Spatial and temporal variability of snowpack stability in the Craigieburn Valley, New Zealand

Gregor R. Macara

A thesis submitted in fulfilment of the degree of

Master of Science in Geography

at the University of Otago, Dunedin, New Zealand

December 2012
Abstract

Spatial variability of snowpack stability has been a topic of considerable contemporary research in the Northern Hemisphere, yet relatively few studies have examined the issue in New Zealand. In order to address this gap in knowledge, the present study has two objectives: (1) to analyse the avalanche terrain of Craigieburn Valley using a geographic information system; and (2) to investigate the spatial and temporal variability of snowpack stability within Craigieburn Valley. To facilitate the achievement of these objectives, 35 consecutive days were spent ‘on-mountain’ at Craigieburn Valley, between 22 June and 26 July 2012. This enabled valuable observations of the weather, and associated implications for the seasonal snowpack of the area, to be obtained prior to snowpack stability testing. Compression tests (CTs) and extended column tests (ECTs) were performed on a 36°, easterly aspect slope at 1,810 m a.s.l. within the Craigieburn Valley ski area boundary, and on a uniform 37°, southerly aspect slope at 1,650 m a.s.l. within the Craigieburn Valley backcountry. In addition, the backcountry testing location was roped off, enabling observations of an undisturbed snowpack to be made.

Over the course of early Austral winter 2012, Craigieburn Valley experienced both significant snowfall and rainfall events. 125 cm of snowfall accumulated as a result of a single storm in early-June, yet 70 mm and 106 mm single storm rain events were recorded in late-June and mid-July, respectively. The primary snowpack weakness observed was persistent weak layers of faceted crystals. The development of persistent weak layers occurred as a result of a relatively thin snowpack depth (approximately 80 cm), relatively high snowpack temperature gradients of up to 2.6°C per 10 cm, and the presence of a significant crust in the snowpack, due to rainfall which occurred in late-June. Terrain analyses showed that 94% (93 ha) of primary avalanche terrain (slope angle between 30° and 45° in the Craigieburn Valley backcountry is of southerly, south-westerly and south-easterly aspect, compared to just 25% (38 ha) of the Craigieburn Valley ski area.
Considerable variability of snowpack stability was observed on the undisturbed uniform slope in the Craigieburn Valley backcountry. As such, stability testing from a single snowpit could not reliably represent the snowpack stability of an entire slope. The proportion of stability ratings that were representative of the expected slope stability varied between 0% when CT results were used, to 30% when ECT results were used. In addition, very unstable stability test results were obtained, despite an expectation that the slope had good stability. The implications of these results is that more than one snowpit should be carried out on a single slope in order to improve the reliability of stability test results obtained. Temporal changes in snowpack stability were also observed. Given a lack of adverse weather conditions, overall slope stability increased. However, the spatial variability increased, and furthermore, very poor stability results were still obtained.

A key theme to emerge from the present study is that considerable spatial variability of snowpack stability may be observed in the early winter months, particularly on aspects of a southerly-component. Given the desire of Craigieburn Valley Ski Club management to expand the current ski area boundary, this presents challenges regarding hazard mitigation; as snowpack weaknesses tend to persist for longer on aspects of a southerly-component. The findings presented in this study offer improvements to the understanding of avalanche terrain within Craigieburn Valley. Combined with insights into the variability of snowpack stability, the understanding of potential avalanche hazard in the Craigieburn Valley is improved, which may contribute to the ongoing mitigation of avalanche hazard in the area. In addition, due to a relative paucity of previous research, the present study offers a valuable contribution to the knowledge of spatial and temporal variability of snowpack stability in the New Zealand setting.
Acknowledgements

I have thoroughly enjoyed all that this thesis entailed, and I am incredibly grateful to the following people who have contributed along the way.

- My supervisor, Nicolas Cullen, for the opportunity to undertake this study. Your guidance, feedback, encouragement, and enthusiasm were an immense contribution to this research.
- Nick Jarmin, and the Craigieburn Valley Ski Club, for the generous support of my fieldwork campaign.
- Jason Konigsberg and Tony Preston, for facilitating the success of the fieldwork campaign, and the wealth of knowledge you both passed on to me over the course of my time at Craigieburn.
- Owen Braddock, for showing great commitment to my cause, and able assistance getting my snow study plot set up.
- Nigel McDonald, Dave Howarth and David McDowell for the technical support.
- Matt Wilkinson, Ian Owens, Karl Birkeland and Jordy Hendrikx for each providing helpful thoughts and feedback.
- Ross Marsden, for providing weather maps and satellite images.
- Todd Redpath, and Sebastian Vivero, for being particularly helpful and generous with their time.
- To all the Craigieburn staff, who were fantastic company and made me feel at home. A special thanks to Adam Toleman. Also, thanks to the Craigieburn Valley members who showed interest in my research, and resisted the urge to ‘duck the ropes’ and ski my plot!
- Lloyd Burr and Louise Ayling. You have both been fantastic over the years, inadvertently provided inspiration, and always helped keep things in perspective.
- Mum, Dad and Soph. I couldn’t have achieved this without you all, thanks so much for everything.
1 Introduction ........................................................................................................... 1
  1.1 Background ...................................................................................................... 1
  1.2 Spatial and temporal variability of snowpack stability ..................................... 3
  1.3 Research objectives and thesis structure ......................................................... 3

