the original distribution of Triassic formations according to thickness from present east (left) to west (right) in facies belts from the lost upland to the present east, into deep waters of the trough far to the present west. The various formations will be discussed in the companion study of rocks beyond the Aoraki Mt Cook National Park. FF = fossiliferous deposits. Rocks of the Aoraki Mt Cook National Park belong to shelf, continental slope and trough environments. The vertical scale is much greater than the horizontal scale.

Source of the sediments

For rocks of the Aoraki Mt Cook National Park, there were two sources of sediment: a basic to intermediate igneous source that provided the rocks of the Liebig Group, and a continental-granitic source that provided most of the rocks of the Mannering and Malte Brun Groups. The source-lands of neither set of rocks are preserved in or near the Park boundaries. Further afield, the Aspiring lithologic association, found in northwest Otago and Nelson[1], includes basic metavolcanic rocks occasionally with pillow lava and cherts, and ultramafic pods, interlayered with thick pelitic (ie. fine-grained) sedimentary schist, interpreted as ocean floor. Around the Central Lakes district of southwest Otago, including Queenstown and Wanaka, the Wanaka lithologic association[1] exposes extensive outcrops of greenish psammitic (that is sand-derived) schist, and greenschist (that is metavolcanics), with chert and ultramafic pods. The two associations are included as “Wanaka Volcanics” in Fig. 8.3. The metavolcanics are not very thick, amounting to only 500m, and only 5% of the total volume, being overwhelmed by metasedimentary rocks, and have been interpreted as forming a plateau, derived from a mantle plume[1]. They offer an interesting comparison with somewhat comparable rocks of D’Urville Island[2], developed in spatial terms further from Torlesse-Aspiring rocks and closer to the Dun Mountain spreading ridge. Sills and apparent flows of serpentinite, formed from ultrabasic lava, are also widespread, at least in the Patuki band of D’Urville Island. The Torlesse metavolcanics, considered to be geochemically close to the Wanaka and Aspiring metavolcanics, would from the distribution and thickness, appear to have developed from scattered and relatively short-lived leaky or blocked transform faults over the sea-floor, which enabled the build-up of igneous rock and hot-spring deposits, and some of these were eroded to yield sediments. The Liebig Group may have belonged to the outer fringe of these rocks, with no ultramafics and minimal lavas, being made up largely of volcanigenic sediment and tuffs. In that case, it may be wondered where the subduction zone was placed on the side opposite to that of the Brook Street Volcanics. Was there none? Or was one placed beyond the confines of the National Park, as part of the plate that included both the Rakaia Basin, and the "Waihoa basin"?

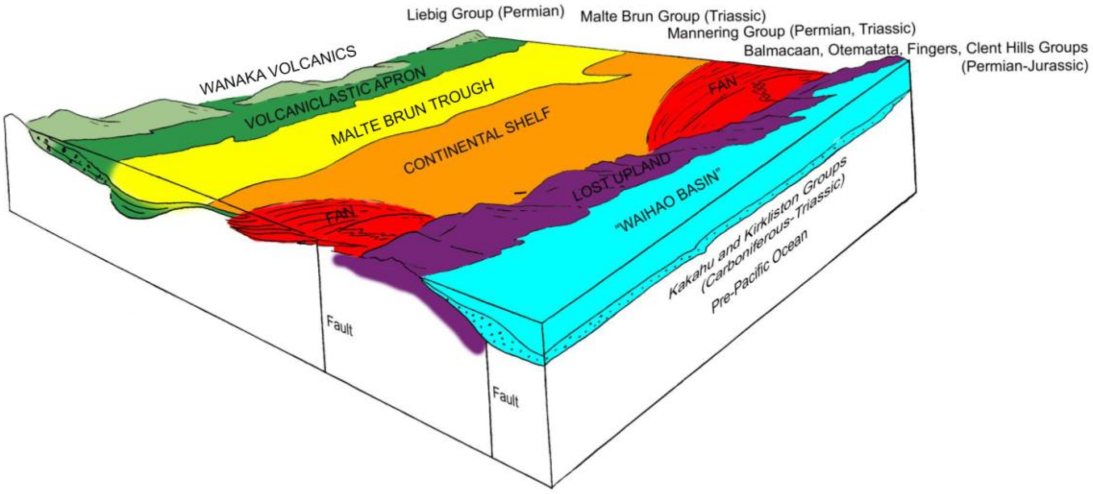


Fig. 8.3. Reconstruction of the environment during the Permian and Triassic Periods in mid-and east South Island of New Zealand, from present west (upper left) to lower right (present east). Igneous rocks supplied sediment into the bordering sea (green). Rocks of the Aoraki Mt Cook National Park are made up of sediments from the apron, and Rakaia Trough, which involved the Malte Brun Sub-basin for Malte Brun Group and continental shelf and submarine fans. A land mass, called "lost upland", supplied sediment to these large sedimentary fans and deltas (red) at the mouths of large rivers, and to a continental shelf (orange) and trough beyond (yellow). On the other side of the lost upland, sediment was eroded from the "lost upland" into the "Waihao Basin", represented by extensive sediments and schist in east Canterbury and north Otago. The "Waihoa Basin" is probably the older part and southerly extension of the Pahau Basin, recognised further north for younger Mesozoic deposits.

The alternative possibility is that the Liebig sediments were washed off a volcanic arc of andesitic or basic volcanoes during Permian time. It could be argued that the substantial volume of sediment, being very thick in the Arrowsmith Range, and the Palmer Range south of the Rakaia River, supports an origin from a volcanic arc rather than sea-floor crust. Furthermore, postulating a now-vanished volcanic arc would explain the distribution of Triassic sediments of the Malte Brun Group, which indicate the presence of a trough, because the presence of a trough is normally explained by postulating a subduction zone, that is normally accompanied by a volcanic arc. But this has no support from any field evidence, and no such volcanic arc has been found. Although it may be argued that it is not difficult in nature for a volcanic arc to vanish from existence, subducted into the depths of the earth, or, less likely, moved out of the region by strike slip movement, detailed geochemical study of the Liebig sediments is

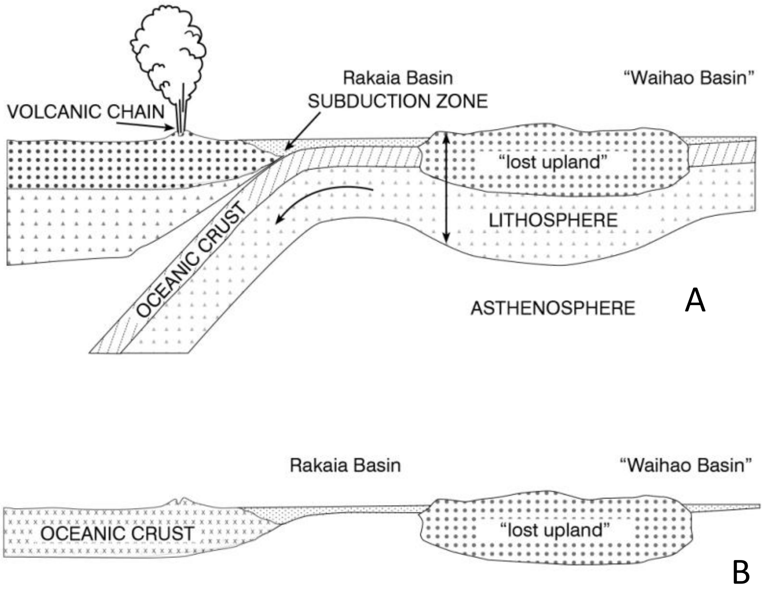


Fig. 8.4. Alternative cross-section scenarios. A,. possible general setting of Aoraki Mt Cook rocks. This suggests that Liebig Group was derived from a volcanic arc, whereas Mannering and Malte Brun Groups were derived from a now lost upland, a continental fragment possibly split away from eastern Australia. The Rakaia Trough lies between the volcanic chain and the "lost upland or "continental crust", and the "Waihao Basin'' to the right of the continental crust. B, an alternative scenario, in which the Rakaia Basin lay between the "lost upland" and ocean crust as represented near Wanaka. On available evidence, this seems more likely.

required to establish that they were indeed sourced from a volcanic arc.

It seems likely that the Mannering and Malte Brun Groups were sourced differently, from land containing granite and acid volcanics, and sediments rich in quartz, to judge from conglomerate found in rocks close to the Aoraki Mt Cook National Park, and from the overall distribution of rock types[3]. The reality of this land is underscored by several lines of evidence, chief of which is the presence of three large fans of sediment that accumulated at the mouths of three large rivers, and involved non-marine beds with plant remains[4]. Further support is provided by the presence of extrusive volcanics and igneous intrusions, that developed from subduction and melting or igneousisation (!) of the "lost upland". On the other side of this upland nearer the Pacific Ocean is found more sandstone and mudstone, which were deposited in the "Waihoa Basin", a name used informally in Fig. 8.1, 8.3 and 8.4. The sediments of this basin are mostly of Permian and Triassic age, with some late Carboniferous, as near Kakahu[5], and the rocks are extensively schistose just north of the Waitaki River, where subducted against the "lost upland". The "Waihoa Basin" appears to be an extension, in older rocks, of the Jurassic and Cretaceous Pahau Basin in north Canterbury and east coast of the North Island. According to this reconstruction, the Mannering Group was derived largely from the lost upland, and the Malte Brun Group was deposited from the same source, in deeper waters, becoming better sorted thanks to the distance from its source. It is suggested that the sediments accumulated in a Malte Brun Sub-basin. This formed within the Rakaia Basin, and both belonged what was originally called "the

New Zealand Geosyncline", or the "Aotearoa Geosynclinal sequence", or the Torlesse Group and Haast Schist[6].

What about the alternative proposal of a volcanic arc that could have provided volcanic sediment for the Liebig Group? Clearly, from the nature of the Triassic sediments, if it ever existed, it was no longer active. It is likely that the nature of sea-floor spreading reversed: the mid-ocean spreading ridge was no longer functioning, and the focus of spreading leap-frogged across the mid-ocean ridge, the Rakaia Basin and the "lost land", ending up in or probably beyond the "Waihoa Basin.

The Rangitata Orogeny

The rocks of the Aoraki Mt Cook National Park record only part of what had happened during the Rangitata mountain building in the upper Jurassic and Cretaceous Periods. The sinking of the trough in which Triassic sediments were accumulating stopped, and the sea-floor with its thick accumulation of sediments rose, or as geologists say, everted, and spilled out eastwards (to use present directions) in the form of tracts, bound by tractator faults. The tracts were developed as slide-slabs, perhaps as nappes or long elongate folds in which the lower anticlinal limb was worn away, or as thrusts – the alternatives are subsumed by the proposed term tractator faults. Such movement is diagrammatically represented in Fig. 8.5, p. 128.

The "lost upland" that had supplied the Triassic sediments, including the large sedimentary fans at the mouths of large rivers, became the location of a new subduction zone, which dragged down the lost upland. The rocks of the lost upland were converted by heat and pressure into Cretaceous intrusives that invaded the "Waihao Basin'' rocks, and overlay them with acid volcanics[7]. The entire land disappeared, so that now the Liebig and Mannering Groups are separated from the rocks of the "Waihao Basin" by a major geosuture which replaced the lost upland. Its nature has been in part revealed by geochemical studies, to suggest that the "lost upland" was a large flake of continental crust, split away from eastern Australia[8]. The so-called "lost upland" may now be lost, but the sediments, marine, deltaic and terrestrial, that it yielded, and the igneous rock into which it melted, are still to be found.

The Kaikoura Orogeny

The Aoraki Mt Cook National Park provides an excellent if complicated record of the effect of the Kaikoura Orogeny on its rocks. The huge deformation which led to the formation of the Alpine Fault is likely to have begun as a gigantic right lateral shear fold, that twisted rocks of the sedimentary basins, and then broke along the Alpine Fault. But as suggested in Chapter 5, the movement invoked some counter-movement, and left lateral faults were also generated. Rocks to the south and west of the Park, including Mt Sefton, are schistose, and are followed to the west by a band of Permian sediment and lava. An area to the east of the Murchison valley and Liebig Range shows rocks arranged in a major thrust sheet of Permian Liebig over Triassic Mannering Group. Folds become less steeply plunging, and indeed folds of the "Waihao Basin" are more subhorizontal than steeply plunging. Faults are mostly vertical in movement, with limited evidence of a strike-slip component, differences reflecting on the greater distance from the Alpine Fault. In short, the affect of the Alpine Fault was markedly less further way from the fault, and reflected more and more the ongoing spread of the Pacific plate towards the Australian plate.

Summary of deformation events

Deformation 1 involved mostly penecontemporaneous submarine slumping, especially in the Burnett, Acolyte and Baker Formations, with attendant crumpling of strata, but not leading to chaotic disaggregation except locally. Examples include bedded chert of the Onslow Formation, and turbidites in the Aiguilles Rouges Formation.

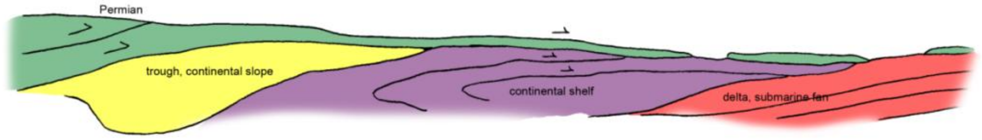
The initial phase of Deformation 2 saw the collapse of huge slide blocks and growth of fold deformations, well preserved around the present Grey and Maud Glaciers, by a process of slurching – sliding and slumping under the influence of gravity and weight of sediment, lubricated not only by the slippery and unstable nature of argillites and mudstones, but by the probable expression of abundant water. The sea-floor gradually rose, and sediment from the trough started to spill out eastwards and southeastwards (in present terms of orientation) as tracts, separated by tractator faults, moving towards and over the continental slope and shelf, much like the nappes of the eastern Canadian Rocky Mountains and southern Himalayas. Folding developed at right angles to the direction of movement, but only involved small folds which could become tightly squeezed or deformed.

Deformation 3 during a late phase of the Rangitata Orogeny folded the strata, tracts and tractator or slide faults into large elongate anticlines and synclines, including the Wakefield and Haeckel Synclines, probably with a wave length of 10-25km, now trending northnortheast, but possibly meandering and anastomosing to some extent. The folds may have resembled those of the inner Appalachians and northern Rocky Mountains.

Deformation 4 commenced with the Kaikoura Orogeny in Late Cenozoic time, with the growth of the Alpine Fault. It involved substantial convergence of the Pacific Plate obliquely on the Australian Plate, with drag along the fault. According to one favoured interpretation[9], the Pacific plate with the Alpine greywackes rode up against the Australian plate, with backthrusting. As an alternative, the Pacific plate could have been involved in initial down-or inpulling (that is induction) against the fault, prior to later retroduction. The onset of glaciation in the Southern Alps depended both on cold climate – during a world-wide ice age, and on having the mountains high enough to have become glaciated. Although the Alpine Fault started some 38 million years ago, the Southern Alps seem to have become high enough to be glaciated only after the early Pleistocene, for there are no early Pleistocene glacial deposits known for the Southern Alps[10]. Yet West Coast sediments include what are interpreted as glacial outwash deposits of early Pleistocene age. So this is something of a puzzle, why such deposits cannot be matched in the rock sequences of Canterbury. Perhaps early glacial deposits had all been destroyed or buried east of the Southern Alps. Perhaps the sources of the West Coast deposits need closer examination – not for the granites and schists which are common, but for the reported greywackes, to determine in detail their source.

Compression tightened the folds, and major faulting commenced. The major early Rangitata tractator faults were rotated mostly into subvertical positions, and some were reactivated into strike-slip vertical and reverse faults. Some fold limbs were removed, and other folds split by new faults such as the Malte Brun Pass Fault. Overall, deformation was complex and changed through time, and was spatially dependent on the distance from the Alpine Fault. The current series of deformations in rocks of the Park seem to have been caused by the West Coast acting as indentor, implying that such deformations occurred after the Caples and Lee River Groups, Dun Mountain ultramafics, Maitai and Murihiku Supergroups and Brook Street arc had been split apart and displaced by the Alpine Fault.

Either schist developed under high pressure at depth along the Alpine Fault, or was brought nearer the surface along this fault, and schist certainly developed along some of the other faults to the east, including the Starvation Saddle Fault. Deformation 5 graded naturally on from deformation 4, and is interpreted, provisionally and in need of substantiation, as primarily as due to widespread release from ultrasevere compaction and induction of rocks against the Alpine Fault, suggestive of reduced strike-slip movement along the Alpine Fault itself – with the convergence being taken up further north and east. Essentially the rocks and structures recoiled from deep against the Alpine Fault, by a process here christened retroduction, involving isostatic compensation and substantial eastward movement over the last 1-5 million years, according to rough initial estimates. But alternatively, the thrusting of the Pacific Plate with the Mt Cook sediments could have been somewhat spasmodic, accelerating perhaps in later Pleistocene time.



