Chapter 2
The Southern Alps

New Zealand's Southern Alps superficially appear especially suited for the investigation of predisposing debris flow controls. The steep topography, extensive regolith reservoirs, and relatively frequent high intensity rainfall events create an ideal environment for debris flow development. Debris flow tracks are common features throughout the Southern Alps, and, in view of documented high regolith production rates, activity levels are expected to be high. This chapter provides a general introduction to the Southern Alps. The following sections briefly outline the geography, geology, climate, and geomorphology of the Southern Alps. The focus of this chapter is the Southern Alps in general; a detailed description of the individual debris flow study areas follows in Chap. 3.

2.1 Geography

The Southern Alps are an elongated, southwest-trending mountain chain on New Zealand's South Island (hatched area, Fig. 2.1, Inset a). The mountain belt, created by the oblique collision of the Pacific and Australian plates, is approximately 800 km long, 60 km wide and consists of a series of ranges and basins (Barrell et al. 2011). Its sharp northwest margin is formed by the escarpment of the Alpine Fault. Severe earthquakes occur on the Alpine Fault and its associated faults approximately every 100–300 years (e.g. Cowan and McGlone 1991; Sutherland et al. 2007; Berryman et al. 2012). The Southern Alps' drainage divide, referred to as the Main Divide, runs parallel to and approximately 20 km southeast of the Alpine Fault. Many mountains along the Main Divide rise above 2500 m a.s.l. and 23 peaks exceed 3000 m a.s.l., including New Zealand's highest Mountain, Aoraki/Mt Cook (3724 m) (Dennis 2012; Sirguey 2014). The Southern Alps are sparsely populated and have limited economic development. Only three mountain road passes connect the eastern foreland with its western counterpart.

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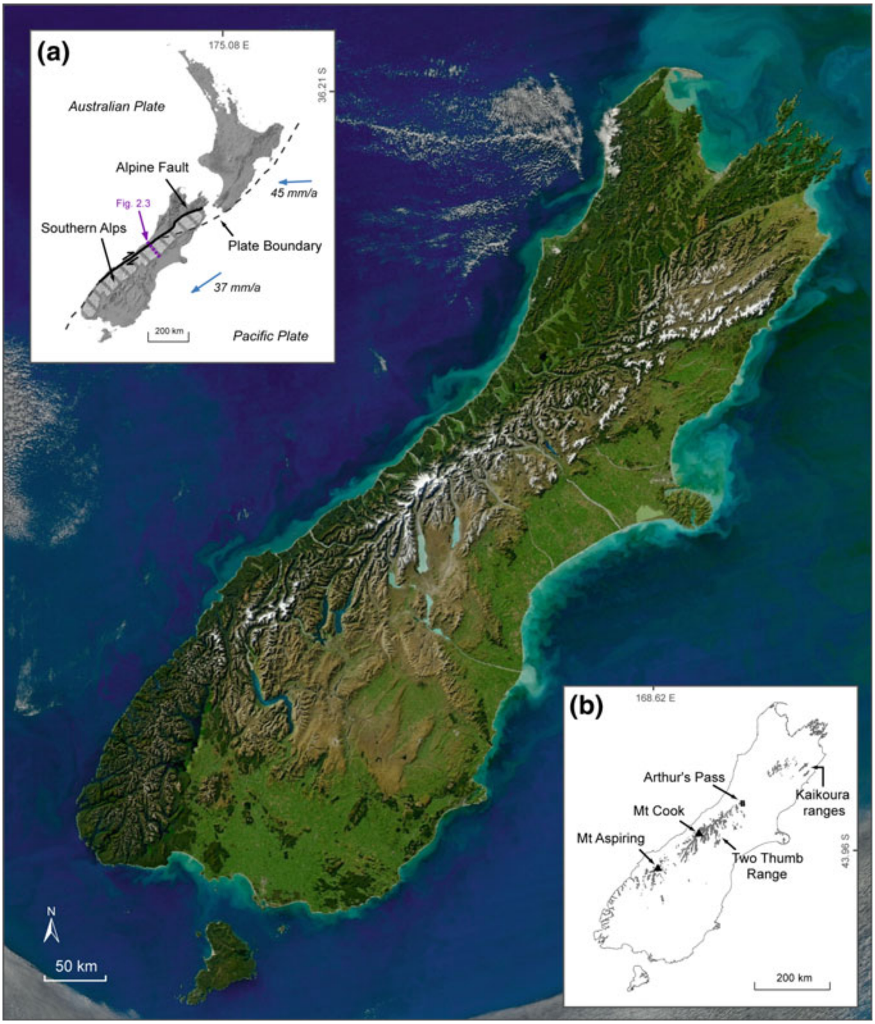

