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Source: Mountain Research and Development, 21(4) : 340-349

Published By: International Mountain Society

URL: https://doi.org/10.1659/0276-4741(2001)021[0340:GAGOTE]2.0.CO;2

Mountain Research and Development Vol 21 No 4 Nov 2001: 340–349

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A Comparison

The European Alps (Alps) and Southern Alps of New Zealand (Southern Alps) are both high mountain ranges formed by the collision of tectonic plates. The Alps resulted from collision of the African and European Plates, which produced complex lithological and structural patterns associated with the development of a series of overthrusted nappes. In contrast, the plate margin deformation that created the Southern Alps produced a relatively simple structural and lithological pattern dominated by a single right lateral oblique slip fault zone known as the Alpine Fault. Strong contrasts are also apparent in the contemporary rates of landscape development. The Alps currently experience modest rates of uplift and denudation because deformation along the plate boundary has slowed. High rates of compressional strain along the Alpine Fault in New Zealand result in very high rates of uplift. These processes and the position of the mountain range across the prevailing atmospheric westerly circulation system result in exceptionally high rates of denudation. Although there are strong contrasts in the lithology and structure of the Alps and Southern Alps, both experienced the growth and decay of expanded valley and piedmont glaciers during the Quaternary. The impact of multiple Quaternary ice advances has left a strong imprint on the landscapes. Both mountain ranges have particularly well-developed, over-deepened troughs and widespread glacial sediments and landforms, which heavily influence modern geomorphic processes and land use. Today numerous glaciers in both regions show strong reactions to global warming since the end of the Little Ice Age.

Keywords: *Orogeny; tectonics; glaciations; chronostratigraphy; landscape development; European Alps; Southern Alps; New Zealand.*

Peer reviewed: *July 2001.* ***Accepted:*** *August 2001.*

Introduction

The name Southern Alps belies the longstanding and frequent comparison of the mountain ranges of the South Island of New Zealand with the European Alps. Comparison of the 2 mountain ranges derives largely from similar geomorphology: They have similar relief, both have numerous glaciers, and the landscapes of both show the strong imprint of expanded glaciers during the Quaternary. This article seeks to understand the basis of similarities and differences by examining geology, tectonic development, the impacts of Quaternary climate change, and the current rates of landscape development.

The European Alps (Alps) are a mountain range almost 1000 km long, running from west to east between Genoa and Vienna (Figure 1a). Southeast of Genoa, they continue into the Apennines, east of the Vienna Basin into the Carpates, and southeast of Ljubljana into the Dinarids. The Alps emerged at the end of the Cretaceous and during the Tertiary. As a result of the collision of the African and European Plates, the Earth's crust thickened from an average of 30 km up to 60 km. The uplift and appearance of the Alps as a high mountain system are relatively recent phenomena, driven by isostatic compensation and an upward movement of the lighter continental crust (2.7 g/cm^3), which had been suppressed into the oceanic crust (3.0 g/cm^3). Due to strong tectonic compression, the western Alps are narrower (ca 150 km, along the Berne–Milan axis) and reach higher elevations (Mont Blanc, 4807 m; Figure 5a) than the Eastern Alps (ca 250 km along the Munich–Venice axis; Grossglockner, 3797 m). From the margins to the center, the topography of the Alps is more or less symmetric, with the highest mountain ranges in the central part. The steep relief and the elevation of the Alps high above the timber- and snowlines continue to favor intense and often catastrophic geomorphic processes. Together with increasing population density, these are the reasons for the high risk of natural hazards.

The South Island of New Zealand is dominated by the Southern Alps, which form an unbroken, 500-km-long mountain range from the inland Kaikoura Range to the mountains of Fiordland (Figure 1b). The central part of the range is 300 km long, 120 km wide, and has summits higher than 3000 m. Compared with the Alps, the Southern Alps of New Zealand are younger, have a sharper topographic expression, and are being shaped by forces of uplift and erosion of considerably greater magnitude. Like the Alps, the Southern Alps owe their origin to the collision of 2 tectonic plates. The main topographic expression of the Southern Alps was formed in Late Cenozoic times, as the Pacific Plate collided with the Indo-Australian Plate. Collision resulted in the leading edge of the Pacific Plate becoming upturned and rapidly uplifted. Rapid uplift along the plate boundary produced a mountain range with an asymmetrical cross-section with a steeper face on the western side, where peaks of 3000 m occur less than 40 km from the Tasman Sea. The topography on the eastern side of the Southern Alps is characterized by intermontane basins and broad alluvial plains that separate the highest peaks from the Pacific Ocean by more than 100 km.