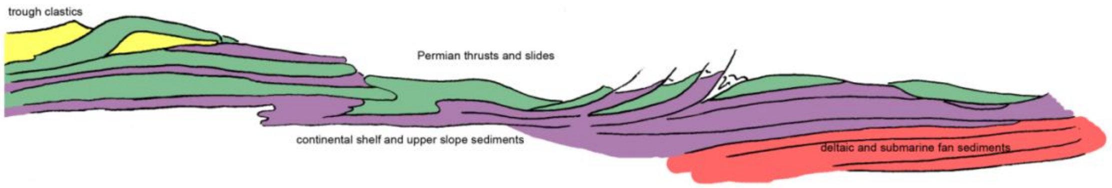
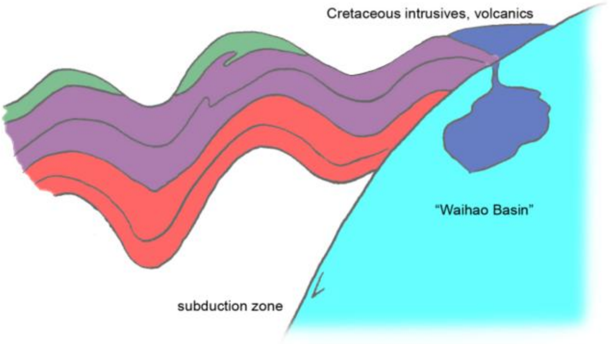


Fig. 8.5. A, B, diagrammatic representations of the development of tracts of sediment (green – Liebig, yellow – Malte Brun, purple Mannering) that moved out over tractator faults from their initial accumulation centres away over the former continental shelf and even over the sedimentary fans (red) at the present east (right). C, the development of volcanics and intrusions (blue) derived from subducted sediments of the “Waihao Basin”. Volcanics are shown as spilling over Rakaia sediments, but in fact no such examples are known.



A number of predominantly strike slip sinistral faults began to actively translate strata away southeast from the Alpine Fault, further deforming the early thrusts and folds, and increasing the angle of plunge along older folds, and reinforcing the number of southward plunging folds. Faults and folds were not fixed, permanent and steady state. Rather the system was extremely dynamic, with growth of new faults, closure and in some cases rotation or reversal of old faults, and in pockets, severe crumpling of sediment caught up in complex fault-folding. Deformation was probably aided by the likelihood that the rocks had already been decoupled from basement during earlier phases of the Kaikoura Orogeny, at least in some areas. Low grade schist foliation crosses comparatively young folds and faults as at Mt Darwin. Recent deformation has involved both recently active strike–slip faulting and local very rapid and also generalized regional uplift. Some of the peaks (Aoraki Mt Cook massif, Minarets, Elie de Beaumont, Mt Hutton) have been uplifted above their neighbours, judged from geomorphic features. It is unlikely that erosion in the Southern Alps is now at steady state and unlikely that peaks are not changing appreciably in height, with slopes having been reduced to concave catenary curves, or "knife-edges". The distribution of glacial erosion benches and cirques strongly shows differential uplift, some areas (Tamaki, southern Liebig Range, Wakefield ridge) show virtually still-stand conditions, or very slow upward tilt and arching, other areas show very rapid uplift. In the nevé regions of the Tasman and Murchison Glaciers, structure and Chlorite 111A, B schist strongly suggest that in pre-Holocene times, a very substantial mountain existed at the culmination of a great bulge east of the Alpine Fault, forming a peak that may have the first massif to attract glaciation because of its height, between 3500m to 5000m. The mountain wasted over millennia under severe erosion, though the area, which may be called "Old Hochstetter" or "Mt Phantomia" (see p. 120), is still the head of two of New Zealand's longest glaciers, and two other substantial glaciers. The Southern Alps are not in steady state, but are a dynamic changing system, in tectonically one of the most active parts of New Zealand. The uplift of some of the peaks is clearly due in part to faulting, with major peaks including Aoraki Mt Cook surrounded and crossed by active faults, helping to induce spectacular rocks falls even in present times. In addition, some of the curvature in fold axes and faults point to substantial warping, whereas other folds have reached stasis. Overall the pattern is very complex and varied, and no more than summarized herein.

Chapter 9

ACKNOWLEDGEMENTS AND BACKGROUND

A number of people have assisted considerably with this project. There were two phases to my understanding something of the geology of the Aoraki Mt Cook National Park. The first involved climbs in the area, in the 1950's, and later initial attempts to unravel aspects of the structure (1960-1970's). I was fortunate to be a member of a party that climbed the last of the so-called Grey virgins, as recounted by J. Wilson in *Joy of the Mountains*[1], with John Harrison, Brian (Snow) Williams and Laurie Osborne, and after climbs with Pat Barcham and Roger Coventry, the great fold of Haeckel Peak was written up[2]. I joined Pat Barcham, John Carruthers, Phil Gardiner, Dave Herron and Graham McCallum for climbs one season[3], and some of the photographs by Pat have proved very useful geologically. But it is one thing to find spectacular structures in the rock, and more intriguing to see how they interrelate. When I started trying to interpret the structure of the Southern Alps, as a project initiated by the New Zealand Geological Survey, along the lines pioneered by Professor Lillie from Auckland, David Smythe helped climb the ridge between Annan and Darwin[4], with approval from the Head Ranger Mervyn Burke, and Faye Kerr accompanied me on a number of trips, with Bruce Jenkinson, Roy Arbon, Lindsay Main[5], Arnold Heine, David Rigby and others assisting from time to time. Later I did some climbing with Greg Retallack, an Australian geologist now working in Oregon, and. Greg took some excellent photographs used in this study. Most valuable help was provided by New Zealand Geological Survey photographer Lloyd Homer, who later produced a splendid series of aerial panoramas of the Park. Before that another fine photographer from the same institution, Nat Beatus accompanied me, and we also overflew the Park in a DC3 plane, taking fascinating aerial photographs – in those days, not in colour, but black and white. Both photographers produced a number of the black and white illustrations used in this study. The geological survey work was undertaken with the encouragement of Dick Willett, followed by David Kear, as Head of the New Zealand Geological Survey[6].

Fig. 9.1. The joy of the summit. A modest peak in the western Malte Brun Range, up high where some of us like to be, fine peaks all around, and the delectable challenge of having to get down safely.

Fig. 9.2. Me, the author, photographed by daughter Catherine Waterhouse.

Fig. 9.3. Was I ever so young? (and by the look of me, hungry?). Roger Coventry in the middle, and well-known mountaineer Pat Barcham in the foreground, with the Hochstetter ice-fall to the right, and lower Anzacs to left. The year was February, 1954, when the Haeckel Syncline was discovered.

Then I went to work in the northern extension of the Rocky Mountains in Yukon Territory of Arctic Canada, and especially in the Himalaya, mostly Nepal. The Himalayas are much longer, wider, and higher than the Southern Alps, over 2000km long, at least 200km across, with peaks over 8000m high, compared with many peaks up to 3000m high in New Zealand, and none more than 4000m. There are staunchly patriotic mountaineers and authors of New Zealand who will tell you that New Zealand climbs are almost as high from top to bottom, and almost difficult as Himalayan peaks, and certainly it is true that New Zealand peaks provide routes which challenge climbers severely. But there are considerable differences. To climb a high peak in New Zealand may require as little as a day, extending to several days for the more severe climbs, in some cases. And being flown to the Grand Plateau knocks off more than 1000m, something rarely feasible in the Himalayas, leaving 1700m at best to be climbed for Aoraki Mt Cook. At one of the more accessible 8000m giants, Annapurna 1, the mountain looms 4000m above the Marsyangdi River, higher than Aoraki Mt Cook measured from sea-level. To climb a Himalayan giant, even by the easiest of routes, takes several weeks. On top of which the affect of altitude is negligible in New Zealand, and kicks in at roughly 3500m, slightly more, slightly less depending on the person's physiology. Yet for all these physical difficulties, the geology of the Himalayas is better known than the geology of the Southern Alps. In New Zealand, it is not always simple to determine whether the folds were plunging north, or in the opposite direction, and in the absence of stratigraphic control, it is difficult to determine which side of a fault had moved up, and which side had moved down, let alone detect bedding-plane faults. In the Himalayas, large scale and often small scale structures had been carefully worked out, and the rocks have been closely divided by age, and extensively mapped whether metamorphosed or not, – stratigraphically, rather than using form-line simplicities – and at a reasonable scale. Why the difference? Just that many more geologists had been able to spend much longer times in the Himalayas – generally at least a full month, but often three months and even longer. I once spent six months in Dolpo of west Nepal, with an Austrian geologist Gerhard Fuchs, and the Austrian assistant, Herwig Lechner.

This ignorance about the geology of the Southern Alps seemed to me a matter that should severely embarrass us New Zealand geologists, because not even a basic stratigraphy had been established. Everything had been lumped as "'homogeneous," a way of avoiding detailed mapping, and excuse the resort to form-line maps.

To me it seemed outrageous that we knew so little of our Southern Alps, and I decided to try mapping some part of the Southern Alps, at least to something approaching the standard of the Himalayas and the remote northern Rocky Mountains of the Yukon Territory, by devoting three or more months a year for several years. I knew the Aoraki Mt Cook region well, and realised that for geological mapping, there was no need to go up the highest peaks, because median level peaks give the best views. Moreover, there was no need for a companion: the work would be much more quickly done if on my own, and distances were not so huge that ferrying two or three loads was unthinkable. Of course the scattering of mountain huts throughout the National Park provided an extra dimension of safety, and again, eased the work-load compared with Himalayan work.

So in 1985, I rebooted the study, focusing on stratigraphy[7], starting with help from Sandy and David Webber, who helped with ferrying loads, and son David, who accompanied me in a trip up the Murchison Glacier. Later I returned briefly with Warwick Sivell, a colleague in geology, and daughter Merrin Waterhouse also took some fine photographs. Chris Adams, GNS, and Dave Craw, Department of Geology, University of Otago, have provided copies of their helpful scientific studies, and Brad Field, GNS, kindly provided a copy of his thesis on the Liebig Range. Staff at the Aorangi Mt Cook National Park provided considerable support, when headed by Ray Slater, and Ray Bellringer has been particularly helpful. I am grateful to Peter Orme for considerable assistance in producing this book. A few ferrying trips were made by the Helicopter Line, saving much time. This phase lasted to 1992. I even managed to present an overview of the mountain huts in the National Park[8], and predicted that the Beetham hut ran the risk of snow avalanche. In due time it was demolished by a snow avalanche. In many ways the late 1980's when I was mapping were the best of times, because radio connections had advanced, and the severe melting of the lower glaciers[9] had only just commenced (Fig. 9.4). Moraines left high and steep by glacial melting in the 1950's and 1960's had started to collapse, especially along gulches worn by rain, offering better access, before even more drastic collapse of the moraines tore away roads and tracks, and made hut access ever more difficult. A couple of later visits to collect photographs were made with Peter Williams of Air Safaris and Malcolm Prouting of Mesopotamia Station, and two trips in 2014 were assisted by photographs taken on my camera by Ray Bellinger and his son Kerry.

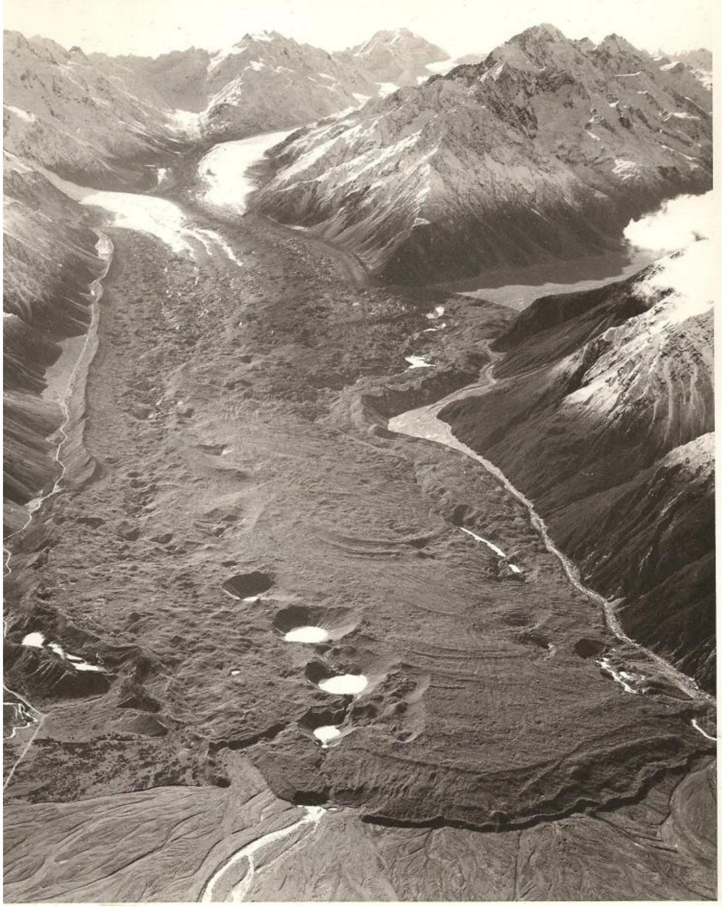


Fig. 9.4. Before the coming of the Tasman glacial lake. Even as recently as 1980, there was no lake, just a few water-filled holes above a glacial river, and few were aware of a warming climate. The ice extended just as far as the lake does now, with a wall of ice at its terminus. From under the face flowed a river of melt-water, that burst up through the outwash gravel in front of the ice, in a frothing fury of water. Here and there, in the plain of outwash gravel, deep hollows testified that the river kept moving from time to time, and scoured out the gravel. Now the lake has grown and grown. Change is what happens constantly in the Park. But the hills and the rocks are also changing – more slowly, and indeed, over time more dramatically, and it is those changes that geologists try to unravel. Photo S. N. Beatus.

Fig. 9.5. My picture of distinguished photographer Nat Beatus, ca 1960, and companion Chan from Malaysia. Taken in the upper Tasman Glacier, and we stayed in the newly built Tasman Saddle Hut, located and planned by another New Zealand Geological Survey geologist, Ian McKellar.

Chapter 10

ILLUSTRATED GLOSSARY

These definitions pertain to words as used as in this text, and are centred on geological usage, without being exhaustive.

abyssal plain a flat sediment-covered part of the sea-floor, with low relief of only 100-200m, found in deep oceans.

accretion in geology, a process by which sea-floor moves with its sediments towards a subduction zone, so that sediments gather in the subduction zone, as if scraped off by the overplate. Such sediment may eventually be built up into mountains. There are implications in the concept which are not always clearly spelled out. The continued infeeding of sediment should mean that deformation was a long-continued process concomitant with accretion. There is no evidence for such ongoing accretionary deformation in the Aoraki Mount Cook National Park, nor any sign that the sediments of the Park had been once spread thinly over ocean floor and then accreted in a trough.

aggregation in geology, a process of side-by side accumulation of basins and geologic entities through strike-slip movement. Aggregated basins will differ sharply from each other, and be separated by geosutures with signs of increased schistocity, and possibly igneous activity, and the basins will retain to varying degree deeper water deposits grading into shallow water and near-shore deposits.

alluvial fan cone-shaped deposits of mud, sand and conglomerate formed by stream or river (on land) or ocean current (in sea) where it runs out on to a flatter plain or sea-floor.

Alpine Fault a major strike-slip fault in the South Island. See Fig. 10.1.

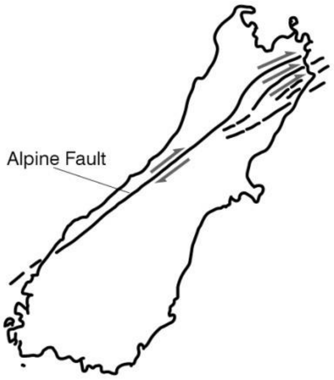


Fig. 10.1. The Alpine Fault, with subsidiary faults in the South Island, New Zealand.

anticline fold in which beds young outwards each side of the fold axis, starting as an uparch or upfold as a rule. But see **introcline**, an exceptional fold formed by drag-faulting.

antiform an uparching fold that looks like an anticline, but requires further analysis to discover its true geometry.

arenite medium-grained clastic sediment, grains of sand-size.

argillite deposit of fine hardened (that is, lithified) muds and clays.

arkose feldspathic sandstone, formed (ultimately) from granitic or gneissose source area, more than 25% feldspar.

asthenosphere relatively weak layer of rock above the earth’s mantle and below the lithosphere.