2 Research context .................................................................................................... 6
  2.1 Introduction ...................................................................................................... 6
  2.2 Principles of avalanches .................................................................................... 7
    2.2.1 Types of avalanches .................................................................................... 7
    2.2.2 Avalanche size classification ...................................................................... 8
  2.3 Avalanche terrain ............................................................................................. 9
    2.3.1 Slope angle characteristics ......................................................................... 9
    2.3.2 Craigieburn Range avalanche terrain ....................................................... 10
    2.3.3 Craigieburn Valley avalanche terrain ....................................................... 11
  2.4 Weather ........................................................................................................... 12
    2.4.1 Implications of weather on snowpack stability .......................................... 12
    2.4.2 New Zealand weather and snowpack stability .......................................... 13
  2.5 Snowpack stability .......................................................................................... 14
    2.5.1 Snowpack structure and associated stability ............................................. 14
    2.5.2 Stability tests utilised to determine snowpack stability ............................. 16
    2.5.3 The three-component model of stability ................................................... 18
  2.6 Spatial and temporal variability of snowpack stability ...................................... 18
    2.6.1 Spatial variability at the mountain range scale ......................................... 19
    2.6.2 Spatial variability at the slope scale ........................................................... 20
    2.6.3 Temporal variability at the slope scale ...................................................... 24
    2.6.4 Stability sampling methodological issues ................................................. 27
    2.6.5 Implications for avalanche hazard ............................................................ 28
2.7 Summary and research opportunities .............................................................. 28

3 Methods .............................................................................................................. 30
3.1 Introduction ...................................................................................................... 30
3.2 Research location ............................................................................................ 30
  3.2.1 Physical setting of Craigieburn Valley ..................................................... 30
  3.2.2 Climate setting .......................................................................................... 33
  3.2.3 Research location justification ................................................................. 36
3.3 Data collection ................................................................................................. 36
  3.3.1 Stability testing sampling strategy ........................................................... 37
    3.3.1.1 Craigieburn Valley backcountry ...................................................... 37
    3.3.1.2 Craigieburn Valley ski area .............................................................. 44
  3.3.2 Meteorological variables and stability forecasts ....................................... 47
  3.3.3 Rain event case study ............................................................................... 49
3.4 Data treatment .................................................................................................. 49
  3.4.1 Stability testing observations .................................................................... 49
    3.4.1.1 Three-component model of stability ............................................... 50
    3.4.1.2 Intra- and inter-pit variability ....................................................... 52
    3.4.1.3 Moran’s I analyses ......................................................................... 55
  3.4.2 Weather and snowpack observations ....................................................... 56
  3.4.3 Craigieburn Valley avalanche terrain ....................................................... 56
3.5 Summary ........................................................................................................... 57

4 Results ................................................................................................................. 58
4.1 Introduction ...................................................................................................... 58
4.2 Craigieburn Valley avalanche terrain ............................................................. 58
4.3 Weather and snowpack .................................................................................. 66
  4.3.1 Early winter 2012 in context .................................................................... 66
  4.3.2 Weather preceding snowpack stability testing ...................................... 69
  4.3.3 Weather during snowpack stability testing ............................................ 71
  4.3.4 Craigieburn Valley backcountry snowpack observations ..................... 73
  4.3.5 Craigieburn Valley ski area snowpack observations .............................. 78
4.3.6 Avalanche observations ................................................................. 82
4.4 Spatial and temporal variability of snowpack stability ............................... 83
  4.4.1 Craigieburn Valley backcountry .................................................. 84
    4.4.1.1 Three-component model of stability ...................................... 93
  4.4.2 Craigieburn Valley ski area ....................................................... 97
    4.4.2.1 Three-component model of stability ...................................... 100
4.5 Rain event case study ........................................................................ 101
4.6 Summary ............................................................................................ 108