Geology and tectonics

European Alps

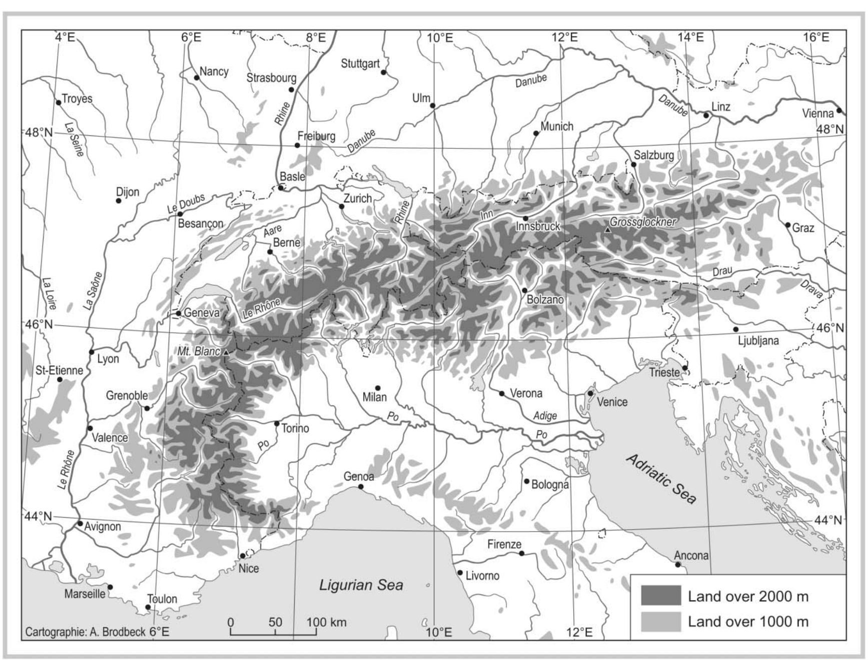
The Alps consist of parts of the European Plate, a former Jurassic to Lower Cretaceous ocean floor, and the Adria Plate as part of the African Plate. A complicated pattern of overthrusted nappes characterizes the tectonic style. As a general rule, tectonically higher nappes originate further south. If the pile of nappes were hypothetically rolled out, the result would be 4 main former facial areas—the Helvetic, Penninic, Eastern, and Southern Alpine (Figure 2a). Additionally, there are the autochthonous to parautochthonous, prealpidic crystalline Helvetic central massifs. Reconstruction of the tectonic evolution resulted in a compression of the former ocean (Tethys) in the order of 500–800 km or even more (Gwinner 1978; Tollmann 1986a; Pfiffner et al 1997). During the collision of the African Plate with the European continent, the western Alps were more heavily compressed than the eastern Alps. This had several consequences: The eastern Alps have the greatest diameter, whereas the highest peaks occur in the western Alps. Eastern Alpine nappes have been almost completely eroded in the western Alps.

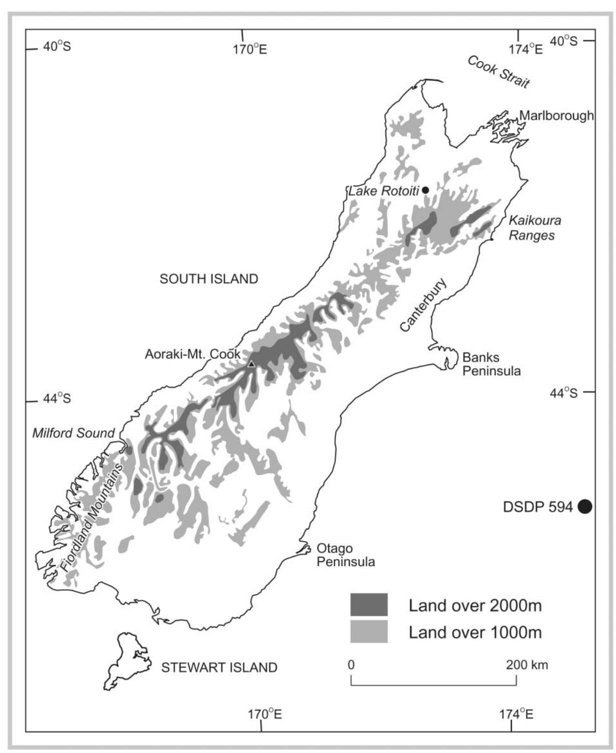
The oldest units belong to the Helvetic basement, including Precambric, Paleozoic, and Hercynian Orogenies. From the Triassic on, a shallow epicontinental ocean developed, accompanied by plate extension and the breakup of the "Pangaea continent," especially since Jurassic times. This was the origin of Tethys, the primeval Mediterranean Ocean. During the Middle Cretaceous, plate motions changed to compression (NE–SW-directed convergence) and subduction of the Penninic Ocean under the European Plate. This led to the eo-Alpine orogenic episode (80–90 million years BP), which was dominated by west–northwest-oriented thrusting and the evolution of an E–SE-dipping subduction zone (Pfiffner 1992). The second alpidic orogenesis occurred during the Upper Eocene and Oligocene, when the African and European Plates collided with N–S-directed plate motions. The Penninic Ocean disappeared at that time and the Alps as a whole began to be lifted above sea level. Tertiary intrusives evolved along the Periadriatic fault. The main uplift occurred during the Miocene/Pliocene (30 million years BP), but the regional uplift pattern is complicated.

Today, the western Alps of Switzerland and France are mainly characterized by Helvetic and Penninic nappes, which in the eastern Alps are only visible in the very northern part. The sediments of the Helvetic nappes were deposited on the European shelf during the Mesozoic and the Lower Tertiary. Therefore, limestones predominate, forming many famous peaks in the Alps. In the eastern Alps, Penninic nappes are extensively covered by Eastern Alpine units. There, Penninic units appear only occasionally in tectonic windows. The largest of these is the Tauern Window, which covers an area approximately 30 km × 160 km (Figure 2a). Schists and ophiolites (metamorphic remnants of the former oceanic crust) are typical rocks in the central part of the former Penninic Ocean. They characterize the suture between the African and European Plates.