Atomodesma a distinctive bivalve of Permian age, with prismatic shell.

axial plane in folds, the plane that most nearly separates two symmetrical limbs. In a simple anticline, it is vertical. In complex folding, it tends to be perpendicular to the direction of compression, but it may be distorted by later deformation.

axis in fold within each stratum involved in a fold, there is an axis connecting all points in the centre of the fold, from which both limbs bend.

basalt a fine-grained, dark, mafic igneous rock composed substantially of plagioclase feldspar and pyroxene.

basic rock any igneous or sedimentary rock containing mafic minerals rich in iron and magnesium, and containing little or no quartz and sodium-rich plagioclase feldspar.

basin in geological sense, a broad or elongate depression in the earth's crust on land or sea that receives sediment, also known as depocentre. May be 10 to 100km and often more than 1000km long. Marine basins have deep-water sediment, and shallow-water sediment around the margins, which should be traceable into estuarine and terrestrial deposits formed on dry land.

bedding, beds distinctive feature which distinguishes many sedimentary rocks from igneous rocks. The beds or layers may be thin or thick, flat or wavy, continuous or lensoidal.

bedding planes successive beds or layers are separated from each other by planar or nearly planar bedding planes. They indicate changes in the character of the sediments, or pauses in sedimentation.

bivalve a major class of shell fish.

boulder large rounded or subrounded clast, bigger than a pebble.

breccia coarse-grained sedimentary rock with angular fragments often more than 1cm across. The matrix surrounding the large fragments may consist of sandstone or mudstone.

burial metamorphism affects sediments and volcanic rocks without influence from orogenesis or magmatic intrusions, by rise in pressure and temperature (200ºC – 450ºC), and influenced by circulating ground-water.

canyon a very large deep valley with steep walls formed by down-cutting, back-wearing and slumping.

carbonate rock made up of calcium carbonate, usually from broken-down shell material, or from chemical sedimentation.

Carboniferous a period of earth's history, poorly represented in New Zealand, that lasted from 359 million years ago to just under 300 million years ago.

cataclasis rock deformation accomplished by fracture and rotation of mineral grains or aggregates under low pressures, without chemical reconstitution.

cataclasite, cataclastic rock a breccia or powdered rock formed by crushing and shearing during tectonic movement.

catenary curve an S-shaped curve with angles becoming low towards extremities.

Cenozoic The era that lasted from just under 2 million years ago to 65 million years ago, and with no known sedimentary record in the Aoraki Mt Cook National Park. Used to be called Tertiary.

chalcopyrite a mineral $CuFeS_2$, copper pyrite.

chaos breccia large inclusions of disaggregated material in a different matrix, usually formed by large-scale submarine slumping, or sudden injection of semi-liquid sediment into semiconsolidated sediment.

chert SiO_2, fine-grained siliceous sediment formed by chemical, biochemical or biological processes.

chipwacke small fragments of argillite or sandstone in a bed, formed by parting of sandstone or argillite, usually by wet sandstone entering into cracks in mudstone, and pushing apart the fragments.

chlorite $(Mg,Fe)_3(SiAl)_4O_{10}(OH)_2(MgFe)_3(OH)_6$, contains some iron compound which colours the rock green or brown.

cirque deep steep-walled bowl-like recess at head of a glacier, or part way along the glacier, produced by mountain glaciers back-wearing through a process of freeze and thaw into the mountain.

clastic detritus sediment eroded by physical or chemical means from older rocks, whether igneous, metamorphic or sedimentary.

cleavage splitting of rock along planes of weakness, as a rule in accord with a regular pattern caused by deformation.

compaction mass of overlying sediment pushes the grains of sediment together, reducing the space between.

competent bed or stratum that is able to withstand the pressures of folding without flowage or much change in original thickness. Generally applies to sandstone or limestone, rather than mudstone.

concretion usually rounded or irregularly shaped very hard body within sediment, cemented by silica or carbonate. May form beds.

conglomerate coarse-grained sedimentary rock in which clasts are rounded to form pebbles and boulders. Matrix surrounding the pebbles much finer.

conodonts intricate teeth of a particular animal, highly useful as fossils for correlation of Paleozoic and early Mesozoic marine sediments.

continental crust forms upper part of lithosphere, of quartz-rich materials as opposed to ocean crust.

continental rise a broad and gently sloping ramp that rises from an abyssal plain to the continental slope at a rate of less than 1:40.

continental shelf gently sloping shallowly submerged marginal zone for continents and islands.

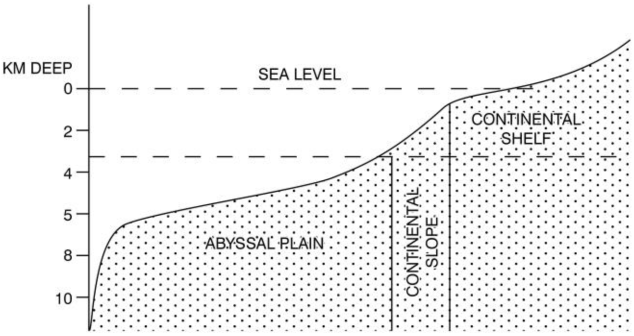


Fig. 10.2. Continental shelf, continental slope, and abyssal plain, on which sediment accumulates under the sea, as shown in cross-section, with vertical scale much exaggerated, so that entities are shown as more steeply inclined than in reality. Abyssal deep lies to the left.

continental shelf deposits sediments deposited on a continental shelf.

continental slope the usually steep slope below the continental shelf and passing into deeper abyssal waters.

convergence zone a band along which moving tectonic plates collide and surface area is lost by crustal shortening and thickening, or subduction. It is or was the site of volcanism, earthquakes, ocean trenches, troughs and mountain building.

convolute bedding layers and beds contorted into an intricate pattern of usually sweeping curves, formed from flat layers when the sand and mud was soft and saturated with water, which then began to slide or move due to an earthquake, or when water was expressed from the sediment.

correlation the matching of rock units which have a similar age, or comparison of rock units through composition, appearance or age.

Cretaceous a period of earth's history, lasting from 149 to 65 million years ago.

cross-bedding laminae inclined more or less regularly in straight, concave or sinuous lines at angle to original deposition surface.

cross-section a drawing showing the geological features that would be exposed by a vertical cut through a structure or structures. Or an exposure carved by machinery or river or ice which reveals a cross-section through rock.

crust the outermost layer of the lithosphere, consisting of relatively light materials. The continental crust consists largely of granite and granodiorite, with allied lavas and derived sediments; the ocean crust is mostly basalt with gabbro and varying amounts of derived sediment.

deformation general term for the process of folding, faulting, shearing compression or extension of rocks as a result of Earth forces.

delta an alluvial deposit assuming a triangular shape in plan, although more intricate shapes are also common, usually formed at the mouth of a river in the ocean or lake. See Fig. 10.3.

deposition a general term for the accumulation of sediments by physical or chemical processes, forming deposits.

detritus material which has not been easily dissolved, surviving from the original rock source.

dextral fault a right lateral fault (qv).

diapir anticline, squeezed into tight fold.

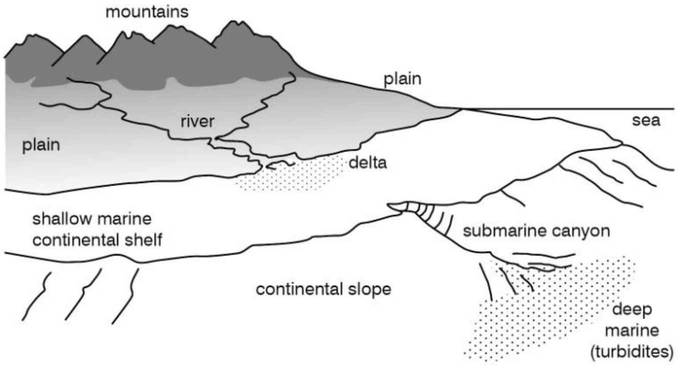


Fig. 10.3. A figure depicting the now lost continent that once lay between the Rakaia and Pahau Basins of the South Island, with mountains that provided the source for a delta at the river mouth and the Mannering Group over the continental shelf. Submarine slumping from these in turn supplied the Malte Brun Group in the deep waters of the Malte Brun Sub-basin with turbidites.

epidote a group of minerals, usually yellowish green with formula $(OH)Ca_2Fe_3Si_3O_{12}$ or variation.

feldspar the most common framework silicate, predominant in most igneous rocks and many metamorphic rocks, hardness of 6.

flysch well graded units of sandstone grading into mudstone, much the same as turbidite, and applied (by Europeans especially) to a sequence of deep-water turbidites.

footwall lower side of fault.

Foraminifera multicelled marine creatures of tiny size, and of great value for determining the age of sediments.

fore-arc basin region between an ocean trench (or trough) and an island arc, often 100-200km wide, and hundreds of kilometres long.

formation in geological terminology, an association of rock type, usually sediment, linked by common source and of similar appearance, composition and age.

fossil part or all of any animal, or impression or track or other sign of a once living form.

fusuline fossils fusulines are comparatively large (but still only mm long) Foraminifera from paleotropical to warm temperate ocean waters, of Carboniferous and Permian age.

gabbro dark coarse-grained intrusive igneous rock composed of calcic feldspars and pyroxene. Intrusive equivalent of basalt.

geomorphology the make-up of the landscape, involving formal study of land and sea forms and processes.

graded bedding bedding in which each layer displays a more or less gradual change in particle size, from coarse at the base (as a rule) to fine at the top. This shows the direction of younging: the bed is said to young in the direction of increasing fineness of grain. Reverse grading is also found, where the sediment gradually became coarser with the passage of time.

granite a coarse-grained intrusive igneous rock composed of quartz, orthoclase feldspar, sodic plagioclase feldspar and micas. May form through metamorphism of rocks of similar composition.

greenschist basic igneous rock which has been metamorphosed, containing chlorite and epidote, which are coloured green, formed by low temperature and low pressure metamorphism. Some geologists also include metamorphosed sediments that have been derived from the igneous rock.

greywacke type of sandstone, in varying shades of grey as a rule, tough, well indurated, poorly sorted, often with clay matrix. Originally used to describe rocks with fragments of volcanic rock, it is now applied loosely to sandstones often with a jumbled mix of clay, sand and rock chips from sedimentary or igneous source, accumulated as thick formations formed often rapidly in deep water, and as rule sparse in fossils. May be extended to cover better-sorted sediment such as flysch and turbidite.

grit, gritstone particles coarser than sand, finer than conglomerate.

groove cast long narrow grooves on the bottom of a bed, mm wide and 10-30cm long, formed by a pebble or small object dragged by a current over the sea-floor.

group two or more formations make up a Group in stratigraphic nomenclature.

hanging wall upper side of fault.

Holocene the international interval of time at the top of the Quaternary “Era”, which started about 8,000 years ago. Many authorities now wish to introduce an Anthropocene Stage, to signal the introduction of substantial change wrought by mankind in very recent times. Perhaps at the start of the glacial lakes at the terminus of glaciers in the National Park?

hyaloclasite rock rich in silica, associated with sea-floor basalts, from hot springs.

igneous rock rock formed by crystallization from molten magma or lava.

induction process by which rock is pulled downwards against a major fault through strike-slip movement, probably where the fault ruptures what was the axis of a major syncline, and where orthogonal or oblique compression is also involved. The pushing of a plate along, over or under another plate may buckle the plate so that it bends downwards.

induration rock hardened by action of pressure, cementation, or heat.

introcline, introclinal fold a fault-drag fold with strata younging backwards, opposite to the direction of the fault movement, so that antiforms, bulging forward in the direction of movement, young inwards, and synforms, arching backwards, young outwards. See Fig. 3.9, p. 31.

intrusion an igneous body of rock that has forced its way in molten state into surrounding rock.

island arc volcanoes [alt. volcanos] and calderas found on the continental side of deep ocean trenches, marking zones of subduction, usually aligned in curve over earth's surface. The volcanoes have arisen from melting of the subducted crust, which may be oceanic or continental.

jigsaw breccia angular fragments of breccia 1-50cm across resulting from disaggregation of a mudstone bed, having moved only a little so that the breccia blocks may be fitted back through imagination into the beds from which they came.

joint planar surface (usually seen in section) left when rock breaks.

Jurassic a period of earth's history that lasted from 199 to 149 million years ago.

lateral fault steep fault with near horizontal (lateral) movement.

lateral slip refers to lateral movement of rock along a fault.

lava molten magma reaching the earth's surface (on land or sea).

left lateral fault a strike-slip fault in which the displacement of the far block is to the left when viewed from either side. Also termed sinistral fault. See Fig. 10.6, p. 143.

limb the relatively planar part of the fold.

limestone general term for carbonates, composed mostly of calcium carbonate (in a New Zealand setting. Dolomite with magnesium component is common in more tropical climes, and is rarely found in New Zealand).

limonite hydrous iron oxide, coloured brown or yellow as a rule.

lineation parallelism of minerals, caused by pressure in metamorphic rocks.

lithification the processes that convert soft sediment into hard rock, which is then said to be lithified.

lithology the systematic description of rocks in terms of mineral composition and texture.

lithosphere layer of cool and moderately rigid rock separated from deeper zones in the Earth by a weak zone called the asthenosphere.

mafic dark-coloured usually heavy mineral, or an igneous rock, rich in iron, manganese or other heavy minerals.

magma molten material and dissolved gases.

main divide the highest part of the ridge system dividing two watersheds for waterways that flow in opposite directions. Refers to a recognisable series of high points along the Southern Alps, and not necessarily including the major peaks. For instance Aoraki Mt Cook and Mt D'Archiac lie east of the Main Divide.

mantle the bulk of planet Earth, between the crust and the core, up to 2900km in thickness, which makes up the mantle. It is composed of dense mafic silicates and is divided into concentric layers by phase changes caused by increase in pressure with depth.

mantle plume conceived as a vertical leak of mantle material on to the earth's crust. Mantle plumes located at triple junctions of major earth sutures cause rifts and spreading.

marker band a distinctive rock type that may be traced widely.

matrix relatively fine-grained material in which coarser fragments such as conglomerate or breccias, or crystals are embedded.

member in stratigraphy, a unit within a formation, smaller (and/or thinner) and with exceptional characteristics, but in many respects like the formation to which it belongs as a rule, or may be highly exceptional but thin, and incorporated within the formation, especially if beds above the member are like those below the member.

Mesozoic a major interval of earth's history, called an era, divided into the Triassic, Jurassic and Cretaceous Periods.

metagreywacke surely a redundant term, because all greywackes are metamorphosed to varying degree. But it looks scientific.

metamorphic grade the relative intensity of metamorphism. Low grade metamorphism implies low pressures and low temperatures. High grade metamorphism implies higher temperatures and pressures.

metamorphic rock a rock in which original mineralogy, texture and/or composition have been changed by pressure or temperature, and may involve gain or loss of chemical components.

metamorphism the mineralogical and structural adjustment of solid rocks to physical and chemical conditions imposed below the surface zones of weathering and cementation, and which differ from the conditions under which the rocks in question were formed. The change in conditions may be the result of burial by sediment, tectonic activity, mountain building, or intrusion of magma.

metasediments sediments altered by metamorphism. All of the hard rock in the Aoraki Mt Cook National Park has been altered to varying degree, so there is a certain element of redundancy about the term. Rock itself has been altered through induration from the original sediment, further emphasizing redundancy.

metavolcanics volcanic rock altered by metamorphism.

mica sheet silicate mineral easily split by parting the sheets.

mid-ocean ridge site of volcanism and intrusion of magmas and shallow earthquake activity usually along an elongate zone within the ocean crust, as a rule far from continental margins. Implies the parting of two tectonic plates, with the gap between filled by igneous rock from below, to form the ridge.

mineral a naturally occurring solid inorganic or organic element or compound with definite composition or range of compositions, and regular internal crystalline structure.

moraine accumulation of angular or rounded boulders deposited by ice. May or may not include finely ground "rock-flour" matrix.

mudstone deposit of fine hardened (lithified) muds and clays.

mylonite fine-grained rock formed by crushing along fault zones.

neve (nevé) snowfield at the upper end of a glacier, which produces the ice that moves in a tongue downvalley.

normal fault steeply inclined fault in which the hanging wall appears to have moved downwards relative to the footwall. The block above the fault has moved downward, the block below has moved upwards.

nose of fold the crest of a fold, including its axis, forming a rounded outline, particularly where the fold is steeply plunging.

obduction a process occurring during convergence of plates or plate segments, when part of the plate is pushed into or over the adjoining plate or segment. Commonly involves ophiolite and serpentinite.

oblique-slip fault a fault that combines some strike-slip movement with some dip-slip movement.

ocean basin area of Earth’s crust deeper than 4000m below sea level.

ophiolite an assemblage of mafic and ultramafic igneous rocks with sediments, often deep-sea, that points to zones of plate divergence.

orogeny process which leads to the deformation of sediments and lavas to form mountains, as a rule understood to terminate the cycles of marine sedimentation that have infilled a trough or basin. Orogeny may be accompanied by fresh or renewed sedimentation, marine or non-marine, beyond the confines of the original trough, because the uplift of mountains supplies abundant material, and in some instances the orogen itself is buried by non-marine sediment.