5 Discussion .............................................................................................. 110
  5.1 Introduction ....................................................................................... 110
  5.2 Weather and snowpack ...................................................................... 111
  5.3 Spatial variability of snowpack stability at Craigieburn Valley ............... 113
    5.3.1 Craigieburn Valley backcountry ................................................. 113
    5.3.2 Craigieburn Valley ski area ....................................................... 118
    5.3.3 Comparisons with New Zealand case studies .............................. 119
    5.3.4 Implications ................................................................................ 120
  5.4 Temporal variability of snowpack stability at Craigieburn Valley ........... 121
    5.4.1 Craigieburn Valley backcountry ................................................. 122
    5.4.2 Comparisons with New Zealand case studies .............................. 123
    5.4.3 Rain event case study .................................................................. 124
    5.4.4 Implications ................................................................................ 126
  5.5 Avalanche terrain of Craigieburn Valley .............................................. 127
    5.5.1 Comparison of ski area and backcountry terrain .......................... 128
    5.5.2 Implications for the Craigieburn Valley Ski Club .......................... 129
  5.6 Research Caveats ................................................................................ 131
  5.7 Summary ............................................................................................ 132

6 Conclusions ............................................................................................ 134
  6.1 Key findings ....................................................................................... 134
  6.2 Future research .................................................................................. 137
References ........................................................................................................................................ 139

Appendices .................................................................................................................................... 146

A  Snow profile interpretation ........................................................................................................ 147
B  Stability test results .................................................................................................................... 152
C  Individual snowpit stability ratings ........................................................................................ 160
# List of Figures

1.1 The avalanche hazard triangle. ................................................................. 2

2.1 Two loose snow avalanches. ................................................................. 7

2.2 Distinctive features such as a crown wall remain after a slab avalanche occurrence. ........................................................................................................ 8

2.3 A conceptual diagram showing the classification of avalanche terrain according to slope angle. ................................................................. 10

2.4 The frequency distribution of avalanche starting zone aspects of 147 Craigieburn Range avalanche paths identified by McGregor (1989). ......... 11

2.5 Results of 24 ECTs obtained from a single slope by Simenhois and Birkeland (2007, 2009), demonstrating a clustering of ECTP results. .................. 21

2.6 Stability sampling strategy of Schweizer and Bellaire (2010). .................... 23

2.7 ECT results obtained in a study by Hendrikx et al. (2009) at one of their two USA study sites. ................................................................. 26

3.1 Map of the Craigieburn Valley. ................................................................. 31

3.2 West-northwest facing view of Craigieburn Valley, subdivided into the current ski area boundary and the backcountry terrain of Middle Basin. ................. 33

3.3 Location of the section of slope where stability testing was performed in the Craigieburn Valley backcountry. ............................................................... 38

3.4 Gridded sampling methodology for the Craigieburn Valley backcountry study slope. ........................................................................................................ 39

3.5 Dimensions of the extended column test (ECT). ........................................ 43

3.6 Locations of stability testing within the Craigieburn Valley ski area. ............... 45

3.7 Sampling methodology for the Craigieburn Valley ski area study slope. .......... 46

3.8 The northern end of the Craigieburn Range, showing the location of the Broken River and Craigieburn Forest automatic weather stations, relative to Craigieburn Valley ................................................................. 48