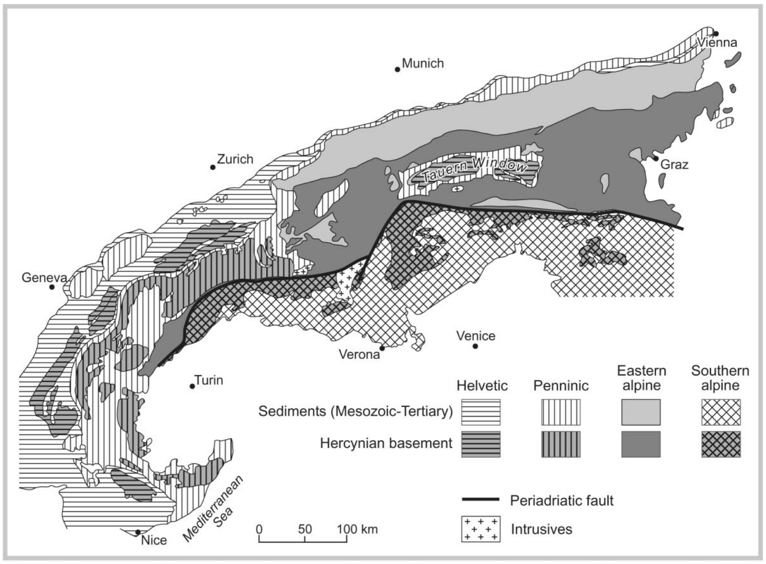
The Eastern Alpine nappes are part of the African Plate, overthrusted for more than 100 km onto the European continent. Due to intense erosion during the Tertiary, these Eastern Alpine units disappeared almost

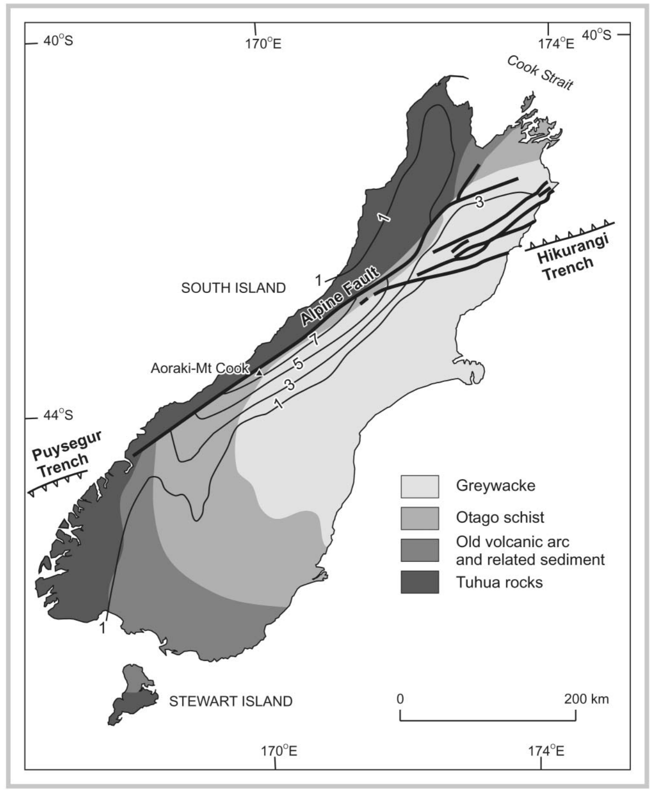
FIGURES 1A AND B (a) Relief map of the Alps (all maps for this article were drawn to the same scale). (Map by Andreas Brodbeck) (b) Location and relief maps of the Southern Alps. (Map by Bill Mooney)





FIGURES 2A AND B (a) Tectonic units of the Alps, based on Frisch (1982, modified). (b) Lithologic and tectonic structure of the Southern Alps, based on data from Kamp (1992). (Map by Bill Mooney)





completely from the western Alps. All the northern Permo-Mesozoic Calcareous Alps of Germany and Austria belong to the Eastern Alpine nappes. Crystalline rocks are more widespread in the central Alps.

The Southern Alpine units are separated from the Helvetic, Penninic, and Eastern Alpine units by a major fault zone (Periadriatic Fault). The deformation of the Southern Alpine units during the Alpine tectonics was minor. The sequence is characterized by a crystalline basement, overlain by Permian volcanic rocks and Mesozoic sediments. As a consequence of the strong uplift in the northern and northeastern part, the crystalline basement is exposed. Toward the south, the Mesozoic sediments (limestones and reef dolomites, alternating with volcano-detritic facies) form the characteristic relief of the Dolomites.

Some of the most famous massifs, such as the highest peak of the Alps (Mont Blanc, 4807 m) are built up of autochthonous to parautochthonous crystalline rocks. The above-mentioned nappes have been eroded more or less completely. These crystalline massifs are prealpidic and form part of the Hercynian European basement.

Southern Alps

Like the European Alps, the South Island of New Zealand comprises a mosaic of geological terrains. Three major tectonic regimes that can be deciphered are the Tuhua Orogeny (Devonian and Carboniferous), the Rangitata Orogeny (Cretaceous), and the Kaikoura Orogeny (Cenozoic to present). The oldest rocks date to some 680 million years BP, when New Zealand was attached to Gondwanaland. These rocks were deformed and uplifted by the Tuhua Orogeny, which produced severe folding and faulting and plutonic intrusions. In the 200 million years following the Tuhua Orogeny, the New Zealand Geosyncline developed and filled. This time was characterized by the formation of an island arc system and deposition of enormous thicknesses of sandstones that later became the greywacke of the axial part of the Southern Alps. Deposition in the New Zealand Geosyncline was ended by the Rangitata Orogeny, which peaked about 130 million years BP and produced a new land area. By 80 million years BP, the land area known as the late Cretaceous Peneplain had broken away from Gondwanaland, as had Australia and Antarctica. Subsequently, most of what was to become New Zealand was below sea level and a series of early to middle Tertiary sediments accumulated. In the South Island, much of this sediment has been removed by the combined effects of uplift and erosion associated with the most recent phase of deformation known as the Kaikoura Orogeny. By 26 million years BP, the boundary between the Pacific and Indo-Australian Plates ran through New Zealand. Convergence and strike slip motion along this boundary initiated large-scale deformation of the Kaikoura Orogeny.