Fig. 2.1 New Zealand's Southern Alps from space, captured by NASA's Aqua satellite on 29/04/2011 (N. Kuring, NASA Earth Observatory; sourced from: http://eoimages.gsfc.nasa.gov/images). **Inset a** Tectonic setting of New Zealand (adapted from McColl 2012). *Blue arrows* indicate inferred inter-plate velocities during the last three million years (cf. Norris and Cooper 2001). The *dashed purple line* marks the approximate location of the transect depicted in Fig. 2.3. Background: Hillshade of a 25 m DEM (Barringer et al. 2002). **Inset b** Approximate area above 2000 m elevation, illustrating the distribution of high-alpine areas in the Southern Alps. Elevation data: 25 m DEM (Barringer et al. 2002)

The extent of the Southern Alps has not been officially defined. In this thesis, the geographic name refers to all South Island mountain ranges related to the orogen along the continental plate boundary, including the Kaikoura ranges in the north (see Fig. 2.1, Inset b). The following sections briefly summarise geologic (Sect. 2.2), climatologic (Sect. 2.3) and geomorphologic characteristics (Sect. 2.4) of the Southern Alps.

2.2 Geology

The geology of the Southern Alps is dominated by well-indurated sedimentary rocks and their metamorphosed equivalents. The northern and central Southern Alps are comprised of hard quartzo-feldspatic sandstones (greywacke) and mud-stones (argillite) of the Torlesse Composite terrane (Fig. 2.2), which are derived from submarine sediments eroded from the ancient Gondwana continent (Coates 2002; Mortimer 2004). This geologic terrane, stratified by age into Rakaia (Older Torlesse) and Pahau (Younger Torlesse), is the largest by area and lithologically fairly monotonous. Towards the Main Divide, the sedimentary rocks are progres-sively replaced by schist (Haast Schist) of increasing metamorphic grade, with the highest-grade metamorphic rocks exposed in the vicinity of the Alpine Fault (Coates 2002; Cox and Barrell 2007). Metamorphic rocks can also be found towards the south, in the Otago Region, where Otago Schist occurs at the contact of

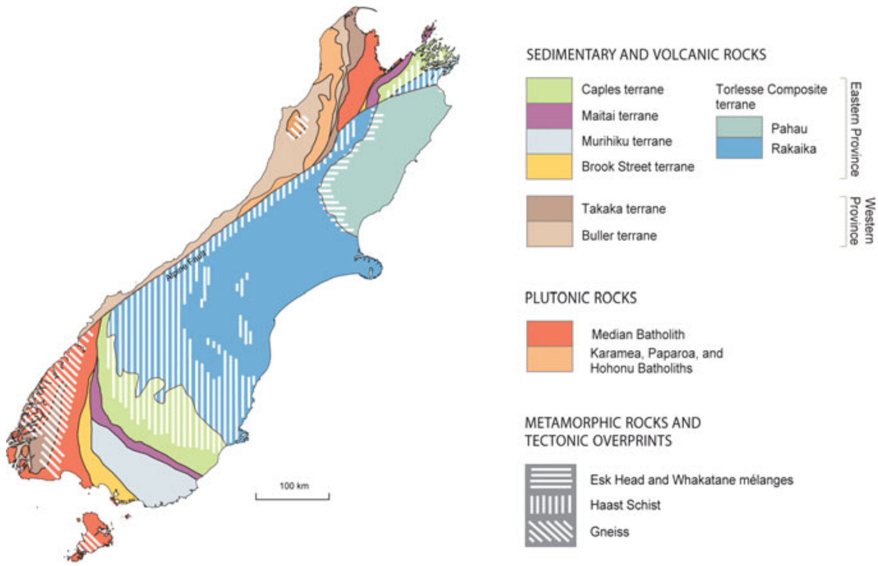

Fig. 2.2 Simplified basement geology of New Zealand's South Island (Adapted from Cox and Barrell 2007, p. 4, after Mortimer 2004)

the Rakaia terrane with the volcaniclastic rocks of the Caples terrane (Mortimer 2004). The southern-most ranges of the Southern Alps, the Fiordland Mountains, comprise plutonic rocks associated with the ancient Gondwana continent, including granites, diorites and orthogneisses (Turnbull et al. 2010).