Ostracoda small marine and estuarine Crustacea, well preserved and widespread as fossils.

outcrop visible exposure of rock.

overburden material that overlies earlier formed sediment, and may help in hardening and even altering the sediment through metamorphism due to increased pressure and raised temperature.

Paleozoic a major interval of earth time, called an era, divided into six periods, Cambrian to Permian.

palynomorph small part of a plant involved in reproduction, resistant to change and so well preserved except under moderately high pressure or temperature. Highly useful as fossils for dating and correlating sediment.

parasitic fold small fold formed on the limb of a larger one.

passive margin boundary between continental crust and oceanic crust which displays little tectonic activity.

penecontemporaneous slumping deformation of sediments soon after accumulation and before lithification is complete.

peridotite plutonic rock consisting of olivine, with or without other mafic minerals. Comes from deep in the earth, and is often found in mid-ocean ridges.

period a major unit of earth-time, lasting usually tens of millions of years. Divided into series and stages.

Permian the last period of the Paleozoic Era, lasting from just over 299 million years ago to 250 million years ago.

petalloid folding fold becomes more and more intricate outwards in the case of an anticline.

pillow lava a type of lava formed underwater in which pillow-shaped tongues exude through the chilled surface and quickly solidify, to look like a pile of sandbags. Though commonly assumed to typify ocean crust, pillows may also occur in volcanic arcs under marine conditions.

plate (=tectonic plate) one of a dozen or more segments of the lithosphere that move independently, meeting in convergence zones and separating at divergence zones.

plate tectonics the movement and interactions and destruction of earth plates, interpreted as explaining seismicity, volcanism, and mountain building.

Pleistocene the formally designated interval of time commencing about 1.8 million years ago, as the main and older constituent of the Quaternary Era. The interval was characterised by episodes of glaciation, but glaciation commenced earlier, and of course glaciation persists in Antarctica, and in the Aoraki Mt Cook National Park.

plunging fold a fold with axis that is not horizontal, but dips steeply.

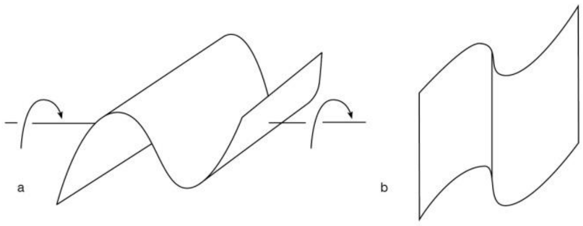


Fig. 10.4. a, ordinary folds, with horizontal axes. b, steeply plunging folds. Folds may originate with horizontal axis and then rotate, but in the Southern Alps, many steeply plunging folds arose from steeply dipping beds, and so plunged steeply from inception.

pluton a large igneous intrusion formed at depth in the earth's crust.

principle of original horizontality states that for any layered sequence, it may be inferred that the bedding surfaces were originally horizontal, or nearly so.

principle of superposition states that in an undisturbed sedimentary sequence, the uppermost strata are younger than those strata or beds on which they rest.

pyroxene single chain silicate mineral group having general formula $ABSi_2O_6$. Good cleavage in two directions at 87^o and 93^o.

quartz SiO_2, silica, a framework silicate mineral, hardness of 7.

quartzite a hard clean white rock, made up largely or entirely of quartz grains.

quartz arenite sandstone composed primarily of quartz.

Quaternary the last major "era" of earth history, with Holocene and Pleistocene Stages. The time involved was very short, but on the other hand, a great deal is known about the two intervals.

Radiolaria a class of one-celled marine animals with skeletons of silica.

recumbent fold an overturned fold with both limbs nearly parallel and at a low angle from horizontal.

regional metamorphism metamorphism occurring over a wide area, caused by deep burial or strong and pervasive tectonic forces.

retroduction process by which sediments pulled below the surface of the earth, often by subduction, or jamming against plate boundary, are released and rise, often with the development of folds and faults.

retrograde metamorphism rock metamorphosed to a high grade of alteration may be remetamorphosed by adapting to different conditions, such as lower temperatures or lower pressures.

reverse fault a fault in which the hanging wall of a steeply inclined fault has moved upward relative to the footwall.

ribbonite thin-bedded turbidite with argillite and sandstone beds no more that 1-5cm thick.

right lateral fault a strike-slip fault for which the displacement of the far block (looking across the fault) is towards the right, as viewed from either side. Same as dextral fault. See Fig. 10.6, p. 143.

rock a solid cohesive aggregate of grains of one or more types of minerals and fragments of sedimentary and igneous origin.

sandstone medium-grained sedimentary rock. Sand-sized particles can be composed of almost any material in nature, but quartz is the most common.

schist a metamorphic rock characterised by strong foliation.

schistosity foliation in schist or other coarse-grained crystalline rock due to the parallel and planar arrangement of platy mineral grains, such as mica.

schuppen small thrust sheets, such as depicted in Fig. 8.5B, p. 128.

scour-cast isolated finger-like projection, also called flow cast, formed by obstruction to a bottom current on the sea-floor, which therefore began to eddy and scour out a small hollow. This was later filled by overlying sediment to form a cast.

scree recently formed deposit of coarse material eroded from mountain flanks, and accumulating by gravity as sheets over the mountain side.

sea-floor spreading formation of new sea-floor material at mid-ocean ridge and its subsequent movement, usually on each side, away from the ridge.

sedimentary rock a rock formed by the accumulation and cementation of mineral grains transported by water, ice or wind. Also loosely includes rocks derived from organic sources, such as coral reefs or plant material that forms coal, or material ejected as tuff by volcanic explosion, but excluding other forms of igneous rock.

sedimentary structure any structure in sediment, including weakly metamorphosed sediment, that was formed at the time of deposition, including bedding, cross-bedding, graded bedding, ripples, scour marks and mudcracks.

series a collection of two or more stages in succession, as part of a world-wide time-scale.

serpentine $MgSi_2O_3(OH)_4$; includes two distinct minerals, antigorite and chrysotile. Formed by hydrogenation of peridotite.

serpentinite rock formed of serpentine.

shale sedimentary rock formed from fine lithified detrital muds and clays, usually soft and weathers rapidly, except in cold climates, when it may split readily. Under pressure, shale converts to slate, which breaks along regular fracture planes.

shingle coarse detritus eroded and deposited by gravity on side of hills and mountains.

shingle fans fan-shaped deposits of shingle, common in high mountains, formed especially after deglaciation.

silicate mineral compound for which crystal lattice contains $Si0_4$ tetrahedra, either isolated or joined through one or more of the oxygen atoms to form groups. Much of the earth’s crust is made up of silicate minerals.

siltstone: lithified detrital sediment with granules of intermediate size range between those of mudstone and sandstone.

sinistral fault see left lateral fault.

slate the metamorphic equivalent of shale or mudstone, fine-grained, and with slaty cleavage.

slaty cleavage fine-grained rock readily parted into thin sheets because of parallel arrangement of sheety metamorphic minerals, may be at angle to bedding plane and reflecting direction of principal stress. Caused by deformation.

slickensides shiny surface which has fine grooves or scratches due to fault movement that has polished or scored the rock. Similar polishing is caused by rock fragments held in ice which is moving over solid rock.

slide fault a fault with fault plane horizontal or parallel to bedding, having arisen usually by sliding of the sediment at a low angle along a bedding plane above more or less stationary sediment (which can itself be independently moving in a slide).

slurching lurching and sliding of wet sediment downslope under the sea, without breaking into an incoherent slurry.

soft sediment deformation deformation of sediments before lithification is complete.

sorting a measure of the homogeneity of the sizes of particles in a sediment or sedimentary rock. Rock grains may be well sorted or poorly sorted.

spreading ridge a mid-ocean ridge formed by igneous material welling up from the mantle, with the ocean floor either side of the ridge spreading and expanding laterally away from the ridge.

stage a formally named interval of time in a world-wide chronology.

stratigraphy the science of the description, correlation and classification of strata in sedimentary rocks, including the depositional environment.

stratum (plural – **strata**) tabular or sheet-like mass or layer of sedimentary material, a sedimentary bed.

striations long, straight lines scratched on a bedrock surface by rock fragments embedded at the base of a moving glacier, or over rock polished by fault movement.

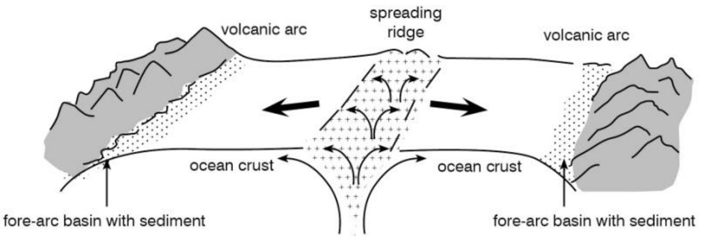


Fig. 10.5. The classic arrangement of a volcanic arc each side of a spreading ridge. In New Zealand, for example east Nelson, the Dun Mountain spreading ridge and Brook Street volcanic arc are developed, but there is no established volcanic arc equivalent to the arc on the right side of the figure. Was there none? Or was one placed beyond the (now western) confines of the National Park, as an edge to the plate that included both the Rakaia Basin, and the southerly Pahau basin? There still seems much to learn about New Zealand geology.

strike direction that a surface takes as it intersects the horizontal. Also involves the angle between true north (ie. North Pole) and that horizontal line, with allowance for the difference in position between the North Pole and the North Magnetic Pole.

strike-slip fault a fault with displacement that is purely horizontal or has a substantial horizontal component.

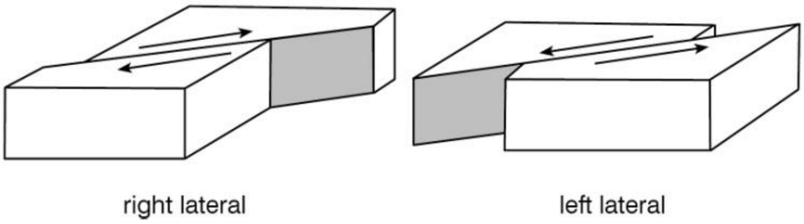


Fig. 10.6. Strike-slip faults, shown as displacing two blocks of earth crust.

subduction zone converging plate boundary where lithosphere is consumed, or at least disappears from the surface, as involving an island arc, trench or fold belt.

submarine canyon underwater gorge cutting the outer edge of the continental shelf.

superposition a law stating that except in deformed strata, a bed that overlies another bed is always the younger.

syncline fold of strata, which young inwards, normally downfolded. The morphology of fault-drag folds may differ, as in extrocline and introcline qv. See Fig. 3.9, p. 31.

synform a fold shaped like a syncline, but requiring closer inspection to determine its true geometry.

synorogenic sedimentation or igneous activity occurring concurrently with orogeny.

tectonics the study of movements and deformation of the earth's crust, including metamorphism, folding, faulting and plate tectonics.

Tertiary a subdivision of earth time, commonly ranked as an era, that started 65 million years ago, and closed at the start of the Pleistocene in the Quaternary Era. Now replaced by the term Cenozoic.

texture characteristics in rock of grain or crystal size, size variability, rounding or angularity and preferred (if any) orientation.

thrust fault fault of very low dip and large displacement resulting from intense external compression. Differing from slide-faults or tractator faults, in which overlying mass has slid under gravity, with compression caused by its own mass, aided by presence of much water acting as a lubricant. A high angle thrust fault is close to a steep subvertical reverse fault.

time scale divisions of geologic history of the earth into eras, periods, and epochs accomplished by stratigraphy, paleontology, and radiometry, reinforced by record of mountain building, volcanicity, climatic change, solar chronology and other world-wide or major events.

trace fossil disturbance of sediment by animal tracks or burrows.

transcurrent fault see lateral fault. Defined by some as shallow faults not connected with the mantle and restricted to decoupled rock above a weak layer.

transform fault a strike-slip fault connecting one end (at the start or growing end) of an offset in a mid-ocean ridge, formed by unequal generation each side of the fault of new ocean crust from the mid-ocean ridge.

transposition in higher grades of schist (above Chlorite 3), bedding becomes replaced by layers that look like beds, but owe their appearance to rearrangement of newly formed minerals formed by metamorphism.

trench a long and narrow deep trough in the sea-floor, as a rule considered to mark where a plate bends down into a subduction zone.

Triassic a period of earth's history that lasted from 250 million years ago to approximately 199 million years ago. It is divided into three series with component stages – Scythian (Lower Triassic), Anisian and Ladinian (Middle Triassic) and Carnian, Norian and Rhaetian (Upper Triassic).

tsunami large waves and often short-term shifts in sea-level caused by submarine earthquake or volcanic eruption, or collapse of sediment, usually on the continental slope.

tuff formed from volcanic explosion as a subaerial or marine ash shower.

turbidite sediment deposited from a turbidity current, typically showing graded bedding, and flow structures on the underside of the bed.

turbidity current distinctive flow of sediment mixed with bottom water, commonly having moved down the continental slope on to the abyssal plain, often through a submarine canyon. But shallow-water sediments such as varves may also form turbidites in glacial lakes.

type section prime exposures of a formation or member, nominated as the basis and exemplar for defining the name and nature of the rock unit.

ultramafic rock an igneous rock composed predominantly of mafic minerals with less than 10% feldspar, including dunite, peridotite, amphibolite and serpentinite.

unconformity erosional surface which defines the base of a younger sequence, and cuts across structures in the older (ie. underlying) sequence of rocks.

varve a well graded turbidite unit seasonally formed in glacial lakes.

verging folds asymmetrical folds, the longer limb signifying the direction of the synclinal axis and the shorter limb signifying the direction of the anticlinal axis of the major fold.

volcanic ash a volcanic sediment of rock fragments, often glass, formed when escaping gases force out a fine spray of magma into the air. Also called tuff.

volcaniclastic sediment that has been derived by erosion of volcanic material.

volcanigenic sediment derived from erosion of volcanic material.

volcano an opening through the earth’s crust that has allowed magma to reach the surface, and build deposits around the vent.

weathering the processes that decay and break up bedrock, through physical and chemical means.

weetbix a term applied by mountaineers to unstable rock, loose because of close-set fracturing or cleavage or schistocity due to faulting or metamorphism, or the frequent crushing from boots and crampons by mountaineers. Also used by some geologists anxious to show they are on speaking terms with mountaineers. Alas, their prose may be judged to be more flaky than the actual rock, which does not in fact necessarily consist of flaky material, and may not turn mushy or liquid under rain (unlike bentonite, for example). Climbers anxious to avoid unstable or flaky rock should be more careful in choosing their route.

younging the direction from the oldest to the youngest (ie. last formed) part of a sedimentary bed. See graded bed.

zeolite a class of silicates containing H_2O in cavities within the crystal structure. Formed by alteration at low temperature and pressure from other silicates, often involving volcanic glass.

REFERENCES AND NOTES

Chapter 1. Individual Places of Interest.

1. Lillie, A. R. 1961: Folds and faults in the New Zealand Alps and their tectonic significance. Proceedings, Royal Society of New Zealand 89: 57-85.

2. Waterhouse, J. B. 1990: Transpression regime in the Southern Alps and possible extension regime in Canterbury, New Zealand. Proceedings, Pacific Rim Congress 93, vol. 3: 229-234.

3. Lillie, A. R., Gunn, B. M. 1964: Steeply plunging folds in the Sealy Range, Southern Alps. New Zealand Journal of Geology & Geophysics 7: 403-423.

4. Findlay, R. H. 1987: Structure and interpretation of the Alpine schists in Copland and Cook River valleys, South Island, New Zealand. New Zealand Journal of Geology & Geophysics 30: 117-138.

5. Campbell, J. D., Warren, G. 1965: Fossil localities of the Torlesse Group in the South Island. Transactions of the Royal Society of New Zealand Geology 3 (8): 99-137 + map. Dusschoten, A. von 2000: Torlesse stratigraphy and paleontology, Balmacaan Stream, mid Canterbury (abstract). Geological Society of New Zealand Newsletter 122: 21-22.

6. Waterhouse, J. B. 1972: Folds of the Mt Cook National Park, New Zealand, and their origin under a wrench regime acting in a subduction zone. Journal of the Royal Society of New Zealand 2 (3): 413-430.

7. Waterhouse, J. B. 1966: The Häckel Syncline and neighboring folds of the Upper Tasman Glacier. Journal of the Royal Society of New Zealand 2 (3): 413-430.

8. Waterhouse, J. B. 1985: Preliminary account of geology of Malte Brun Range, New Zealand. The Australian Geologist Newsletter 57: 7-13.