Compared with the previous orogenies, deformation associated with the Kaikoura Orogeny is relatively simple. The current structural setting is a continental–continental transpressional transform boundary between the Indo-Australian and Pacific Plates (Bull and Cooper 1986; Kamp and Tippett 1993; Bull 1996). In the center of the Southern Alps where the South Island is narrowest, a single right lateral, oblique slip fault zone called the Alpine Fault bounds the western edge of the mountains (Figure 2b). The Alpine Fault marks a 500-km-long discontinuity in the South Island that runs from Milford Sound in the south to Lake Rotoiti in the north. Oblique plate convergence in the central segment of the Southern Alps results in uplift in the order of 5–8 mm/y. The topographic expression of the 3000-m mountains in this location reflects only a small part of the total uplift, which is thought to be of the order of 15–20 km (Kamp et al 1989). The modest topographic expression, together with the relatively youthful development of the boundary, implies enormous erosion rates, which are discussed below.

North of the central segment, the Alpine Fault splays into numerous faults that strike through north Canterbury and Marlborough. The fault crosses Cook Strait and extends through Wellington on the North Island of New Zealand, on the frontal ridge zone of a subduction zone formed as the Pacific Plate descends beneath the Indo-Australian Plate. The offshore extension of the plate boundary is marked by the Hikurangi Trench. Inshore, the subduction zone is marked by an active volcanic arc on the North Island that extends from Mount Ruapehu at the southwest end to White Island in the northeast.

In the south, the Alpine Fault crosses the coast and extends offshore close to Milford Sound. The offshore extension of the fault is marked by the Puysegur Trench where the Indo-Australian Plate is being subducted beneath the Pacific Plate (Figure 2b).

Three models of the development of the Southern Alps have been proposed: the dynamic cuesta model of Adams (1980), the numerical model of Koons (1989), and the evolutionary model of Tippett and Kamp (1995). The dynamic cuesta model of Adams (1980) used uplift data from deformed surfaces of known age to calculate rock uplift rates between 2 and 12 mm/y at the Alpine Fault and 0.5–2.0 mm/y east of the main divide. The model presents the evolution of the Southern Alps with time and distance from east to west as the evolution of rising flat-topped mountains that evolve into spiky-topped mountains as they are moved toward the plate boundary and eroded. Adams argued that the Southern Alps resemble a cuesta, which is dynamically renewed by uplift, and that, because the rate of rock uplift appeared to be in balance with river sediment loads, the relief of the Southern Alps is in a dynamic steady state.

Koons' (1989) one-dimensional numerical model of the development of the Southern Alps modeled the simultaneous uplift and erosion of the Southern Alps using a diffusion equation. The model was run with an uplift rate of 10 mm/y adjacent to the Alpine Fault and decreasing linearly away from the fault. The model predicted that a near steady-state elevation would be reached within 0.25–0.5 million years.

Tippett and Kamp (1995) found that both models were unrealistic and developed an evolutionary model based on new fission-track data from basement rocks. The model suggested that the earliest indications of mean surface uplift date to 4–5 million years BP. Three uplift domains were identified: a high uplift rate domain (8–10 mm/y) that extends southeastward from the Alpine Fault to just east of the main divide; a 0.8–1.0 mm/y domain along the southeast margin of the mountains; and a domain of no uplift east of the mountains. Tippett and Kamp argued that the mountains east of the main divide have continued to increase in elevation and relief since the start of uplift and that the altitude and form of the mountains are related to the age of initiation of uplift and the amount of uplift.

Tertiary landscape development

European Alps

Besides steep valley slopes, the Alps are characterized by relatively flat surfaces at higher elevations, especially in the alpine altitudinal belt. Steep areas are frequent in the subalpine and montane belts as well as above the snowline. The relatively flat areas are remnants from the Tertiary, which developed under tropical to subtropical climates during periods of slight tectonic activity. Up to the Miocene, the Alps appeared as an undulating planation surface with inselbergs. This planation ceased due to the strong uplift since the Upper Miocene, and morphodynamics changed to valley incision. The plain surfaces may be divided into several generations at different altitudes. But despite the wide occurrence of these plains, it is impossible to correlate them across the Alps because tectonic movements have been too varied. Correlations with Tertiary sediments in the northern and southern molasse basins permit estimations of the age of the plains (Tollmann 1986b).

The oldest preserved planation surface probably dates from the Miocene ("Raxlandschaft"; Lichtenecker 1926). It is especially well preserved in karstic limestone areas. A previously existing older plain ("Augensteinlandschaft," probably Oligocene in age; Lichtenecker 1926) is not preserved at all but documented by crystalline pebbles lying on the northern limestone Alps. These sediments are derived from the central crystalline Alps, which were not disconnected from the limestone Alps by deep valleys, as they are today. During the Upper Tertiary, the tectonic uplift of the Alps increased, leading to river incision. Before this period, the drainage pattern was radial, from the central Alps to the foreland. From the Upper Tertiary on, longitudinal valleys developed, underlining the geologic-tectonic

TABLE 1 Late Cenozoic glaciations of the Alps and Southern Alps.

Million years BP	Southern Alps (Suggate 1990)	Alps: Bavaria (Doppler and Jerz 1995)	Alps: Baden-Württemberg (Ellwanger et al. 1995)	Alps: Switzerland (Schlüchter and Kelly 2000)
	Otira Waimea Waimaunga Nemona	Würm	Würm	Ultimate glaciations
		Riss	Riss	Penultimate glaciation
				Extensive glaciation
0.5		Mindel Haslach Günz		Extensive glaciation
				Most extensive glaciation
1.0		Donau Biber	Mindel Haslach Günz	
1.5	Porika		Donau Biber	9 glaciations
2.0				
2.5	Ross			

structures such as the fault zones and contact zones of different nappes. Therefore, longitudinal valleys frequently underline petrographical limits.