4.1 Proportions of avalanche terrain within the Craigieburn Valley Ski Area. ....... 59
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>Proportions of avalanche terrain of the Craigieburn Valley Backcountry.</td>
</tr>
<tr>
<td>4.3</td>
<td>Spatial distribution of avalanche terrain within the Craigieburn Valley ski area.</td>
</tr>
<tr>
<td>4.4</td>
<td>Spatial distribution of avalanche terrain within the Craigieburn Valley backcountry.</td>
</tr>
<tr>
<td>4.5</td>
<td>Distribution of primary avalanche initiation terrain between different elevation bands within the Craigieburn Valley ski area.</td>
</tr>
<tr>
<td>4.6</td>
<td>Distribution of primary avalanche initiation terrain between different elevation bands of the Craigieburn Valley backcountry.</td>
</tr>
<tr>
<td>4.7</td>
<td>Distribution of primary avalanche initiation terrain between different slope aspects within the Craigieburn Valley ski area.</td>
</tr>
<tr>
<td>4.8</td>
<td>Distribution of primary avalanche initiation terrain between different slope aspects of the Craigieburn Valley backcountry.</td>
</tr>
<tr>
<td>4.9</td>
<td>Spatial distribution of slope aspect within the Craigieburn Valley ski area.</td>
</tr>
<tr>
<td>4.10</td>
<td>Spatial distribution of slope aspect within the Craigieburn Valley backcountry.</td>
</tr>
<tr>
<td>4.11</td>
<td>Daily minimum and maximum air temperatures, and rainfall, measured at the Craigieburn Forest AWS.</td>
</tr>
<tr>
<td>4.12</td>
<td>Mean sea level isobar map, valid at 1200 hours NZST on 6 June 2012, and the Craigieburn Valley Ski Club Manager beside 1.25 m of fresh snowfall.</td>
</tr>
<tr>
<td>4.13</td>
<td>Infrared satellite image, valid at 0000 hours NZST 26 June 2012, and mean sea level isobar map, valid at 1200 hours NZST on 26 June 2012.</td>
</tr>
<tr>
<td>4.14</td>
<td>Mean sea level isobar maps and infrared satellite images valid at 1200 hours NZST, for 7 July 2012, 9 July 2012, and 11 July 2012.</td>
</tr>
<tr>
<td>4.15</td>
<td>Looking north from the western ridgeline of Craigieburn Valley, showing the predominant weather observed at Craigieburn Valley from 7 July to 11 July 2012.</td>
</tr>
<tr>
<td>4.16</td>
<td>Snow profile obtained at the Craigieburn Valley backcountry on day one of testing, 7 July 2012 at 0900 hours.</td>
</tr>
<tr>
<td>4.17</td>
<td>Snow profile obtained at the Craigieburn Valley backcountry on day two of testing, 11 July 2012 at 0900 hours.</td>
</tr>
</tbody>
</table>
Snow profile obtained at the Craigieburn Valley ski area, 9 July 2012 at 1200 hours. .................................................. 79

Snow profile obtained at the Craigieburn Valley ski area, 9 July 2012 at 1730 hours. .................................................. 80

A skier-triggered loose snow avalanche. ................................................. 83

CT results obtained from the Craigieburn Valley backcountry. .............. 85

ECT results obtained from the Craigieburn Valley backcountry. .............. 87

Median, lower and upper quartiles of CT results obtained from the Craigieburn Valley backcountry study slope on each day of testing. .......... 90

Median, lower and upper quartiles of ECTN results obtained from the Craigieburn Valley backcountry study slope on each day of testing. .......... 91

Median, lower and upper quartiles of ECTP results obtained from the Craigieburn Valley backcountry study slope on each day of testing. .......... 91

Public avalanche advisory for the Craigieburn Range. ........................................ 95

Individual snowpit stability ratings with respect to the ECT scores, utilising the three-component model of stability, obtained from the Craigieburn Valley backcountry study slope. ........................................ 97

CT results obtained from the Craigieburn Valley ski area. .................... 98

ECT results obtained from the Craigieburn Valley ski area. .................... 99

Median, lower and upper quartiles of CT results obtained from the Craigieburn Valley ski area. ........................................ 100

Median, lower and upper quartiles of ECTN results obtained from the Craigieburn Valley ski area. ........................................ 100

Mean sea level isobar map and infrared satellite image, valid at 1800 hours NZST on 14 July 2012. ........................................ 102

Snow profile obtained at the Craigieburn Valley backcountry on 21 July 2012 at 1000 hours. ........................................ 103

Snow profile obtained at the Craigieburn Valley ski area on 22 July 2012 at 1100 hours. ........................................ 105

Distribution of point stability observations with respect to the associated regional avalanche danger level forecast. ........................................ 116
5.2 Backcountry avalanche advisory board posted at Craigieburn Valley skifield. ................................................................. 118

5.3 A plume of smoke rises from the ridgeline of the “Middle Basin Chutes” after the blast of a bomb deployed by Craigieburn Valley staff. ................. 130

A.1 An example full snow profile. ................................................................. 148

A.2 Deconstruction of layer identification, layer hardness, layer thickness, snowpack temperature, and weak layer/interface of primary concern. .......... 149

A.3 Deconstruction of snow crystal type, snow crystal size and snow density. ........................................................................ 150

A.4 Snow crystal types observed in the present study. ........................................... 151
## List of Tables