2.3 Climate

The Southern Alps form a topographic barrier for the prevailing, moisture-laden westerly winds, creating a strong orographic precipitation regime with a steep negative rainfall gradient towards the east (Fig. 2.3). Annual precipitation is highest on the western flank near the Main Divide (up to 14 m a^{-1}, Henderson and Thompson 1999). Significant rainfall is also recorded immediately east of the Main

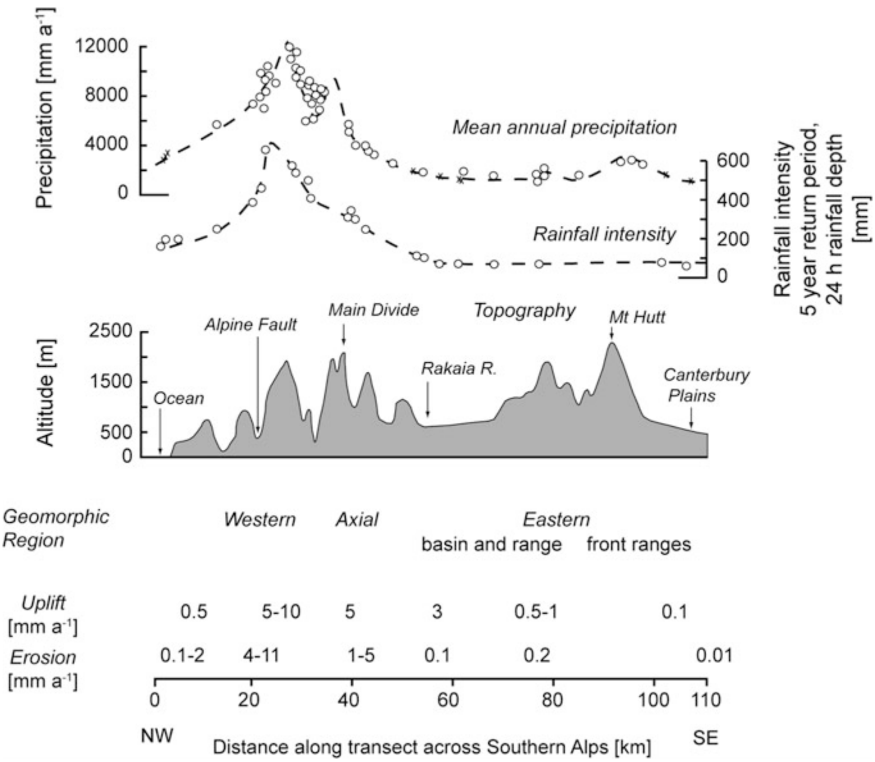

Fig. 2.3 Transect across the Southern Alps (Adapted from Whitehouse 1988, p. 107, based on mean annual precipitation from Griffiths and McSaveney 1983, rainfall intensity from Whitehouse 1985, uplift rates from Wellman 1979, and erosion rates calculated from the relationship between sediment yield and rainfall in Griffiths 1981). The approximate location of the transect is marked as a *purple dashed line* in Fig. 2.1, Inset a