Today the continuing isostatic uplift reaches values up to 1–2 mm/y. Although destructive earthquakes have been known from historical times, they are not very frequent. The strongest recorded earthquake in Austria (with a magnitude of 10 on a scale of 12) occurred in 1348 AD. In Switzerland, 18 earthquakes with magnitudes of 8 or greater were recorded between 1000 and 1975 AD (Labhart 1995).

Southern Alps

Because most of the uplift in the Southern Alps has occurred since the Pliocene, there is little evidence of Tertiary landscape development in these mountains. The main exceptions are fragments of the Pliocene Ross Glaciation sediments in Westland (Fitzsimons et al 1996) and the Porika Glaciation in Nelson (Suggate 1990). However, east of the mountains, there are widespread Tertiary marine sediments deposited during a middle Tertiary marine transgression and volcanoes that have not been active since the Miocene. The largest of these extinct volcanoes are the Otago Peninsula near Dunedin and Banks Peninsula near Christchurch.

Quaternary landscape development

European Alps

In the Alps today, glaciers cover an area of about 3000 km^2, or ca 2–3% of the surface. Glacier equilibrium lines rise from 2400 m at the northern and southern margins to 3400 m in the central Alps. Several intense glaciations, with snowline depressions of more than 1000 m and glaciers reaching the alpine foreland, have been documented. The classic scheme of Penck and Brückner (1909), comprising Günz, Mindel, Riss, and Würm glaciations, has to be refined, as the older glaciations, at least, consist of several glacial–interglacial complexes (eg, Habbe 1989; Schlüchter 1992; Jerz 1993). During the Würm glaciations, the glaciers of the Alps advanced into the foreland twice. Up to now, it has been difficult, if not impossible, to correlate the older glaciations of the European Alps and the Southern Alps (Table 1). It is not even possible for the Alps alone, due to the lack of absolute dating and chronostratigraphic problems.

The typical alpine relief, with U-shaped valleys, hanging valleys, and steep mountain peaks, is a consequence of the Quaternary glaciations. Glacial erosion is also well documented by an overdeepening of the valley floors. Solid rock as the base of the Quaternary fillings is often situated at or some hundred meters below sea level. This has important impacts on groundwater flow and tunnel construction.

During the Last Glacial Maximum (LGM), the ice-covered area of the Alps increased to 126,000 km^2 (Figure 3a). Especially in the western and northern Alps, the glaciers reached well into the forelands, reflecting temperature depressions around 15°C and dry conditions with 70–80% less annual precipitation than today (Haeberli and Penz 1985). After 14,000 ^{14}C years BP, glaciers started to melt rapidly. A prominent readvance occurred during the Younger Dryas period (Egesen stade, 11,000–10,000 ^{14}C years BP), but already in the early Holocene, snowlines and treelines reached modern altitudes.

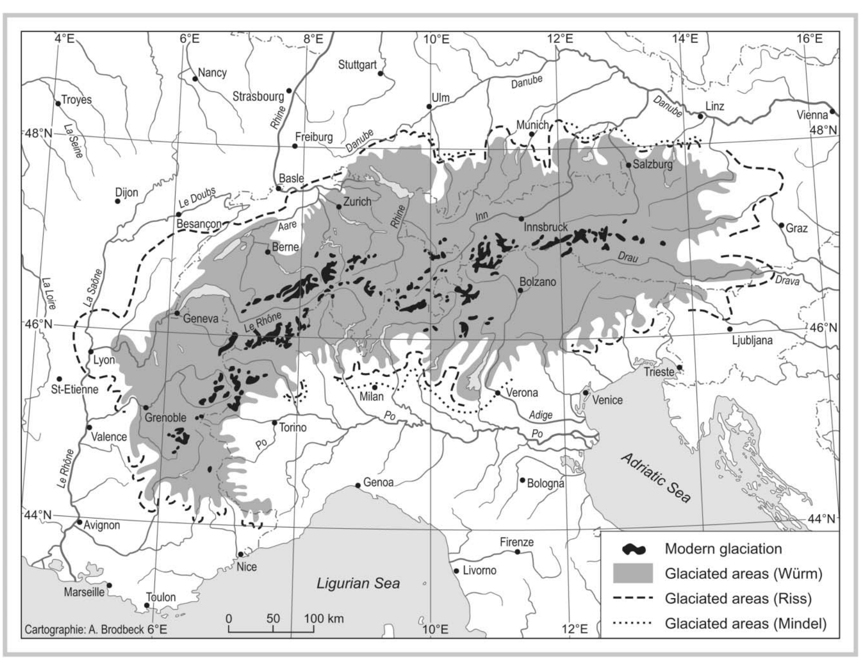
At the end of the last glaciation (Würm), the oversteepened and almost vegetation-free slopes led to widespread mass movements. Besides till and fluvioglacial sediments, the valleys are therefore characterized by rockfalls and debris cones. The largest rockfalls occurred in the limestone areas, such as the Flimser Rockfall in Switzerland, which is the largest one in the Alps (12 km^3; Abele 1974). Up to now, the Rhine River has cut a 600-m-deep canyon into these probably late-glacial deposits. In the crystalline areas, rockfalls are smaller, the largest being the Early Holocene Köfels Rockfall in Austria (2 km^3). Many rockfalls initiated debris flow and catastrophic floods.