2.1 Snow avalanche size classification. ................................................................. 9
2.2 Weak layer variables, identified from full snow profiles carried out at the
crown wall of 145 skier-triggered avalanches. ................................................... 16
3.1 Craigieburn Range monthly air temperature data. ......................................... 35
3.2 Compression test classification scheme. .......................................................... 40
3.3 Fracture character classification scheme. ......................................................... 41
3.4 ECT classification scheme. .............................................................................. 42
3.5 Hand hardness test recording standards. .......................................................... 44
3.6 Stability indication thresholds developed for the present study, which
attribute a number rating to the associated stability indication. .......................... 52
3.7 Criteria used to determine intra-pit (pit scale) and inter-pit (slope scale)
similarity, with respect to the CT score and fracture character. .......................... 54
4.1 Meteorological variables measured at the Craigieburn Forest AWS. ............... 67
4.2 Significant weather events occurring in the Austral winter of 2012,
pertinent to the Craigieburn Valley snowpack, and prior to snow
stability testing. .................................................................................................. 71
4.3 Daily maximum and minimum temperatures recorded at the Craigieburn
Valley weather observation plot over the course of the snow stability testing
period. ................................................................................................................ 73
4.4 Variability of snow depth and slab thickness observed within the
Craigieburn Valley backcountry. ........................................................................ 77
4.5 Weak layer variables (structural ‘lemons’) observed within the
Craigieburn Valley backcountry snowpack. ....................................................... 78
4.6 Variability of snow depth and slab thickness observed within the
Craigieburn Valley ski area snowpack. ............................................................... 81
4.7 Weak layer variables (structural ‘lemons’) observed within the Craigieburn
Valley ski area snowpack. ................................................................................. 81
4.8 Avalanches within Craigieburn Valley that occurred between 22 June and 26 July, 2012. ................................................................. 82
4.9 Descriptive statistics of CT and ECTP results obtained from the Craigieburn Valley backcountry. .................................................. 88
4.10 Regression analyses testing the relationship between slab thickness and CT score. .................................................................................. 88
4.11 Statistical significance in the temporal change of CT, ECTP and ECTN scores, calculated using the Mann-Whitney test. ...................... 89
4.12 Spatial variability of CT scores and fracture character obtained from the Craigieburn Valley backcountry. ........................................ 90
4.13 Moran’s I analysis undertaken on data obtained from the Craigieburn Valley backcountry study slope. .............................................. 93
4.15 Descriptive statistics of stability test results obtained from the Craigieburn Valley ski area on 9 July 2012. ......................................................... 99
4.16 Spatial variability of CT scores and fracture character obtained from the Craigieburn Valley ski area. ......................................................... 100
4.17 Snowpack stability ratings of individual snowpits, and the overall stability of the Craigieburn Valley ski area slope. ......................... 101
4.18 Minimum temperature, maximum temperature, and 24 hr rainfall totals at the Craigieburn Valley Ski Club weather observation plot over the course of the 13 July – 15 July rain event. .............................................. 102
4.19 Weak layer variable (structural ‘lemons’) thresholds, and whether or not they were observed within the backcountry and ski area when stability testing was carried out on 21 July and 22 July 2012, respectively. .......... 106
4.20 Descriptive statistics of stability test results obtained from the Craigieburn Valley backcountry on 21 July 2012, and from the Craigieburn Valley ski area on 22 July 2012. .......................................................... 107
4.21 Snowpack stability ratings of individual snowpits, and the associated overall stability rating of the Craigieburn Valley ski area and Craigieburn Valley backcountry, as a result of stability testing carried out subsequent to the July 13 – July 15 rain event. ........................................... 108

B.1 CT results obtained from the Craigieburn Valley backcountry study slope on 7 July 2012. ........................................................................................................... 153

B.2 ECT results obtained from the Craigieburn Valley backcountry study slope on 7 July 2012. ........................................................................................................... 154

B.3 CT results obtained from the Craigieburn Valley backcountry study slope on 11 July 2012. ........................................................................................................... 155

B.4 ECT results obtained from the Craigieburn Valley backcountry study slope on 11 July 2012. ........................................................................................................... 156

B.5 CT results obtained from the Craigieburn Valley ski area study slope on 9 July 2012. ...................................................................................................................... 156

B.6 ECT results obtained from the Craigieburn Valley ski area study slope on 9 July 2012. ...................................................................................................................... 157

B.7 CT and ECT results obtained from the Craigieburn Valley backcountry study slope and the Craigieburn Valley ski area study slope, on 21 July 2012 and 22 July 2012, respectively. ................................................................. 159

C.1 Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 7 July 2012, with respect to the CT score. ................................. 161

C.2 Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 7 July 2012, with respect to the ECT score. ................................. 162

C.3 Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 11 July 2012, with respect to the CT score. ................................. 163

C.4 Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 11 July 2012, with respect to the ECT score. ................................. 164

C.5 Individual snowpit stability ratings obtained from the Craigieburn Valley ski area on 9 July 2012, with respect to the CT score. ................................. 165

C.6 Individual snowpit stability ratings obtained from the Craigieburn Valley ski area on 9 July 2012, with respect to the ECT score. ................................. 166
C.7 Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 21 July 2012, with respect to the CT and ECT score, respectively. ................................................................. 167