9. Waterhouse, J. B. 1955: An isoclinal fold on Häckel Peak, Southern Alps, New Zealand (S79). Transactions of the Royal Society of New Zealand 83: 345-346.

10. Wilson, J. 2012: Joy of the Mountains. A climber’s life. John Harrison (1932-1966). Te Waihora Press, Christchurch. See also Williams, S. 1954: What the Butler saw. The Canterbury Mountaineer 1953-1954, vol. 6 (23): 152-156. (S. must stand for Snow, Brian Williams’ nickname).

Chapter 2. Recent and active Faults

1. Tippett, J. M., Kamp, P. J. J. 1993: The role of faulting in rock uplift in the Southern Alps, New Zealand. New Zealand Journal of Geology & Geophysics 36: 497-504. These authors compared uplift along faults, based on fission track data, with overall uplift. They did not assess any faults within the Park.

2. Lillie, A. R., Gunn, B. M. 1964: Steeply plunging folds in the Sealy Range, Southern Alps. New Zealand Journal of Geology & Geophysics 7: 403-423.

3. Waterhouse, J. B. 1985: Preliminary account of geology of Malte Brun Range, New Zealand. The Australian Geologist Newsletter 57: 7-13.

4. Findlay, R. H., Sporli, K. B. 1984: Structural geology of the Mount Cook Range and Main Divide, Hooker Valley region, New Zealand. New Zealand Journal of Geology & Geophysics 27: 257-276. See Fig. 1.

5. The course of the fault on the western side of Malte Brun Pass coincides with the dashes for the lower part of route 7.79 below the pass, shown in Palman, A. J.: 2005: Aoraki Mount Cook, a guide for mountaineers. A New Zealand Alpine Club Publication: See Fig. 37, photo D. L. Homer.

6. The concept of a Main Divide Fault in the National Park was put forward by Simon Cox in Making Mountains the rocks and formation of the Southern Alps. New Zealand Alpine Journal 1995, vol. 48:

85-87, and Cox, S. C., Findlay, R. H. 1995: The Main Divide Fault Zone and its role in formation of the Southern Alps, New Zealand. New Zealand Journal of Geology & Geophysics 38: 489-499, and vigorously defended in Letters to the Editor: Reply by S. C. Cox and by R. H. Findlay in 1997 New Zealand Journal of Geology & Geophysics 40: 118-120, after I had commented that there seemed to be very limited field evidence in support, and that it was unwise to rely largely on experimental data (which seemingly failed to predict the presence of tight folding, or even accurately locate the fault). See Waterhouse J. B. 1997: The so-called Main Divide Fault Zone from the Tasman and Murchison to Godley Glaciers Comment. New Zealand Journal of Geology & Geophysics 40: 117-119. Two small faults along part of the Hooker Glacier were illustrated by Cox & Findlay (1997, Fig. 2B), and a map provided to claim that the Main Divide was accompanied on the eastern side by a series of very short scallop-like faults, concave to west and towards the divide, perhaps reflecting the interplay between more or less straight faults and topography. The pattern differed to some extent from the faults mapped by Findlay & Sporli (1984, Fig. 1), as in the reference above in item 4. The Main Divide Fault seems to have been visualized as dividing schist to the west from less metamorphosed rocks to the east, but there is little accuracy in the depiction of the extent of the schist north of the Hooker Glacier, and little documentation has been provided. The concept was clearly illustrated by Cox (1995, Fig. 3), in which the Main Divide Fault was shown as a powerful fault branching off the Alpine Fault, inclined steeply to the west and entering the lower slopes of the Tasman valley east of the Main Divide. Cox, S. C. & Barrell, D. J. A. 2007: Geology of the Aoraki area. Scale 1:250 000. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 15. GNS Science, Lower Hutt, showed the fault as having an uplift of thousands of metres (see Fig. 28), equivalent to the full thickness of all the greywackes in the Park. I know of no such powerful fault in either the western Hooker or western Tasman valley: any displacement in the western Tasman wall is no more than a few hundred metres. Cox (1995, Fig. 3) argued that the uplifted side was on the west, and showed the fault as lying well below the Main Divide, as if eroded from the east, yet he claimed in his text that erosion was most rapid from the west, thanks to heavier precipitation. (Apparently the difference in snow-fall as opposed to rain, and the heaver cover of vegetation on the western side made no difference, which seems highly disputable). It was implied in the map that the fault possibly coincided with a semi-schist boundary, but supporting evidence is meagre. The disposition and degree of schistocity in the relevant regions cannot be sustained, and the presence of only slightly metamorphosed Burnett and Rose Formations along the entire western wall of the Tasman Glacier, and lack of any prominent active fault scarp, implies that there was no very significant fault in this area. What seems possible is that a significant fault lies close to the Main Divide for some distance, and is concealed by ice. Another possibility is that rather than a fault, a major long arch developed east of the Alpine Fault, and this is split along its length by a number of faults which cross the Main Divide obliquely. Such an arch is conjectural, whereas a Main Divide Fault in the position as mapped can be discounted.

Chapter 3. Folds

1. Lillie, A. R. 1964: Fold patterns in New Zealand Alps indicative of drag along the axial belt. International Geological Congress Report 22nd session, Part 1V: 171-182. The title of the article conveys exactly what the folds and rocks indicate.

2. Analyses that steep dips preceeded folding have been provided for the folds of the Kaimanawa Range in the North Island, and Hawarden region of north Canterbury, and schists of Dansey Pass, both in the South Island, by Sporli K. B. 1978: Mesozoic tectonics, North Island, New Zealand. Bulletin of the Geological Society of America 89: 415-425; Bradshaw J. D. 1972: Stratigraphy and structure of the Torlesse Supergroup (Triassic-Jurassic) in the foothills of the Southern Alps near Hawarden (S60-61), Canterbury, New Zealand. New Zealand Journal of Geology & Geophysics 15: 71-87 and Bishop, D. G. 1974: Stratigraphic, structural and metamorphic relationships in the Dansey Pass area, Otago, New Zealand. New Zealand Journal of Geology & Geophysics 17: 301-335.

3. According to normal methods of measuring, the formations in the Aoraki Mt Cook National Park seem to be extraordinarily thick. This is because the measurement is taken along the crest of the fold. But the approach is wrong. The folds in the Aoraki Mt Cook National Park have a large component of fault-drag geometry, and have arisen from strata originally not at right angles to the fault – but parallel to the fault. That implies that the crest of the fold will extend as far as the strata and the fault, irrespective of the thickness of the beds. When the fault ruptures, it will drag the adjoining strata, and probably will

both break the strata into segments, or schuppen, or fold the beds into a series of closely spaced folds. These schuppen or small folds bend into a fold across the fold-axis, apparently seamlessly, although there are often signs of repeated beds, as in some of the folds illustrated herein. But more detailed study is required to substantiate this, and clarify the mechanics.

4. What if subhorizontal beds are crossed by a steeply inclined fault at a high angle? Presumably the block moving upwards will develop fault-drag folds that conform with normal anticlines and synclines, or be "extrocline". If the block moves downwards against the other block, folds will be "introcline".

5. Findlay, R. H., Sporli, K. B. 1984: Structural geology of the Mount Cook Range and Main Divide, Hooker Valley region, New Zealand. New Zealand Journal of Geology & Geophysics 27: 257-276. Findlay & Sporli noted that low angle faults would generate distinctive minerals in rocks along the plane of movement, and stated that the absence of such minerals showed there had been no low angle thrusts. But given the absence of stratigraphic control, they would not have known where to look for such minerals. The likelihood of special mineral development along slide planes remains a prospect, but the minerals would likely have been removed, or metamorphosed, or obscured, if the fault plane has later been reactivated under the Kaikoura Orogeny.

6. Waterhouse, J. B. 1985: Preliminary account of geology of Malte Brun Range, New Zealand. The Australian Geologist Newsletter 57: 7-13.

7. Lillie, A. R. 1962: Geology of the Malte Brun Range, Central Alps, New Zealand. New Zealand Journal of Geology & Geophysics 5: 256-268.

8. Sylvester, A. G. 1988: Strike slip faults: Geological Society of America Bulletin 1703. See p. 1688.

9. Directions may correspond with Riedel shears of R fractures, and these in turn are likely to have been controlled, without freedom to respond de novo as according to simplistic model theory. Vertical shear is predominant, both along faults and distributed as mostly synthetic (sympathetic) and secondary synthetic shear with schist and folds. Movement is complex and predominantly antithetic to strike slip. Not enough is known about the low angle relationship to the fault: perhaps it matches the P fracture of simple shear (angle 12°). (See Aydin, A., Page, B. M. 1984: Diverse Pliocene-Quaternary tectonics in a transform environment, San Francisco Bay region, California. Geological Society of America Bulletin 95:1303-1317.) The structure is widespread in New Zealand and other areas subject to wrench regimes, being close to diapirs that have worked their way up faults and often have been connected with growth faults in New Zealand, as discussed by Kingma, J. T. 1958: Geology of the Wakara Range, central Hawkes Bay. New Zealand Journal of Geology & Geophysics 1: 76-91 and 1959: The tectonic history of New Zealand. New Zealand Journal of Geology & Geophysics 2: 1-55.

Chapter 4. Making sense of the rocks through stratigraphy

1. See Haast, Julius 1862: Notes on the geology of the Province of Canterbury, New Zealand. New Zealand Government Gazette, Province of Canterbury 9 (18): 121-131, and 1879: Geology of the Provinces of Canterbury and Westland, New Zealand. A report comprising the results of official explorations. Times Office, Christchurch, 486p., and also Park, J. 1910: The Geology of New Zealand: 488p. Christchurch, Whitcombe & Tombs Ltd. Haast has been criticized for naming a number of New Zealand mountains in the National Park in honour of overseas scientists, as in Haast, J. 1866: Report on the Headwaters of the River Rakaia. Canterbury Provincial Government, Christchurch: p. 17ff. and 1870: Map of the Southern Alps in the province of Canterbury (New Zealand). Of course at that time there were few New Zealand scientists or artists in even the broadest of senses, and it seems doubtful that the names of the military, or politicians and leaders appointed by the Crown would have provided a better option, though admittedly there are always those obsequious enough in the face of power who seek to commemorate those of such ilk, under the banner of patriotism, though the undeclared hope of patronage might be more apposite. Needless to add, there was no consideration by Haast of Maori, and some of their names have simply been ignored. The names of landscape features named by Haast have been summarized in Burroughs, C. J. 2005: Julius Haast in the Southern Alps. Canterbury University Press: 177-180, and broader coverage of the authorship of names has been provided by Dennis, A. 1985: Where are you Aoraki? Place naming at Mt Cook. New Zealand Alpine Journal 1985, vol. 38:

114-116.

2. See the 1:250 000 geological maps that encompass part or all of the Park, by Gair, H. S. 1967: Sheet 20 Mt Cook. Geological Map of New Zealand 1:250 000. Department of Scientific and Industrial Research, Wellington, New Zealand. Also Warren, G. 1967: Sheet 17 Hokitika. Geological Map of New Zealand 1:250 000. Department of Scientific and Industrial Research, Wellington, New Zealand; and Cox, S. C., Barrell, D. J. A. 2007: Geology of the Aoraki area. Scale 1:250 000. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 15. 1 sheet plus 71p. GNS Science, Lower Hutt.

3. Waterhouse, J. B. 1985: Preliminary account of geology of Malte Brun Range, New Zealand. The Australian Geologist Newsletter 57: 7-13.

4. Mackinnon, T. C. 1980: Geology of *Monotis*-bearing Torlesse rocks in Temple Basin near Arthur's Pass, South Island, New Zealand. New Zealand Journal of Geology & Geophysics 23: 63-81.

5. See Waterhouse, J. B. 1990: Transpression regime in the Southern Alps and possible extension regime in Canterbury, New Zealand. Proceedings, Pacific Rim Congress 93, vol. 3: 229-234.

6. See Craw, D. 1984: Lithologic variations in Otago Schist, Mt Aspiring area, northwest Otago, New Zealand. New Zealand Journal of Geology & Geophysics 27: 151-166; and Craw, D., Norris, R. J. 1987: Aspiring terrane: an oceanic assemblage from New Zealand and its implications for terrane accretion in the southwest Pacific. In Leitch, E. C., Schelber, E. (ed.) Terrane accretion and orogenic belts. Boulder, Geological Society of America: 169-178, with overview by Turnbull, I. M. 2000: Geology of the Wakatipu area. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 18. 1 sheet plus 72p. GNS Science, Lower Hutt.

7. Waterhouse, J. B. 1987: Permian fossils in the Malte Brun Range, Mt Cook National Park, New Zealand. New Zealand Journal of Geology & Geophysics 30: 91-92.

Chapter 5. Stratigraphy of the Liebig, Mannering and Malte Brun Groups in the Aoraki Mt Cook National Park.

1. Waterhouse, J. B. 1985: Preliminary account of geology of Malte Brun Range, New Zealand. The Australian Geologist Newsletter 57: 7-13.

2. Waterhouse, J. B. 1987: Permian fossils in the Malte Brun Range, Mt Cook National Park, New Zealand. New Zealand Journal of Geology & Geophysics 30: 91-92.

3. Field, B. D. 1976: Geology of the Torlesse rocks of the central Liebig Range, Mt Cook. M. Sc. thesis, University of Auckland. Unpublished.

4. Grapes, R. H., Campbell, H. J. 1994: Red Rocks: a Wellington geological excursion. Geological Society of New Zealand Guidebook 11. Also: Roser, B. P., Grapes, R. H. 1990: Whole-rock and mineral analyses of volcanic, pelagic and turbidite lithologies from Red Rocks, Wellington. Research School of Earth Sciences. Geology Board of Studies Publication no. 6. Victoria University of Wellington. Analytical Facility Contribution No. 14.

5. Leven, E. Y., Campbell, H. J. 1998: Middle Permian (Murgabian) fusuline faunas, Torlesse Terrane, New Zealand. New Zealand Journal of Geology & Geophysics 41: 149-156. The stratigraphy has been placed in a regional setting in Waterhouse, J. B. 2002: The stratigraphic succession and structure of Wairaki Downs, New Zealand, and its implications for Permian biostratigraphy of New Zealand and marine Permian of eastern Australia and Gondwana. Earthwise 4: 1-260 plus map. A geological map involving the Palmer Range, which lies just east of the Arrowsmiths, is provided in Fig. 3.13, p. 147.

6. Waterhouse, J. B. 1990: Transpression regime in the Southern Alps and possible extension regime in Canterbury, New Zealand. Proceedings, Pacific Rim Congress 93, vol. 3: 229-234.

7. Andrews, P. B., Speden, I. G., Bradshaw, J. D. 1976: Lithological and Paleontological content of the Carboniferous-Jurassic Canterbury Suite, South Island, New Zealand. New Zealand Journal of

Geology & Geophysics 19: 791-819. *Terebellina* has been considered to be an annelid, or a large Foraminifera, and is illustrated in Stevens, G. R. 1978: Paleontology: 255-262, Fig. 4.97.4 in Suggate, R. P., Stevens, G. R., Te Punga, M. T. 1978: The Geology of New Zealand. Government Printer, Wellington, 2 vols., 820p. A figure of *Torlessia* is also provided by this author. Biological affinities of *Torlessia* have been discussed by Hannah, M. J., Campbell, H. J. 1996: *Torlessia mackayi* and other Foraminifera from the Torlesse Terrane. New Zealand Journal of Geology & Geophysics 39: 75-81.

8. Dusschoten, A. von 2000: Torlesse stratigraphy and paleontology, Balmacaan Stream, mid Canterbury (abstract). Geological Society of New Zealand Newsletter 122: 21-22.

9. Campbell, H. J. 1994: The Triassic bivalves *Daonella* and *Halobia* in New Zealand, New Caledonia and Svalbard. Institute of Geological and Nuclear Sciences Ltd Monograph 4.

10. Campbell, J. D., Warren, G. 1965: Fossil localities of the Torlesse Group in the South Island. Transactions of the Royal Society of New Zealand Geology 3 (8): 99-137 plus map.

11. Lillie, A. R., Gunn, B. M. 1964: Steeply plunging folds in the Sealy Range, Southern Alps. New Zealand Journal of Geology & Geophysics 7: 403-423.

12. Three generalist names have been proposed for the large tracts of Carboniferous to Cretaceous rocks found in the axial and eastern mountain ranges of New Zealand. Wellman, H. W. 1956: Structural Outline of New Zealand. DSIR Bulletin 121, 36p. suggested "New Zealand Geosyncline", and Kingma, J. T. 1959: The tectonic history of New Zealand. New Zealand Journal of Geology & Geophysics 1: 1-55. proposed the term "Aotearoa". The name Torlesse was first applied by Haast, J. 1865: Report on geological exploration of the West Coast. Proceedings of the provincial council of Canterbury, Session 23: 13-21 and revived in modified form by Suggate, R. P. 1961: Rock-stratigraphic names for the South Island schists and undifferentiated sediments of the New Zealand geosyncline. New Zealand Journal of Geology & Geophysics 4: 392-399. Suggate's proposal has been adjusted, and applied as a general term, and his definition as being applicable to undifferentiated rocks places a reasonable limitation on usage: once the rocks are differentiated, Torlesse is no longer appropiate, except according to a record of past usage.