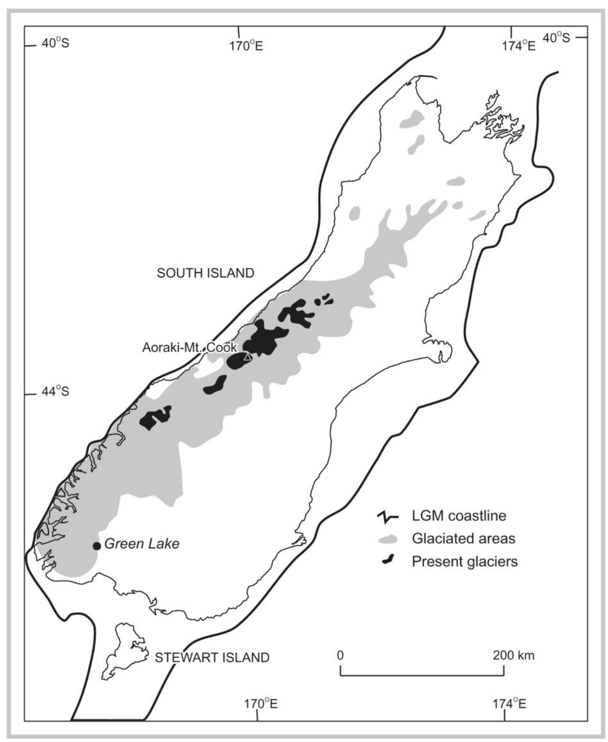
During the Holocene, 8–9 prominent glacier advances took place, reflecting altitudinal variations in the glacier equilibrium lines in the order of ±100 m (Patzelt and Bortenschlager 1973; Maisch et al 2000), accompanied by variations in treeline of the same magnitude. The last high stand occurred around 1850 AD at the end of the Little Ice Age. Since then, the ice volume of the glaciers has diminished in the order of 50%, mainly due to atmospheric warming. This corresponds to a 30–40% decrease in the glacierized area. This, together with warming of the permafrost and an accompanying rise in the elevation of the lower permafrost limit, might lead to increased instability of the slopes and accelerated activity of debris flows in the future (Haeberli et al 1997). Aside from glaciers and treelines, a relatively warm Holocene Climatic Optimum between 8000 and 5000 ^{14}C years BP is represented by well-developed soils and reduced periglacial activity above the treeline (Gamper 1981; Steinmann 1978; Veit 1993; Veit and Höfner 1993).

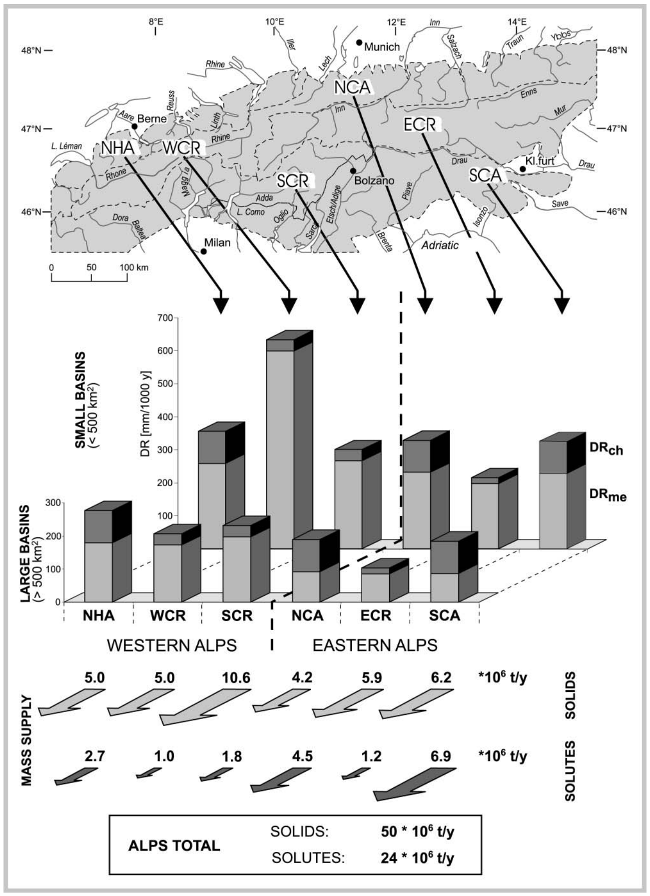
Southern Alps

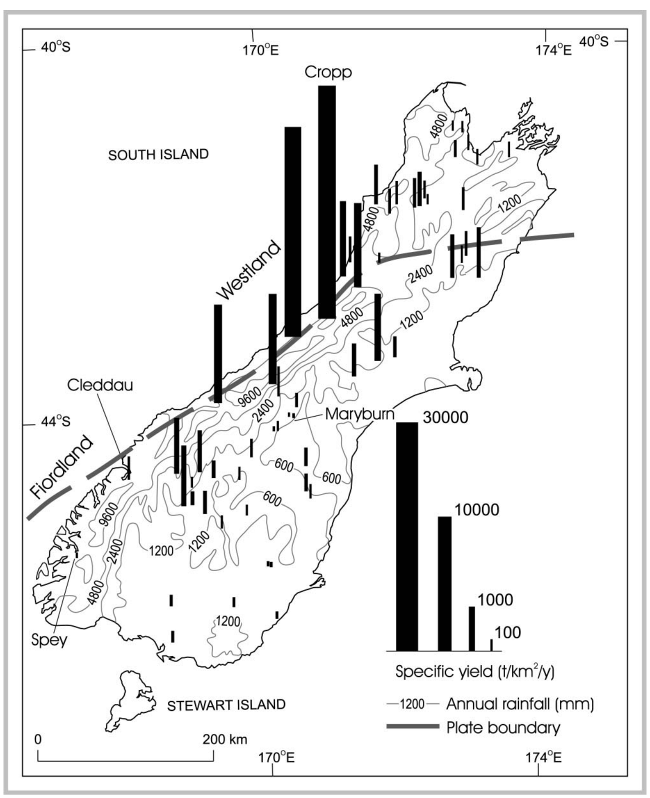
Examination of the landscape of the Southern Alps demonstrates that the mountains have experienced multiple glaciation recorded by the large glacially eroded troughs and multiple belts of lateral and end moraines that lie well beyond the present glaciers. Today the regional snowline lies between about 1500 m in the southwest and about 1900 m in the central South Island, and over 3000 glaciers have been identified (Chinn 1989). The glaciers cover about 116 km^2, which is about 5% of the land area of the South Island. During the Pleistocene, a large, complex glacier system consisting of expanded valley and piedmont glaciers extended 700 km along the Southern Alps (Figure 3b) and averaged 100 km in width (New Zealand Geological Survey 1973). The longest continuous record of glaciation in the Southern Alps comes from a core drilled from the sea floor about 300 km off the east coast of the South Island. This site, known as Deep Sea Drilling Programme (DSDP) site 594, consists of alternating layers of pelagic sediment derived from free-swimming marine organisms and hemipelagic deposits that consist in part