C.8 Individual snowpit stability ratings obtained from the Craigieburn Valley ski area on 22 July 2012, with respect to the CT score. ................................................................. 168

C.9 Individual snowpit stability ratings obtained from the Craigieburn Valley ski area on 22 July 2012, with respect to the ECT score. ................................................................. 168
Chapter 1

Introduction

1.1 Background

Avalanches pose a potential threat to recreationalists and infrastructure in New Zealand’s alpine terrain. As such, avalanches may be deemed hazardous; with the level of hazard increasing as the number of users and amount of infrastructure exposed to avalanches increases. Implicit then, is that the avalanche hazard within New Zealand is pronounced at skifields, where a relatively high concentration of recreationalists and infrastructure are located. Many skifields are progressively seeking to expand their ski area boundaries, in order to gain a competitive advantage over other skifields by encouraging more visitors to their field. For example, Porter Heights ski area in Canterbury have been granted approval to expand their ski area boundary into the neighbouring Crystal Valley, and the Remarkables ski area in Queenstown has recently outlined plans to install a new lift accessing what is presently backcountry terrain. In addition, skifields facilitate relatively easy access into uncontrolled backcountry terrain. With the advent of equipment such as splitboards, avalungs, and airbags, backcountry travel has never been more accessible and enticing for the alpine enthusiast, and is rising in popularity as a result. Worryingly, such equipment can support a ‘bullish’ attitude amongst backcountry users, who may feel a false level of safety due to the use of such equipment, increasing the likelihood that they may make more risky decisions in the backcountry. Therefore, it appears potential avalanche hazard is mounting in New Zealand, due to an increasing number of people being exposed to an increasing amount of avalanche terrain.
The avalanche hazard triangle, consisting of four components, provides a conceptual framework for the assessment of potential avalanche hazard (Figure 1.1). The three foundation components are terrain, snowpack, and weather, and knowledge of these enable an interpretation of potential avalanche formation to be made (McClung and Schaerer, 2006). The final component of the triangle comprises people and infrastructure. As such, avalanche hazard is introduced if people and or/infrastructure are located in areas which may be affected by avalanches. Therefore, this necessitates awareness of terrain where avalanches initiate, as well as of terrain that is affected by the path of avalanches once initiated. The implication of this, from a management of avalanche hazard point of view, is that it is important to establish a database of where avalanches may initiate, as well as the typical and maximum extent of individual avalanche paths. This is achieved through mapping of avalanche terrain. In New Zealand, avalanche paths have been mapped for ski areas (e.g. McNulty, 1984), and for the Milford Road transport corridor (Fitzharris and Owens, 1980; Fitzharris et al., 1999; Hendrikx et al., 2005).

![Avalanche hazard triangle diagram](image)

**Figure 1.1** The avalanche hazard triangle. Knowledge of terrain, snowpack and weather enables an interpretation of avalanche formation to be made. Avalanche hazard is introduced when people and infrastructure are located in areas that may be affected by avalanches.
1.2 Spatial and temporal variability of snowpack stability

The contribution of terrain and weather to potential avalanche formation is now relatively well understood (Schweizer et al., 2003; McClung and Schaeerer, 2006). In contrast, the spatial variability of snowpack stability has proven perplexing, as evidenced by avalanches being triggered by not the first, but subsequent skiers on a slope (e.g. Harvey and Signorell, 2002). As a result of this perplexity, spatial variability of snowpack stability has emerged as a topic of contemporary research. Spatial variability of snowpack stability has been demonstrated by a number of studies, including at the slope scale (e.g. Föhn, 1988, Kronholm and Schweizer, 2003). One issue with such studies pertains to the discrepancy in scale triplet (Blöschl and Sivapalan, 1995) used; that is, the support size of stability test measurements; the spacing of stability test measurements; and the spatial extent of stability test measurements. As a result, it is difficult to make meaningful comparisons between the results of different studies. Hendrikx and Birkeland (2008) addressed this issue by applying a consistent sampling strategy between different study slopes. In addition, the sampling strategy employed by these authors enabled temporal changes in spatial variability of the same area of slope to be observed. Despite a considerable effort to improve understanding of the spatial variability of snowpack stability, the controls on that variability are yet to be fully understood. In order to unravel these controls, previous authors cite the need for more studies to be carried out on a range of slopes, in a range of different settings and snow climates (e.g. Hendrikx et al., 2009). Notably, relatively few studies have addressed the spatial and temporal variability of snowpack stability in New Zealand. Furthermore, the value of previous New Zealand based studies is somewhat limited due to a relative lack of spatial variability being observed.