13. See Reed, J. J. 1957: Petrology of the lower Mesozoic rocks of the Wellington district. New Zealand Geological Survey Bulletin 57. Also Korsch, R. J. 1984: Geological aspects of the Torlesse Complex, south coast of Wellington. Geological Society of New Zealand miscellaneous publication 31B: 67-90.

14. Johnston, M. R. 1995: Geology of the St Arnaud District, southeast Nelson (sheet N29). New Zealand Geological Survey Bulletin 99.

15. Findlay, R. H. 1979: Age and structure of Torlesse rocks (Canterbury Suite), Otira Gorge, Westland, New Zealand. New Zealand Journal of Geology & Geophysics 22: 285-289.

16. MacKinnon, T. C. 1980: Geology of *Monotis*-bearing Torlesse rocks in Temple Basin near Arthur's Pass, South Island, New Zealand. New Zealand Journal of Geology & Geophysics 23: 63-81. Cave, M. P. 1981: Geology of *Monotis*-bearing Torlesse rocks in Temple Basin near Arthur's Pass, South Island, New Zealand. New Zealand Journal of Geology & Geophysics 24: 575-576.

17. A fine black & white photograph of the Frind Formation and underlying units exposed along the Malte Brun Range from Aiguilles Rouges to beyond Mt Nathan is provided in Palman, A. J. 2005: Aoraki Mount Cook, a guide for mountaineers. A New Zealand Alpine Club Publication. See Fig. 38, opposite p. 159. The photograph is by D. L. Homer.

18. See Adams, C. J., Maas, A. 2004: Rb-Sr age and strontium isotope characterisation of the Torlesse Supergroup in Canterbury, New Zealand, and implications for the status of the Rakaia terrane. New Zealand Journal of Geology & Geophysics 47: 201-217, and Sheppard, D. S., Adams, C. J., Bird, G. W. 1975: Age of metamorphism and uplift in the Alpine schists, New Zealand. Geological Society of America Bulletin 86: 1147-1153. The maximum age of alteration was given as 177 million years ago, or Middle Jurassic, for Otago schist by Adams, C. J., Robinson, P. 1993: Potassium-argon age studies of metamorphism/uplift/cooling in Haast schist coastal sections south of Dunedin, Otago, New Zealand. New Zealand Journal of Geology & Geophysics 36: 317-325. Various other age data were

discussed in this article on p. 323.

19. Cox, Simon [S. C.] 1995: Making mountains, the rocks and formation of the Southern Alps. New Zealand Alpine Journal 1995, vol. 48: 85-87. K-Ar ages of 11-17 million years ago in schists near Lewis Pass, crossed by the Alpine Fault, were recorded by Sheppard, D. S., Adams, C. J., Bird, G. W. 1965: Age of metamorphism and uplift of the Alpine Schist Belt, New Zealand. Bulletin of the Geological Society of America 86: 1147-1153.

20. The distribution of metamorphic rocks across the Park is summarised by Findlay, R. H., Sporli, K. B. 1984: Structural geology of the Mount Cook Range and Main Divide, Hooker Valley region, New Zealand. New Zealand Journal of Geology & Geophysics 27: 259, with prehnite-pumpellyite being most widespread. The occurrence of key minerals is summarised on the same page.

21. Cox, S. C., Barrell, D. J. A. 2007: Geology of the Aoraki area. Scale 1:250 000. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 15. 1 sheet plus 71p. GNS Science, Lower Hutt, give a table to show textural subdivision of rocks on p. 15.

22. Bishop, D. G. 1976: Geological Map of New Zealand 1: 63 360 Mt Ida Sheet S126. New Zealand Geological Survey, Department of Scientific and Industrial Research: 1-24 plus map. This author showed that mapping schist in stratigraphic units was eminently feasible.

Chapter 6. Ancient Faults

1. This phrase is quoted from Findlay, R. H., Sporli, K. B. 1984: Structural geology of the Mount Cook Range and Main Divide, Hooker Valley region, New Zealand. New Zealand Journal of Geology & Geophysics 27: 272, without authorative source provided, but reasonable in view of the experience of Bernhard Sporli in the Alps of Europe. However I have seen overthrusts in the Alps without mylonite, and in the Rocky Mountains and Himalayas, where I have worked extensively for many years, there are low angle thrusts separated by no mylonite – the contact zone is very thin. The recumbent folds developed along the Main Divide south of Mt Hicks do not show any mylonite bands at their base, as far as can be seen, and there do not seem to be any either at the base of the huge recumbent folds developed in the Otago Schist. Mylonite bands in the Park are developed, but none are clearly related to the tracts and tractator faults mapped in the Park.

2. This widely accepted diagram is provided by various texts, without credit to the origin. See Understanding the Earth published in 1971 by I. G. Gass, P. J. Smith & R. C. L. Wilson (ed). MIT Press, Cambridge Massachusetts.

3. Haast, Julius 1877: Notes on the geology of the Clent Hills and Mount Somers districts, in the province of Canterbury. New Zealand Geological Survey Reports of geological exploration during 1872-3, 8: 1-19. Oliver, P. J., Campbell, J. D., Speden, I. G. 1982: The stratigraphy of the Torlesse rocks of the Mt Somers area (S81), mid-Canterbury. Journal of the Royal Society of New Zealand 12: 243-271. Oliver, P. J., Keene, H. W. 1989: Mount Somers – Sheet K36 AC and part Sheet K35. Geological Map of New Zealand 1:50 000. Wellington, Department of Scientific and Industrial Research. Oliver, P. J., Keene, H. W. 1990: Clearwater – Sheet J36 BD and part Sheet J35. Geological Map of New Zealand 1:50 000. Wellington, Department of Scientific and Industrial Research.

4. Some studies regard the West Coast as forming an indentor that pushed into the sediments now making up the Southern Alps, presumably during the opening of the Tasman Sea. But during the Rangitata Orogeny, and at the start of the Kaikoura Orogeny, the sediments of the Southern Alps were separated from the West Coast rocks by further basins and igneous rocks, involving the Brook Street volcanic arc, Maitai Supergroup, Murihiku Supergroup, Dun Mountain spreading ridge, Lee River and Caples groups, and other stratigraphic components. Eventually the Southern Alps came to rest against West Coast rocks through the development of the Alpine Fault, and the West Coast acted as an indentor pushing obliquely against the Southern Alps.

5. See Wood, B. L. 1978: The Otago Schist megaculmination: its possible origins and tectonic significance in the Rangitata Orogen of New Zealand. Tectonophysics 47: 339-368 and Craw, D. 1985: Structure of schist in the Mt Aspiring region, northwestern Otago, New Zealand. New Zealand Journal of Geology & Geophysics 28: 55-75.

Chapter 7. Geology in different parts of the Park

1. Lillie, A. R., Gunn, B. M. 1964: Steeply plunging folds in the Sealy Range, Southern Alps. New Zealand Journal of Geology & Geophysics 7: 403-423. Their Fig. 3 shows a splendid reconstruction of the strata, folds and faults. The Hoophorn fold lies within Baker Formation, and an anticline extending north from Sealy Peak lies within Chudleigh Formation. Interestingly, the unnamed fault through what is now termed Acolyte Formation (s.l.) suggests left lateral strike slip.

2. Spörli, K. B., Lillie, A. R. 1974: Geology of the Torlesse Supergroup in the northern Ben Ohau Range, Canterbury. New Zealand Journal of Geology & Geophysics 17: 115-141.

3. Findlay, R. H., Sporli, K. B. 1984: Structural geology of the Mount Cook Range and Main Divide, Hooker Valley region, New Zealand. New Zealand Journal of Geology & Geophysics 27: 257-276.

4. Croll, W. G. 1956: Climbs and traverses of Mt. Cook. New Zealand Alpine Journal vol 16 (43): 299-319. See photograph facing p. 303.

5. Lillie, A. R. 1961: Folds and faults in the New Zealand Alps and their tectonic significance. Proceedings, Royal Society of New Zealand 89: 57-85.

6. Waterhouse, J. B. 1966: The Häckel Syncline and neighboring folds of the upper Tasman Glacier. Transactions of the Royal Society of New Zealand 3 (14): 183-195. (See pl. 3, fig. 2).

7. A large photographic panorama at Christchurch airport shows strata and younging directions on the southwest side of Nazomi and Pibrac. Waterhouse in reference 9 below, p. 419 reported a likely southward younging anticline, and Lillie A. R., Gunn B. M. & Robinson P. 1957: Structural observations in central Alpine region of New Zealand. Transactions of the Royal Society of New Zealand 85: 113-129 claimed the Pibrac fold might continue south from a Haidinger Anticline, although Lillie A. R. 1963: Structural Geology in high mountains, especially the New Zealand Alps. The New Zealand Alpine Journal 1963, vol. 20: 161-178 later suggested that the Pibrac fold was synclinal – see Fig. 15.

8. Readers interested in deglaciation might like to compare this figure with that provided by Harper, A., P. 1930: New Zealand glaciers Their origin, characteristics and effects. Wanderlust Magazine 1 (3): 1-14. See p. 4. This picture also provides a good view of the ice below Engineer Col, and shows two major ice-steps, just as David Herron and I encountered on our way to Mt Tasman in late 1954. The steps probably betoken two head-walls within the glacier, and below the ice. Peculiarly, this route is now of some mystery, for Palman, A. J. 2005: Aoraki Mount Cook, a guide for mountaineers. A New Zealand Alpine Club Publication: pp. 129, 257 recorded no first ascent of Mt Tasman via this route, only a descent, which is hardly the same.

9. Park, J. 1910: The Geology of New Zealand. 488p. Christchurch, Whitcombe & Tombs Ltd.

10. Waterhouse, J. B. 1972: Folds of the Mt Cook National Park, New Zealand, and their origin under a wrench regime acting in a subduction zone. Journal of the Royal Society of New Zealand 2 (3): 413-430. See also reference 6.

11. Monteath, C. 1972: A ridge to "crow" about and a buttress to boot. New Zealand Alpine Journal 1972, vol. 25: 8-11. 1973: The central Alps season. New Zealand Alpine Journal 1973, vol. 26: 48-51.

12. Waterhouse, J. B. 1966: From Annan to Darwin. New Zealand Alpine Journal 1966, vol. 21 (2): 257-260.

13. Waterhouse, J. B. 1990: Transpression regime in the Southern Alps and possible extension regime in Canterbury, New Zealand. Proceedings, Pacific Rim Congress 93, vol. 3: 229-234.

14. The Classen Glacier and the Godley Glacier with subsidiaries are well illustrated by several oblique aerial photographs in Palman, A. J. 2005: Aoraki Mount Cook, a guide for mountaineers. A New Zealand Alpine Club Publication. See Fig. 53-58. Unfortunately snow covers much of many upper peaks in most of the photographs, for it seems customary in New Zealand to regard rocks with dismay, and prefer them to be coated in grass, bush, or plastered with snow, whether or not climbers might

prefer clearer route guidance, let alone interest ordinary spectators.

15. Craw, D., Rattenbury, M. S., Johnstone, R. D. 1994: Structures within greenschist facies, Alpine Schist, central Southern Alps, New Zealand. New Zealand Journal of Geology & Geophysics 37: 101-111. This article mapped boundaries of textural alteration for some small areas, but provided no lithological data, other than “greenschist” mentioned in the title. The “greenschist” as mapped in the upper Whymper valley and its southwestern boundary agrees with the present study, and it is sedimentary, not volcanic. Rocks on the other side of the Whymper Glacier do not belong to the Rose Formation, but are of slightly higher metamorphic grade, falling chiefly within the Acolyte Formation.

16. The 1:250 000 geological map published in 2007 that covers the National Park also indicates a large eastward step in the same position. This is based it would appear largely on schistocity of the rocks, but as shown by rocks in the southwest corner of the Park, and in rocks to the south, the schistocity is independent of the rock formations. See Cox, S. C., Barrell, D. J. A. 2007: Geology of the Aoraki area. Scale 1:250 000. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 15. 1 sheet plus 71p. GNS Science, Lower Hutt.

17. See illustrations in Stevens, G. R. 1974: Rugged Landscape. The geology of central New Zealand. Front and back inside covers, and Fig. 9.3, for example. A. H. & A. W. Reed, Wellington.

Chapter 8. Regional setting for hard rock geology of Aoraki Mt Cook National Park

1. Craw, D. 1984: Lithologic variations in Otago Schist, Mt Aspiring area, northwest Otago, New Zealand. New Zealand Journal of Geology & Geophysics 27: 151-166. Craw, D., Norris, R. J. 1987: Aspiring terrane: an oceanic assemblage from New Zealand and its implications for terrane accretion in the southwest Pacific. In Leitch, E. C., Schelber, E. (ed.) Terrane accretion and orogenic belts. Boulder, Geological Society of America: 169-178. Cox, S. C. 1991: The Caples/Aspiring terrane boundary – the translation surface of an early nappe structure in the Otago Schist. New Zealand Journal of Geology & Geophysics 34: 73-82. Mortimer, N. 1993: Geology of the Otago schist and adjacent rocks. Scale 1:500 000. Institute of Geological and Nuclear Sciences geological map. Lower Hutt, GNS. Turnbull, I. M. 2000: Geology of the Wakatipu area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 18. 1sheet plus 72p. Allied rocks are confirmed for the northern South Island by Begg, J. G., Johnston, M. G. 2000: Geology of the Wellington area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 10. 1 sheet plus 64p. Bierlein, F. P., Craw, D. 2009: Character and provenance of metabasalts in the Aspiring and Torlesse terranes, South Island, New Zealand: implication for the gold endowment of the Otago Schist? Chemical Geology 260 (2009): 330-344 provided an important assessment of the Wanaka rocks, showing that the metabasalts formed an ocean plateau built by a ?Permian mantle plume. Two samples of metabasalts from the Torlesse were considered to be identical (though they whether they were sourced from a mantle plume, or from a leaky or blocked transforms may be moot). At least some rocks of the Aspiring lithological association are considered to be Jurassic, as shown by Jugum, D. Norris, R. H., Palin, J. M. 2013: Late Jurassic detrital zircons from the Haast Schist and their implications for New Zealand terrane assembly and metamorphism. New Zealand Journal of Geology and Geophysics 56: 223-238. The Aspiring rocks were regarded as part of the Waipapa terrane by Adams, C. J., Mortimer, N., Campbell, H. J., Griffin, W. C. 2009: Tracing the Caples terrane through New Zealand using detrital zircon age patterns and radiogenic isotope signature. New Zealand Journal of Geology & Geophysics 52: 223-245, yet the Waipahi Formation of south Otago, also included in Waipapa by these authors, certainly has no Jurassic whatsoever, and Jurassic of the Waipapa belt in North Auckland lies in an assemblage distinct from the Permian-Triassic of that region. Is it possible that the Jurassic in the southerly schists, yet to be adequately mapped, formed as synorogenic deposits near the commencement of the Rangitata Orogeny, akin to the Clent Hills Group of Canterbury?.

2. For information on the mid-ocean spreading ridge, see Sivell, W. J., Rankin, P. C. 1982: Discrimination between ophiolitic metabasalts, D’Urville Island, New Zealand. New Zealand Journal of Geology & Geophysics 25: 275-293. Sivell, W. J., Waterhouse, J. B. 1984: The Patuki intrusive suite: closed-system fractionation beneath a slow-spreading ridge. Lithos 17: 1-17. Waterhouse, J. B., Sivell, W. J. 1987: Genesis of the Permian ophiolites and ultramafics in the Dun Mountain terrane, New Zealand. Proceedings Pacific Rim Congress vol. 1: 615-620. Sivell, W. J. 1987: Geochemistry of

Croisilles and Patuki metavolcanics, New Zealand: implications for early Permian subduction polarity. Proceedings Pacific Rim Congress vol. 1: 405-408. Sivell, W. J. 2002: Geochemistry and Nd-isotope systematics of chemical and terrigenous sediments from the Dun Mountain ophiolite, New Zealand. New Zealand Journal of Geology & Geophysics 45: 427-451, and Sivell, W. J., McCulloch, M. T. 2000: Reassessment of the origin of the Dun Mountain ophiolite, New Zealand: Nd-isotopic and geochemical evolution of magma suites. New Zealand Journal of Geology & Geophysics 43: 133-146. This latter study showed that late phase magma intrusions associated with the earlier "spreading-type" lavas of stage 1 had developed geochemical signatures of infant arc tholeiites, precursor to normal subduction-related volcanism. That signifies that the ridge was no longer actively spreading.