FIGURES 3A AND B (a) Pleistocene glaciation of the Alps, based on Glückert (1987) and Lister et al (1998). (Map by Andreas Brodbeck) (b) Geological survey (New Zealand Geological Survey 1973). (Map by Bill Mooney)









of sediments derived from the Southern Alps (Nelson et al 1985). Analysis of the top 100 m of the core has yielded an apparently uninterrupted record of sedimentation that records 12 major periods of alpine glaciation over the last 730,000 years. In contrast, only 6 major periods of ice advance can be recognized in the terrestrial record of glaciation of the Southern Alps. The 2 oldest reconstructed ice advances (the Ross and Porika glaciations), known from evidence in south Westland and Nelson, are thought to have occurred in the late Pliocene. The next 4 glaciations (the Nemona, Waimaunga, Waimea, and Otira glaciations) occurred in the middle and late Pleistocene and are best known in north Westland (Suggate 1990). Comparison of the terrestrial model of glaciation with information from DSDP 594 suggests that the 1.75-million-year gap between the late Pliocene and middle Pleistocene glaciations is an indication that much of the terrestrial evidence of glaciation is missing. This gap in the record has been attributed to the combined effects of uplift of the Southern Alps and erosion. However, recent applications of uranium series and paleomagnetic dating have suggested that at least some of the deposits thought to be middle Pleistocene in age are much older. Thus, they are likely to lie within the period that constitutes this gap in the terrestrial record (McSaveney et al 1992; Fitzsimons et al 1996).

There is widespread evidence of numerous ice advances since the LGM, including deposits thought to correlate with the Younger Dryas event in Europe. The chronology of the post-LGM events has been reviewed by Fitzsimons (1997).

As well as resulting in uplift, the interactions of the Pacific and Indo-Australian Plates cause earthquakes. One outcome of large earthquakes is the triggering of rockfalls and landslides, which are widespread throughout the Southern Alps. The distribution of coseismic landslides has been used to estimate the timing and intensity of prehistoric earthquakes. Using the growth of lichens on rock debris from 3 events, Bull (1996) suggested that the Cook segment of the Alpine Fault ruptures regularly about every 260 years. The last event occurred in 1748 ±10 AD.

The largest documented subaerial landslide on earth is the Green Lake Landslide, which occurred on the southern end of the Hunter Mountains in Fiordland about 13,000 years ago. This landslide has an area of 45 km^2 and involved the movement of about 27 km^3

FIGURES 4A AND B (a) Modern chemical (DR_{ch}) and mechanical (DR_{me}) denudation rates for different morphotectonic zones of the Alps (based on Hinderer 1999). NHA, Northern Helvetian Alps; NCA, Northern Calcareous Alps; WCR, Western Crystalline Alps; SCR, Southern Crystalline Alps; ECR, Eastern Crystalline Alps; SCA, Southern Calcareous Alps including subordinate outcrops of the crystalline and Palaeozoic basement of the South-Alpine zone, which is mainly covered by Triassic carbonates. (b) Modern sediment yields for South Island catchments, based on Hicks et al (1996). (Map from Hick et al, 1996) of material from the collapse of a 9-km section on a 1500-m-high ridge (Hancox and Perrin 1994). The material moved 2.5 km laterally and 700 m vertically into a deep glacial trough where an 800-m-high dam was formed. The failure was thought to have been triggered by a large (>M 7.5) earthquake.

On the eastern side of the Southern Alps, the lower parts of several glaciers are debris-covered because rock avalanches from the valley sides deposit large quantities of debris on the glaciers (Figure 5b). A good example of this process was provided by the debris avalanche that occurred on the northern face of Aoraki-Mount Cook on 14 December 1991. The rock avalanche involved approximately 14 million m^3 of rock that flowed across Tasman Glacier and up to 70 m above the glacier on the opposite wall of the valley (Chinn et al 1992).

FIGURES 5A AND B (a) Mont Blanc (4807 m), the highest peak in the European Alps with the Glacier des Bossons near Chamonix. The glacier retreat from the recent moraines of the 19th century is clearly visible. Geologically, Mont Blanc belongs to the prealpidic crystalline Hercynian basement. The peak at the left is the Aiguille du Midi (3842 m), accessible by cable car. For location, see Figure 1. (Photo by Heinz Veit, 18 July 2000). (b) The highest peak in the Southern Alps is Aoraki/Mount Cook (3754 m). Also shown is Tasman Glacier, which is covered with rock avalanche debris from the Mount Cook Range. The lake at the terminus of Tasman Glacier has developed as the ice has retreated from the late 19th century position at the present day source of the Tasman River. (Photo by Trevor Chinn, 1998)

Contemporary landscape development

The calculation of modern denudation rates for a whole mountain range is complicated. Most data come from small catchments and experiment plots. On the other hand, modern suspended loads and bedloads of large rivers may be affected by human impact and upstream sediment storage. In addition, contemporaneous monitoring of solid and dissolved load is rarely undertaken.