1.3 Research objectives and thesis structure

This thesis seeks to address the considerable gap in knowledge of the spatial variability of snowpack stability in New Zealand. As such, this thesis will investigate the avalanche terrain and snowpack stability within Craigieburn Valley, New Zealand. Craigieburn Valley includes both ski area terrain, where snowpack stability is actively controlled, and backcountry terrain, where snowpack stability is not controlled. A primary goal of
Craigieburn Valley snow safety practitioners is to mitigate avalanche hazard. As well as a ‘hands-on’ approach to the mitigation of avalanche hazard performed by snow safety practitioners, avalanche practitioners provide avalanche forecasts for the entire Craigieburn Range, which encompasses Craigieburn Valley. These help facilitate an awareness of potential avalanche hazard for those who wish to recreate in the backcountry terrain of Craigieburn Valley. The mitigation of avalanche hazard at Craigieburn Valley is pertinent, given the exposure of recreationalists to avalanche hazard in the area. As such, Craigieburn Valley represents an appropriate location to carry out a study of snowpack stability.

The present study has two objectives:

1. Analyse the avalanche terrain of Craigieburn Valley using a geographic information system.
2. To investigate the spatial and temporal variability of snowpack stability within Craigieburn Valley.

It is anticipated that addressing the two research objectives will lead to an enhanced awareness of potential avalanche hazard in the Craigieburn Valley, and contribute knowledge to support the awareness and mitigation of avalanche hazard in the area. Furthermore, the present research will provide a valuable contribution to the knowledge of the spatial and temporal variability of snowpack stability in the New Zealand context.

This thesis is divided into six chapters. Research objectives and background information regarding avalanches as a hazard are provided in Chapter 1. Chapter 2 provides context for the present research. The principles of avalanches, and the primary factors contributing to snowpack stability, are described. Methods of snowpack examination and stability testing are addressed, highlighting how snowpack stability may be determined. A critical evaluation of previous studies examining the spatial and temporal variability of snowpack stability is presented, and gaps in the current knowledge identified. Chapter 3 introduces the field location, and justifies its suitability for the present study. Methods used to collect and process data are described. Chapter 4 presents the results obtained from this study, which comprise the avalanche terrain, and the spatial and temporal variability of snowpack stability, within the Craigieburn Valley. A discussion of the results obtained is the focus of
Chapter 5. Implications of the results are provided, with significant results that distinguish this study from previous studies highlighted. Chapter 6 summarises the main findings of the present research, and based on these, suggests avenues of future research.
Chapter 2

Research context

2.1 Introduction

The following chapter synthesises literature that pertains to the two research objectives of this study. Namely, these objectives are: (1) to analyse the avalanche terrain of Craigieburn Valley using a geographic information system, and (2) to investigate the spatial and temporal variability of snowpack stability within Craigieburn Valley. Section 2.2 provides important background information by describing key principles of avalanches. The current state of knowledge regarding avalanche terrain is addressed in Section 2.3, with particular focus on the field site of this study (Craigieburn Valley). As a result, it is shown that the most recent analysis of Craigieburn Valley avalanche terrain could be supplemented with a more in-depth analysis of avalanche terrain. Section 2.4 identifies the effects of weather on snowpack stability. A review of field methods developed that enable snowpack stability to be determined is provided in Section 2.5. Despite inherent uncertainty in determining snowpack stability, the method which best enables this to be achieved is described. Section 2.6 critically evaluates previous studies that have examined the spatial and temporal variability of snowpack stability. Resultantly, gaps in the current knowledge are identified, providing further justification for this research. Section 2.7 provides an overall summary, and utilises the examination of previous studies to highlight the opportunities for research.
2.2 Principles of avalanches

2.2.1 Types of avalanches

A snow avalanche is a moving mass of snow which descends rapidly over sloped terrain (Schweizer et al., 2003). In order for a snow avalanche to occur, a trigger is required. Such triggers are usually in the form of additional weight or stress added to the snowpack, either from natural or artificial sources. Natural sources include new snowfall or rain, and artificial sources include skiers, or bombing during avalanche control work. Avalanches may be broadly defined as loose snow or slab. Loose snow avalanches are characterised by an initial fracture from a point (Hopfinger, 1983), with their path often creating a triangular shaped disturbance to the snowpack (McClung and Schaerer, 2006) (Figure 2.1). Loose snow avalanche motion propagates progressively, and initiates in surface snow with poor cohesion (Schweizer, et al., 2003). Whilst only near-surface snow is initially involved, deeper subsurface snow may be incorporated during descent (McClung and Schaerer, 2006).