Divide due to orographic spillover (cf. Sinclair et al. 1997; Chater and Sturman 1998). Further eastwards, rainfall totals drop progressively to less than 1000 mm on the eastern plains and in the drier inland mountain basins (Griffiths and McSaveney 1983). The proportion of snow increases with elevation. Persistent winter snow cover forms above 1200–1500 m; permanent surface ice exists in shaded locations above 1600 m west and above 2200 m east of the Main Divide (cf. Chinn 1995; Barrell et al. 2011). The modern glacial equilibrium line altitude in the Inland Kaikoura Range lies at about 2500 m (Chinn 1995; Bacon et al. 2001). Overall, more than 3000 glaciers larger than 1 ha, covering approximately 1150 km^2, were mapped in the Southern Alps from aerial photographs taken 1978 (Chinn 2001). However, many of these have been retreating or thinning since that time (Chinn et al. 2012). Annual to multi-annual climatic variations in the Southern Alps are influenced by large-scale atmospheric circulation variations associated with the El Niño—Southern Oscillation (ENSO) phenomena (Sturman and Wanner 2001; Mullan et al. 2008). Related change in the dominant wind direction causes variations in the movement of synoptic weather systems across the region. Enhanced south-westerly air flow in El Niño years leads to higher than normal precipitation and cooler air temperatures in the Southern Alps. Conversely, in La Niña years, the predominant wind direction changes to north-east, leading to generally warmer conditions, increased precipitation in the north-eastern Alps, and less rainfall in the southern and western ranges (Salinger and Mullan 1999; Lorrey et al. 2007). The Interdecadal Pacific Oscillation (IPO) is thought to modulate ENSO-related climate variability on an interdecadal scale, leading to more frequent and more prolonged El Niño events during its positive phase and vice versa (Salinger et al. 2001). During the most recent positive phase (1977–1999) several major El Niño events occurred in comparatively short succession, including the exceptionally strong 1997/1998 event (Mullan et al. 2008). The Southern Annular Mode (SAM) influences the Southern Alps on a shorter time scale of several weeks (e.g. Renwick and Thompson 2006). The SAM is a ring of pressure anomalies centred over the South Pole that produces alternating meridional shifts in the subpolar westerly winds. In a positive phase, the westerly zone is displaced towards higher latitudes (50°–70°), resulting in calmer and more settled weather over New Zealand, including warmer temperatures and less rainfall in the Southern Alps (Renwick and Thompson 2006). In a negative phase, the belt of westerly winds moves over New Zealand, resulting in lower temperatures and increased rainfall for the Southern Alps.

New Zealand's high natural climatic variability partly obscures signals of ongoing global climate change. However, continuous temperature records since the late 1800s indicate that mean temperatures have increased in the 0.7 °C since the 1940s (e.g. Salinger and Mullan 1999; Mullan et al. 2001). There is reasonable statistical evidence that global warming is already causing a rise in mean temperatures in New Zealand (e.g. Dean and Stott 2009). Furthermore, an increase in positive phases of SAM since the 1940s has been linked to increased greenhouse gas levels and ozone depletion (e.g. Arblaster and Meehl 2006; Abram et al. 2014), likely contributing to the positive temperature trend observed in New Zealand. Future projections estimate an increase in temperature of about 2 °C from 1990 to 2090 (Mullan et al. 2008). The warmer atmosphere will be able to hold more moisture. A projected general increase in annual precipitation in the Southern Alps (up to 12 % from 1990 to 2090) will thus be likely accompanied by a significant increase in frequency and magnitude of heavy rainfall events (Mullan et al. 2008).

2.4 Geomorphology

The topography of the Southern Alps is the expression of modern tectonic uplift, high orographic precipitation, and past glaciations (cf. Whitehouse 1988; Whitehouse and Pearce 1992; Fitzsimons and Veit 2001; Barrell et al. 2011). The mountain ranges are deeply dissected by glaciated valleys. The relief is generally steep and intensely eroded. The location of the Main Divide towards the west of the mountain chain creates an asymmetrical cross-profile. Westwards-draining catchments have consequently overall steeper gradients than eastwards-draining catchments. The high relief on the western flank, in combination with exceptionally high contemporary uplift and rainfall rates (see Fig. 2.3), produces catchment sediment yields that are among the highest in the world (Whitehouse and Pearce 1992). Uplift, rainfall, and subsequently erosion rates decrease towards the east; with them the landscape transitions to more depositional environments.

Whitehouse (1988, see also Whitehouse and Pearce 1992) differentiates three geomorphological regions in the Southern Alps based on characteristic landforms and erosional processes (Fig. 2.3): The western Alps are intensely fluvially dissected and experiences rapid uplift and erosion. The steep topography is maintained by constant fluvial downcutting and frequent rockslides (Hovius et al. 1997; Korup 2005). Comprehensive regolith storages are rare, and erosional landforms dominate. The axial Alps exhibit the highest elevations and steepest relief. Many of the valleys are still glacierised, and both modern and historic glacial features, such as moraines or cirques, are frequent. Valley slopes are characterised by bare bedrock, snow and ice with prominent talus slopes at lower altitudes. Rockfalls and debris flows are widespread. The eastern Alps comprise the drier eastern ranges, intermontane basins, and front ranges. Where elevations are still high, but rainfall insufficient to sustain glaciers, intact and relict rock glaciers are frequent. The relief decreases progressively towards the east. Valley flanks are increasingly rectilinear with scree and frost-rubble sheets extending up to the ridge crests. Uplift and erosion rates are low. Depositional features dominate the landscape and small-scale rockfalls, debris flows, and debris slides are, aside from water floods, the predominant erosional processes.

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