European Alps

Based on studies of sediment yields in rivers and sediment budgets in reservoirs of various size, Hinderer (1999, 2001) estimates mechanical denudation rates between 100–650 mm/ky for different morphotectonic zones of the Alps (Figure 4a). The highest rates are observed in the Western Crystalline Alps (WCR), whereas the Northern Calcareous Alps (NCA) exhibit the lowest rates. Specific sediment yield of large catchments is less than half of that from small catchments, implying important intermittent storage of sediments in pediments and floodplains. Hence, denudation rates calculated from the sediment load of large rivers do not represent effective denudation rates in the headstream areas. Based on the sediment export of large rivers, the modern area-weighted mean denudation rate of the Alps is about 0.125 mm/y, which corresponds to a mass export of 50 million t/y. Dissolved load accounts for an additional mass export of 24 million t/y, ie, one third of the total load. Due to different calculation methods, the denudation rates in Figure 4a are not directly compatible with the specific sediment yields of the Southern Alps (Figure 4b).

Southern Alps

The Southern Alps of New Zealand form a southwest–northeast trending barrier that lies across the prevailing westerly circulation in the middle latitudes of the Pacific Ocean. Orographic uplift of the maritime winds results in extremely high precipitation on the west coast and a steep precipitation gradient into the rainshadow areas to the east of the main divide. The maximum precipitation falls in a zone parallel to the first range a few kilometers west of the main divide and peaks at around 12,000 mm/y (Griffiths and McSaveney 1983). Within 10 km east of the main divide, the precipitation falls to less than 300 mm/y. The interaction of the tectonic setting and the westerly circulation has an important impact on landscape development (Whitehouse 1988).

In New Zealand, there has been considerable debate about the controls of contemporary erosion processes, and several studies have suggested that rainfall is the major control on denudation rates. In a study of South Island catchments, Griffiths (1979, 1981) concluded that rivers draining the western Southern Alps have suspended sediment yields that are about 10 times higher than world average rates for mountainous areas. He suggested that almost all the variations in sediment yield are explained by variations in mean annual rainfall. In another study, Adams (1980) argued that lithology, tectonic uplift rates, and Quaternary geomorphological history including glaciation were also important controls on sediment yields. In yet another study, Pickrill (1993) examined sediments that have accumulated in fiords and suggested that sediment yields ranged from 28 to 209 t/km^2/y, in comparison with Griffiths' figure of 13,300 t/km^2/y for the Cleddau River, which flows into Milford Sound. More recently, Hicks et al (1996) examined a larger, updated data set for 203 New Zealand catchments and found that average annual sediment yields vary over 4 orders of magnitude, from less than 20 t/km^2/y to almost 30,000 t/km^2/y (Figure 4b). This study concluded that the main controls on sediment yield are mean annual rainfall and basin geology, which includes lithology, the level of tectonic activity, and the Quaternary history of the catchment. The high sediment yields from the west coast are a consequence of the combined effects of the high mountains and the high orographic precipitation produced by the interaction of the mountains with the prevailing westerly airstream (Whitehouse 1988).

Whitehouse (1988) suggested that 3 geomorphological regions can be identified in the Southern Alps on the basis of distinct landform assemblages and erosion processes. These regions are the western Southern Alps, which are characterized by extremely steep, intensely dissected slopes formed by fluvial erosion and debris avalanches; the axial Southern Alps, which are dominated by high glaciated mountains; and the eastern Southern Alps, which can be divided into a basin and range subregion and an eastern front range subregion. The basin and range subregion consists of moderately dissected, scree-covered ranges separated by large valleys with braided rivers, while the eastern front ranges subregion consists of dissected greywacke mountains with rounded ridge crests and V-shaped valleys. Identification of these geomorphological regions recognizes that the form of the land surface is an expression of the endogenic and exogenic processes that currently operate and the processes that have operated in the recent geological past.

Conclusions

Both the Alps and Southern Alps are high mountain areas that are products of plate collisions. Both mountain ranges have high relief, and their landscapes have been imprinted by multiple glaciation during the Quaternary. However, the similarities are to a large extent superficial. The geological and structural evolution of the mountains, together with rates of uplift and denudation, are quite distinct.

Although both mountain ranges are the product of plate collisions, the Alps are structurally and lithologically considerably more complex than the Southern Alps. The structural and lithologic complexity is a consequence of the mosaic of terrains that were deformed together as parts of the European Plate, an ocean floor, and part of the African Plate collided and produced a series of overthrust nappes. The relative structural and lithologic simplicity of the Southern Alps is a consequence of the linear nature of the boundary between the Pacific and Indo-Australian Plates and the youth of the orogeny. It is also due to the fact that the vast bulk of the deformed rocks are derived from a single source—the New Zealand Geosyncline.

The current uplift rates in the Alps are in the order of 1–2 mm/y, whereas the Southern Alps experience rates at a greater order of magnitude because the strain across the Pacific and Indo-Australian Plate boundaries is very high. The high uplift rates in the Southern Alps appear to be matched by similarly high denudation rates. The high denudation rates are a consequence of the maritime location of the Southern Alps and their geometrical relationship to a westerly dominated atmospheric circulation system that gives rise to very high orographic precipitation. The high precipitation in parts of the Southern Alps together with the high relief, deformed rocks, and seismically active environment combine to produce rates of denudation that peak several orders of magnitude higher than those experienced in the Alps.

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