Available fossil and stratigraphic data indicates that the Croisilles Complex was of Early Permian age (see Waterhouse, J. B. 2002: The stratigraphic succession and structure of Wairaki Downs, New Zealand, and its implications for Permian biostratigraphy of New Zealand and marine Permian of eastern Australia and Gondwana. Earthwise 4: 1-261 plus map. Also 2015: The Permian faunal sequence at Gympie, southeast Queensland, Australia. Earthwise 12. The Patuki was dated as Middle Permian, as summarized in Waterhouse, J. B. 1975: The Rangitata Orogeny. Pacific Geology 9:35-73 – see p. 45. Yet various authors lump the two. The Brook Street volcanic arc has been studied in Sivell, W. J. 1983: Arc-tholeiite and ultramafic cumulate, Brook Street volcanics, west D'Urville Island, New Zealand. New Zealand Journal of Geology & Geophysics 26: 239-257. Ultramafic pods and pillow lavas are found in the Owhai volcanics of the Brook Street volcanic arc, as shown by Johnston, M. R. 1996: Geology of the D'Urville area. Sheets P26AC and part P25 1:50 000. New Zealand Geological Survey, Lower Hutt, so that the assumption that pillow lava and ultramafics indicate ocean crust rather than volcanic island arc must be viewed with caution. The time of emplacement of the massive Dun Mountain ultramafics (see earlier reference, Waterhouse & Sivell 1987) is likely to have been mid to early late Permian, hypothetically a little before the time that any hypothetically possible but questionable subduction zone to the (present) east commenced, to enable the accumulation of the Malte Brun Group in a sub-basin.

Waterhouse J. B. 1964 Permian stratigraphy and faunas of New Zealand. New Zealand Geological Survey Bulletin 72: p. 27, Fig. 15 illustrated a likely surface flow of serpentinite.

3. Waterhouse, J. B. 2005: Torlesse sequence stratigraphy and formations between the Rakaia and Waitaki Rivers. Geological Society of New Zealand Miscellaneous Publication 119A: 93.

4. Retallack, G. J. 1983: Middle Triassic estuarine deposits near Benmore Dam, southern Canterbury, New Zealand. Journal of the Royal Society of New Zealand 13: 107-127.

5. Hitching, K. D. 1979: Torlesse geology of Kakahu, south Canterbury. New Zealand Journal of Geology & Geophysics 22: 191-198.

6. The New Zealand Geosyncline was proposed by Wellman, H. W. 1956: Structural Outline of New Zealnd. DSIR Bulletin 121, 36p., followed by Aotearoa Geosyncline proposed by Kingma, J. T. 1959: The Tectonic History of New Zealand. New Zealand Journal of Geology & Geophysics 2: 1-55 (see p. 8), replaced in part by Torlesse, designated by Suggate, R. P. 1961: Rock-stratigraphic names for the South Island schists and undifferentiated sediments of the New Zealand geosyncline. New Zealand Journal of Geology & Geophysics 4: 392-399.

7. Oliver, P. J., Campbell, J. D., Speden, I. G. 1982: The stratigraphy of the Torlesse rocks of the Mt Somers area (S81), mid-Canterbury. Journal of the Royal Society of New Zealand 12: 243-271. Oliver, P. J., Keene, H. W. 1989: Mount Somers – Sheet K36 AC and part Sheet K35. Geological Map of New Zealand 1:50 000. Wellington, Department of Scientific and Industrial Research. Oliver, P. J., Keene, H. W. 1990: Clearwater – Sheet J36 BD and part Sheet J35. Geological Map of New Zealand 1:50 000. Wellington, Department of Scientific and Industrial Research.

8. Various geochemical aspects of the "Torlesse" (Triassic and Permian), which includes rocks of the Aoraki Mt Cook National Park, are shared with rocks of the New England Orogen in eastern Australia. It seems likely that the "lost upland" of south Canterbury was once part of the New England orogen, which had split off by sea-floor spreading or strike-slip movement, and then became a source for Permian and Triassic sediments to the (present) west. In Adams, C. J., Maas, R. 2004: Rb-Sr age and

strontium-isotope characterisation of the Torlesse Supergroup in Canterbury, New Zealand, and implication for the status of the Rakaia terrane. New Zealand Journal of Geology & Geophysics 47: 201-217, it was concluded that the Rakaia sediments (including sediment from the southerly Pahau Basin, which was not discriminated), were sourced from the south-central New England Orogen of northeast Australia, including Triassic sediment from Late Permian- Early Triassic granitoids. That implies that the “lost upland” shared granitoids with the New England Orogen, suggesting that the lost upland shared the same attributes with parts of the New England Orogen. Other articles which elaborate on the theme are provided by Adams, C. J., Kelley, S. 1998: Provenance of Permian-Triassic and Ordovician metagreywacke terranes in New Zealand: evidence from 40Ar/39Ar dating of detrital micas. Geological Society of America Bulletin 110: 422-432, Pickard, A. L., Adams, C. J., Barley, M. E. 2000: Australian provenance for Upper Permian to Cretaceous rocks forming accretionary complexes in the New Zealand sector of the Gondwanaland margin. Australian Journal of Earth Sciences 47: 987-1007, and Adams, C. J., Korsch, R. J., Griffin, W. L. 2013: Provenance comparison between the Nambucca Block, east Australia and the Torlesse composite terrane, New Zealand: connections and implications from detrital zircon age patterns. Australian Journal of Earth Sciences 60: 241-253. In Adams, C. J., Mortimer, N., Campbell, H. J., Griffin, W. C. 2009: Tracing the Caples terrane through New Zealand using detrital zircon age patterns and radiogenic isotope signature. New Zealand Journal of Geology & Geophysics 52: 223-245, it was stated that zircons in the Mt Aspiring lithological assemblage also pointed to a source from the New England Orogen. An article by Adams, C. J., Campbell, H. J., Griffin W. C. 2007: Provenance and comparisons of Permian to Jurassic tectonostratigraphic terranes in New Zealand: perspectives from detrital zircon age patterns. Geological Magazine 144: 701-729, elaborated on the proposed sources and dispositions of New Zealand Permian to Jurassic basins. As implied by various articles, and setting aside the likelihood of a “lost upland” that clearly did provide much of the sediment as judged from facies changes and the igneous record, it would seem that the most likely way for the sediments to have been derived from the New England Orogen would be to have a series of narrow depocentres, linearly arranged seaward of east Australia, and brought together, that is aggregated, into a side-by side distribution through sustained strike-slip faulting. This is depicted by Adams, Campbell & Griffin 2007, who recognized basins named after Caples, Maitai, Rakaia and Waipapa, arrayed separately off the central Queensland coast. Yet not one of these basins has been demonstrated to show near-shore deposits, or megafacies changes as shown herein in Fig. 8.1 to Fig. 8.3. Even more significantly, the interbasins are completely hypothetical. There is no evidence of sediment supply into the so-called basins from the interbasinal rocks, nor any geological evidence for strike-slip displacements and metamorphic belts like those along the Alpine Fault. No proofs or even indications of extensive interbasinal separation between the Caples, Maitai and Waipapa Basins seem to exist, and that is not surprising, because the interbasinal separations did not exist. Instead, the basins overlapped and graded into each other: Caples with Rakaia, Maitai with Caples, and Maitai with Waipapa. Formations as well as faunas are shared at some intervals, especially between Maitai, Waipapa and Caples, which means they all formed one large basin, not a number of small and separate ones. And in placing the Brook Street of New Zealand as being located far from the other basins, the elaborate geochemical studies led by W. S. Sivell were ignored, as well as the evidence that the Brook Street and Maitai of New Zealand were contiguous with the Highbury and South Curra-Kin Kin of Gympie, south Queensland as summarized in Waterhouse, J. B. 2015: The Permian faunal sequence at Gympie, south-east Queensland, Australia. Earthwise 12: 1-199. There is no evidence at all for huge strike-slip displacements between the so-called terranes or basins, comparable to the evidence of profound schistocity developed along the Alpine Fault, which involved only a few hundred kilometres of displacement, much less than postulated for the basins originally offshore from Queensland. Nor is there evidence for sharp lithological, metamorphic and paleontological boundaries and substantial igneous intrusions, as for Fyfe’s Line between west South Island and central New Zealand, and the sharp tectonic and sedimentary facies boundary between the southerly Pahau Basin and rocks to the west.

Does this mean that the geochemical studies have no value? Of course they have value, but they need to be properly interpreted. If New England sediment could cross belt after belt of sediments and volcanics, or enter a string of basins derived from various sources and placed at different distances and paleolatitudes compared with northeast Queensland – (or should it be the Nambucca Block in New South Wales, or south central New England orogen, as according to other articles?) - involving Maitai Supergroup, Lee River and Caples Groups, and Rakaia and probably Pahau Basin, then the value of zircons and Sb/Sr data as discriminants would seem to have limitations. But it seems more likely that the geochemical ratios have considerable significance in pointing to facies signatures and modal difference across a large and complex basin. After all the discrimination of the Waipapa terrane, or so-called basin, and its linkage with the Waipahi volcanics of south Otago, endorsed on the basis of geochemical studies by C. J. Adams, was first proposed in Waterhouse J. B. 1964: The Permian of New Zealand. 22 International Geological Congress India 1964. Part 9, Proceedings of section 9: 203-224 (see p. 207), and sustained in other studies such as 1975: The Rangitata Orogen. Pacific Geology 9: 35-73. These two studies, based on the recognition of a large complex sedimentary region, revealed the commonality of the so-called Pukeawa Facies at both the Arthurton district in South Otago, and the Waipapa Group of North Auckland. The geochemical studies provide further evidence in support of that distinction, and support the reconstruction of a complex and varied single large basin of Permian to Jurassic age through central New Zealand postulated in those articles, rather than a number of little basins for which there is no sedimentary or facies or structural support.

9. See figure 28, p. 40 for the model by Cox, S. C., Barrell, D. J. A. 2007: Geology of the Aoraki area. Scale 1:250 000. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 15. 1 sheet plus 71p. GNS Science, Lower Hutt.

10. Four main glacial phases are recognised in New Zealand, and although the West Coast has evidence for the first, no equivalent has been recognised in Canterbury.

Chapter 9. Acknowledgements and background

1. Wilson, J. 2012: Joy of the Mountains. A climber’s life. John Harrison (1932-1966). Te Waihora Press, Christchurch. Williams, S. 1954: What the Butler saw. The Canterbury Mountaineer 1953-1954, vol. 6 (23): 152-156.

2. Waterhouse, J. B. 1955: An isoclinal fold on Häckel Peak, Southern Alps, New Zealand (S79). Transactions of the Royal Society of New Zealand 83: 345-346.

3. Barcham, H. P. 1955: Ten days in the Tasman. The Canterbury Mountaineer 6 (24): 252-253. 1955: Mount Dampier – a face climb from the Hooker. The New Zealand Alpine Journal vol. 16 (42): 68-72. Waterhouse , J. B. 1955: Mt Hicks and a new route on Dampier. The Canterbury Mountaineer 6 (24): 231-236. 1955: Mt Tasman. The Canterbury Mountaineer 6 (24): 256-257.

4. Waterhouse, J. B. 1966: From Annan to Darwin. New Zealand Alpine Journal 21 (2): 257-260 + fold-out.

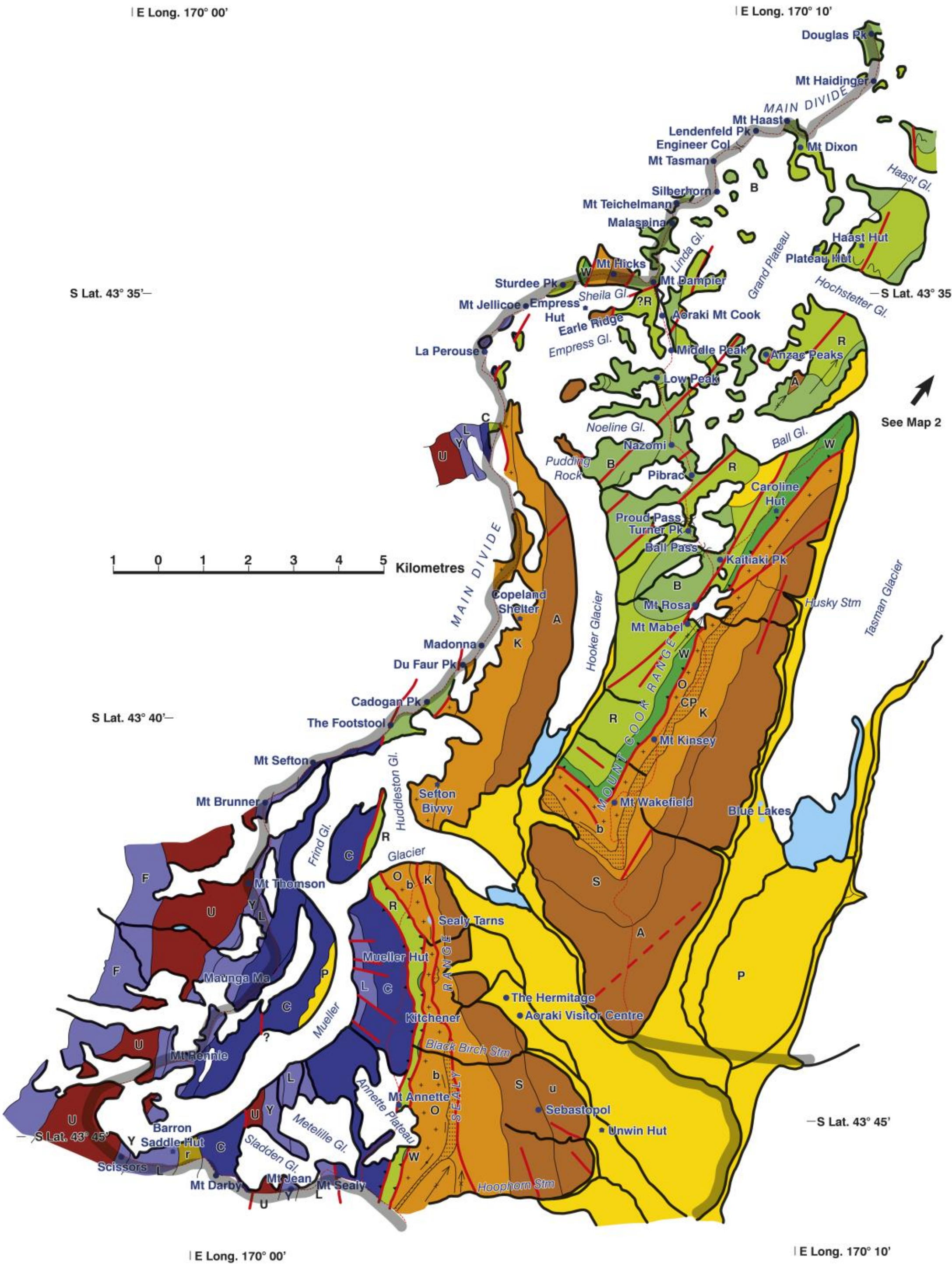
5. Waterhouse, J. B. 1979: Mad Professor in the Murchison. New Zealand Alpine Journal 1979, vol. 32: 34-35.

6. Waterhouse, J. B. 1966: The Häckel Syncline and Neighboring folds of the Upper Tasman Glacier. Journal of the Royal Society of New Zealand 2 (3): 413-430. 1972: Folds of the Mt Cook National Park, New Zealand, and their origin under a wrench regime acting in a subduction zone. Journal of the Royal Society of New Zealand 2 (3): 413-430.

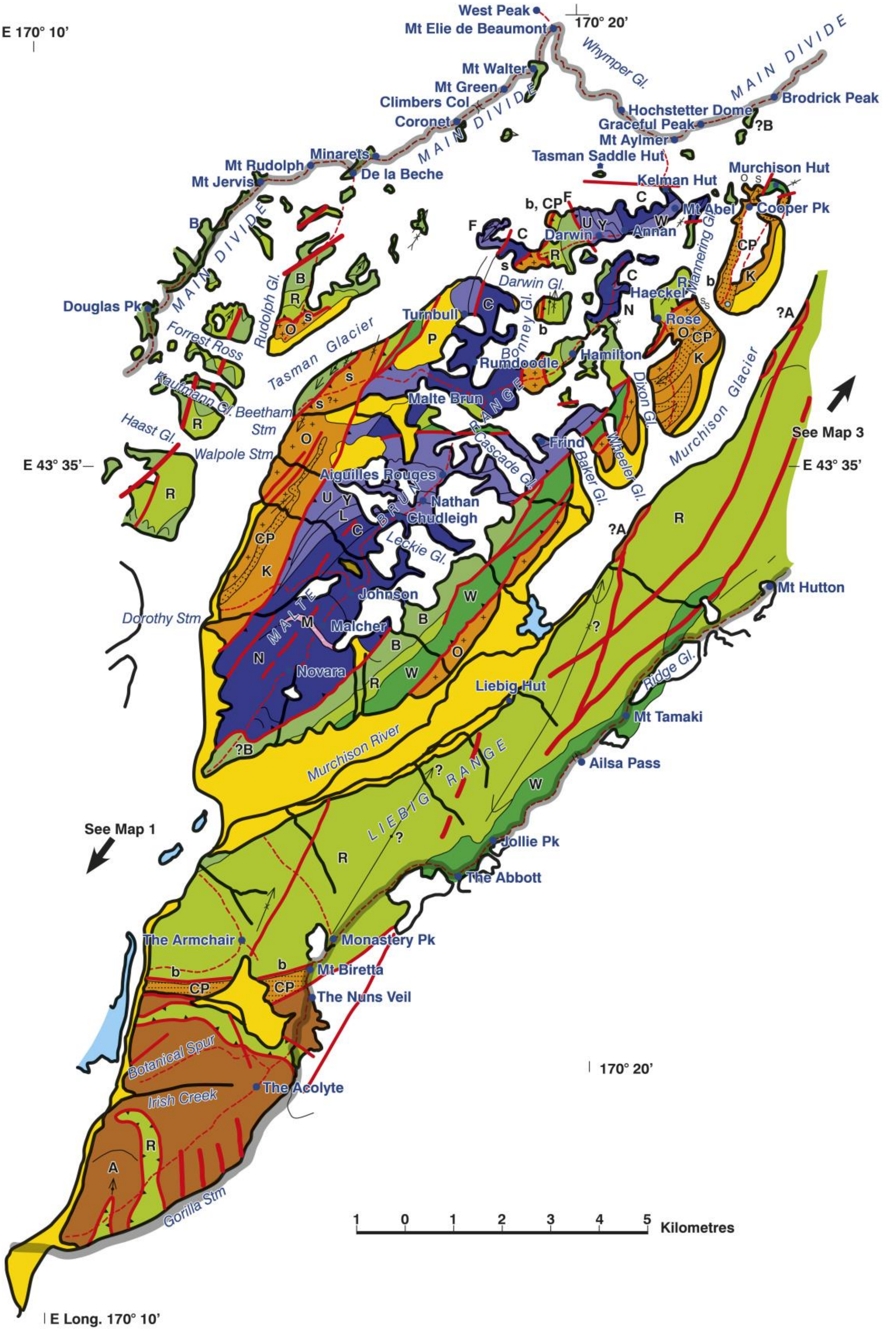
7. Waterhouse, J. B. 1985: Preliminary account of geology of Malte Brun Range, New Zealand. The Australian Geologist Newsletter 57: 7-13. 1990: Transpression regime in the Southern Alps and possible extension regime in Canterbury, New Zealand. Proceedings, Pacific Rim Congress 93, vol. 3: 229-234.

8. Waterhouse, J. B. 1992: Safety of mountain huts in the Mt. Cook National Park. New Zealand Alpine Journal 1992, vol. 45:106-110.

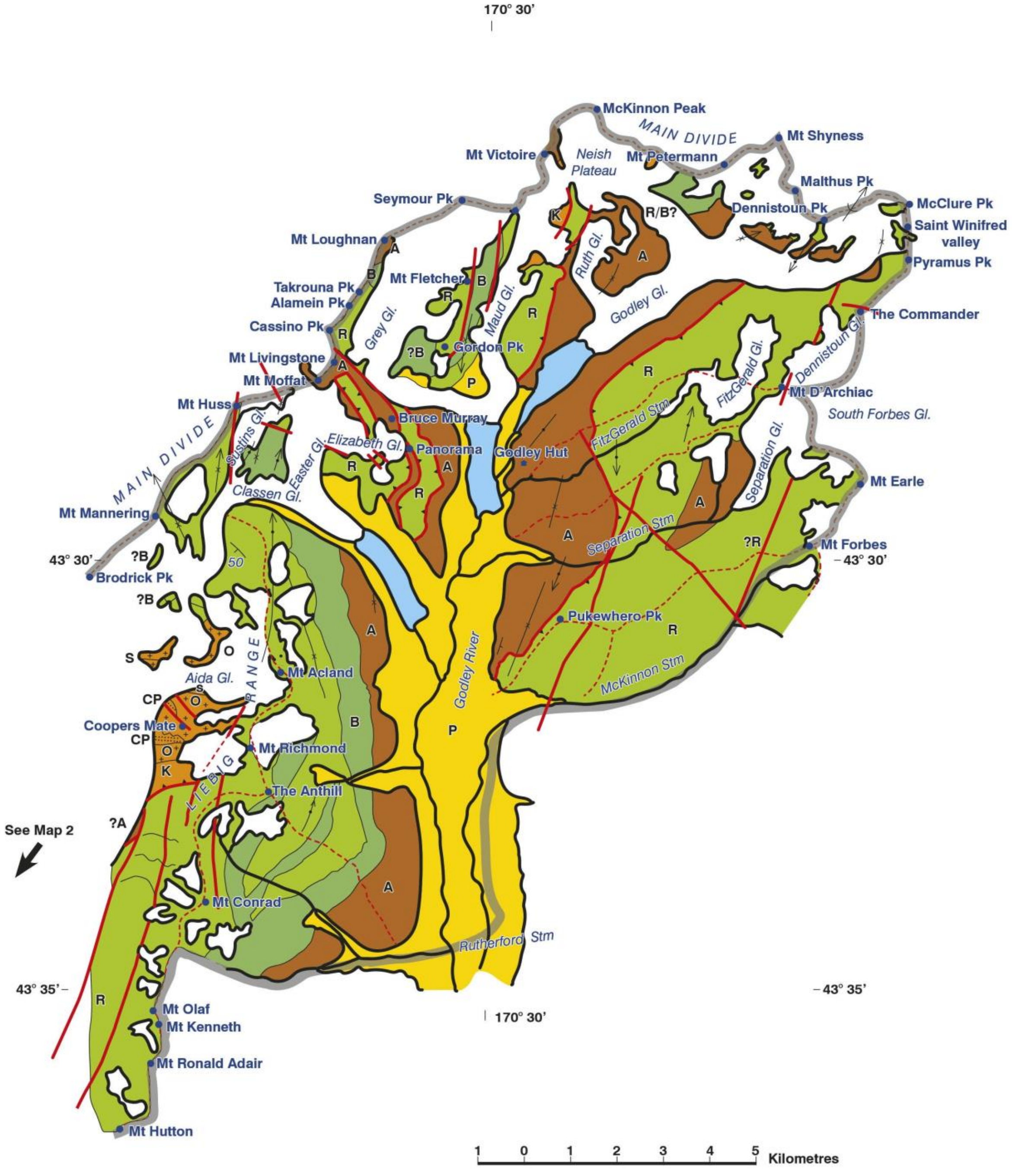
9. Chinn, T. J. 1996: How much ice has been lost? New Zealand Alpine Journal 1996: 88-95. Further detail is also provided in his article of 1996: New Zealand glacier response to climate change of the past century. New Zealand Journal of Geology & Geophysics 39: 415-528, with an excellent figure of the Godley proglacial lakes in Fig. 4, p. 419.



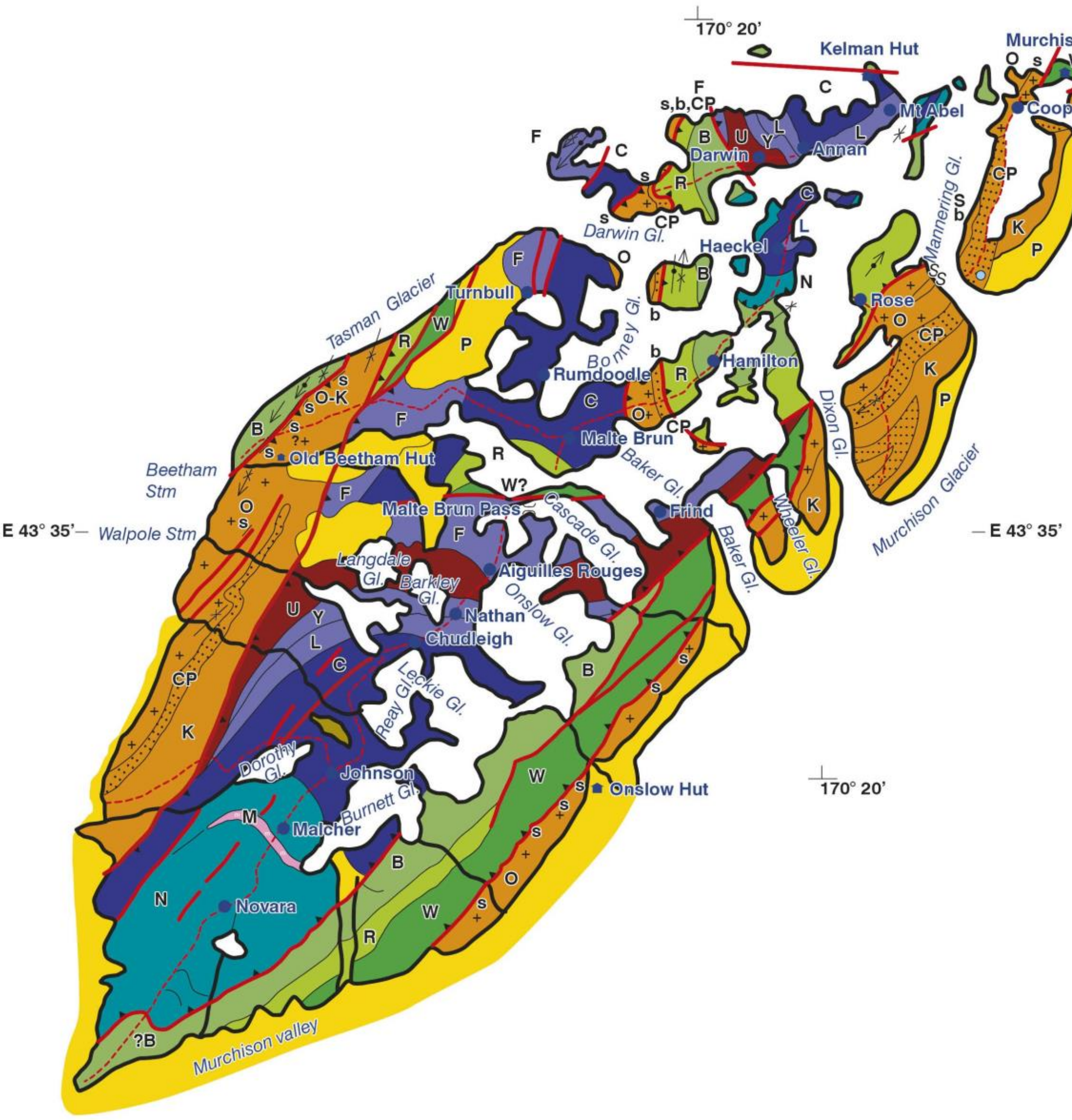
Map 1. Geological map of Aoraki Mt Cook Park in the neighbourhood of Mueller and Hooker Glaciers. This map, like Maps 2, 4, and part of Map 3, is based on Terramap Aoraki/Mt Cook Alpine Area 1:50,000, edition 2, 2003. Since publication of that edition, glacial lakes have expanded, and many ice-fields have reduced in size. The Key for colours and letters is provided on the inside back cover.



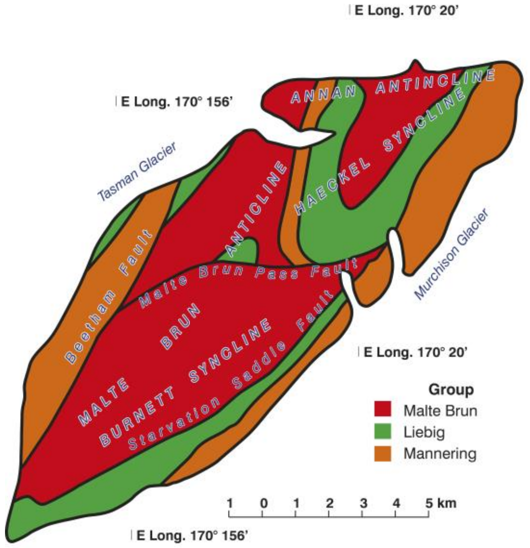
Map 2. Geological map of part of Main Divide from Douglas Peak to Mt Brodrick, the Malte Brun Range, and the southern and middle Liebig Range. The scale has forced the depiction of members to be indicated mostly by letter, and formations of the Malte Brun Group have shared colours, are lumped, Novara with Chudleigh, and Walpole, Barkley, Aiguilles Rouges with Frind, though still coded by coded by letter. Map 4 provides an enlargement of the Malte Brun Range. Key largely provided on the inside back cover.



Map 3. Reconnaissance geological map of the northwest part of the Aoraki Mt Cook National Park, showing the formations west of the upper Murchison Glacier, and around the Godley Glacier and its tributaries. Many aspects of the rocks are better conveyed by oblique aerial photographs provided in the text, which show formations and structures over steep rock walls, too crowded to be adequately shown on a map except at a very large size. This map is partly based on Terramap Aoraki/Mt Cook Alpine Area, 2003 edition, and 1:50 00 Topographic Map 260-135 Whataroa edition 1993, revised 1996. Key provided on the inside back cover.



Map 4. Enlarged version of Malte Brun Brun Range. This is an enlarged version of part of Map 2. Even so information is crowded, so that terms such as peak and mount are mostly elided, and thin members still reduced to an indication by letter. Key provided on the inside back cover.



Map 5. Simplified geological map of Malte Brun Range, showing distributions of the groups and major folds and current faults. Both faults and folds have been grossly simplified. The Annan Anticline sould arguably be interpreted as squeezed mainly along an east-west axis, yet could be interpreted as having its axis as north-south. The Haeckel Syncline shows a triangular outline. The Starvation Saddle Fault is complex, often dipping at close to 45º west so that it is directed westwards in valleys, and the Beetham Fault shows several major subparallel displacements.

Geographic Index

Place names and geographic features mentioned in the text and shown in figures and maps. Abbreviations follow the usage in the maps, by and large.

KEY

P	QUATERNARY fans, river deposits, moraine

MALTE BRUN GROUP

F	Frind Formation
U	Aiguilles Rouges Formation
Y	Barkley Formation
L	Walpole Formation
C	Chudleigh Formation
r	Reay Member
N	Novara Formation
M	Malcher Member

MANNERING GROUP

K	Baker Formation
s	Steffan Member
O	Onslow Member
b	Bonney Member
CP	Cooper Peak Member
A	Acolyte Formation
S	Sebastopol Member
u	Unwin Member

LIEBIG GROUP

B	Burnett Formation
R	Rose Formation
W	Wheeler Formation

SYMBOLS

╱	edge of mountain/valley or river
╱	fault
╱	tractator or slide fault, teeth on upper tract
+	syncline
•	anticline
↗	syncline and direction of plunge
↗	anticline and direction of plunge
⊥	strike and dip
≍	mountain pass
☐	glacier, nevé, ice
⌂	mountain hut
•	divide ridge & peak
🟦	glacial lake
▨	park boundary

This provides the coded and coloured key to maps 1-4, and to Fig. 3.10.
Exceptional use of colour or symbols explained where relevant in the appropriate map or figure.

Cover. Aoraki Mt Cook is a highly photogenic peak, and this picture suggests a somewhat mysterious mountain, partly swathed in cloud, above the waters of Lake Pukaki, as if it had arisen like Venus from the sea. As indeed Aoraki Mt Cook did. Long ago the rocks which build Aoraki Mt Cook spread over the sea-floor from volcanoes and ancient lost lands, and then the sea-floor rose, and grew into mountains. Their history is recorded in stone, which make up the bones of the mountain, and this book, written especially for tourists and mountaineers, explores those bones, how they formed, grew and changed. To understand the bones is to help understand mountains. The overview is supported by more than 170 photographs and diagrams, together with detailed geological maps, covering the entire Park.

Bruce Waterhouse studied geology at Victoria University of Wellington (then University of New Zealand, Wellington), and after winning an overseas scholarship went on to a Ph.D. at Cambridge, England. Specialising in stratigraphy and paleontology, he worked at the New Zealand Geological Survey, then as a professor at the University of Toronto in Canada, and was head-hunted to be Dorothy Hill Professor of Stratigraphy and Paleontology at the University of Queensland in Brisbane. Author of more than thirty books and monographs, and several hundred scientific articles, he here offers the first detailed and widely illustrated overview of the make-up of the mountains in the Aoraki Mt Cook National Park.

ISBN 978-0-9864601-1-3-5

Printed by BRACKENSPRINT | Oamaru