Figure 2.1 Two loose snow avalanches, which have initiated near rock outcrops and run side by side, showing the distinctive triangular shaped disturbance to the remaining snowpack. The total length of each avalanche was approximately 150 m.
In contrast, slab avalanches result from a relatively strong cohesive layer of snow (the slab) that has either formed above a weak layer, or is poorly bonded to the interface below it (Schweizer, 1999). This requirement of a certain level of cohesion distinguishes slab avalanches from loose snow avalanches (McClung and Schaerer, 2006). Slab avalanche release is characterised by sudden fracture propagation underneath and at all boundaries of the slab, and distinctive features such as a crown wall remain (Figure 2.2).

Figure 2.2 Distinctive features such as a crown wall (pictured) remain after a slab avalanche occurrence. This size 2 slab avalanche (debris not pictured) was triggered naturally by a smaller loose snow avalanche. The average height of this crown wall was approximately 0.8 m.

2.2.2 Avalanche size classification

Avalanches may be further classified according to their size. Table 2.1 provides a description of each size class of avalanche, as well as the typical mass and path lengths of such avalanches. The smallest avalanches observed are known as size 1 avalanches, and are usually harmless to people. The largest avalanches observed are known as size 5 avalanches. These are rare, and have the potential to cause significant destruction.
Table 2.1 Snow avalanche size classification. Adapted from Goddard (2008).

<table>
<thead>
<tr>
<th>Size</th>
<th>Description</th>
<th>Typical mass (t)</th>
<th>Typical path length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Relatively harmless to people</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Could injure, bury or kill a person</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>Could bury a car, destroy a small building or break a few trees</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>4</td>
<td>Could destroy a large truck, several buildings, or a forest up to 4 ha in area</td>
<td>10,000</td>
<td>2,000</td>
</tr>
<tr>
<td>5</td>
<td>Could destroy a village, or a forest of 40 ha in area</td>
<td>100,000</td>
<td>3,000</td>
</tr>
</tbody>
</table>

2.3 Avalanche terrain

2.3.1 Slope angle characteristics

Slope angle is of critical importance regarding the formation of avalanches. Quite simply, an avalanche will not initiate if the slope angle is not steep enough. Avalanches primarily initiate on slope angles between 30° and 45° (Perla, 1977; Schweizer and Jamieson, 2001; Schweizer and Lutschg, 2001; Goddard, 2008), with 38° considered the “bulls-eye” (Tremper, 2008). As such, terrain with a slope angle between 30° and 45° inclusive will hereby be referred to as primary avalanche terrain (Figure 2.3). Avalanches may initiate on slope angles as low as 15°, and as high as 60° (McClung and Schaarer, 2006; Goddard, 2008), however avalanches on this terrain are considerably less frequent compared to primary avalanche terrain. Therefore, terrain with a slope angle of between either 15° to 30°, or 45° to 60° will be referred to as secondary avalanche terrain (Figure 2.3). Evidence of avalanches initiating on the remaining slope angles of less than 15° and greater than 60° is scarce (McClung and Schaarer, 2006). However, it must be remembered that avalanches which initiate elsewhere can affect such terrain. This remaining terrain will hereby be referred to as tertiary avalanche terrain (Figure 2.3).
2.3.2 Craigieburn Range avalanche terrain

McGregor (1989) identified 137 active avalanche paths across the entire Craigieburn Range. The author found that the upper limits (i.e. avalanche starting zone) of these avalanche paths are located between 1,660 m a.s.l. and 2,134 m a.s.l. The aspects of these starting zones were found to range between 30° and 250° (i.e. north-easterly through to westerly aspects). No starting zone of any avalanche path identified had an aspect that was either northerly or north-westerly (Figure 2.4). Of the 137 active avalanche paths identified, 30 were selected by the author for slope angle analyses. Slope angle measurements were determined by field survey using surveying equipment. Resulting analyses by the author found the slope angle of avalanche path starting zones ranged between 31° and 38°, and averaged 34.8°. McGregor (1989) measured slope angles of up to 34° within avalanche paths below their supposed starting zone. Thus, this introduces complexity to the author’s analyses of avalanche paths on the Craigieburn Range. Specifically, areas outside of avalanche starting zones meet the criteria for primary avalanche terrain. As a result, the actual extent of the Craigieburn Range where avalanche initiation is possible is unclear. Notably, no explanation was provided by McGregor (1989) as to the selection of the 30 avalanche paths for slope angle analyses. Therefore, whether or not these paths are representative of the 147 active paths identified remains in question.
Figure 2.4  a) The location of the study area, and b) the frequency distribution of avalanche starting zone aspects of 147 Craigieburn Range avalanche paths identified by McGregor (1989). Images obtained from McGregor (1989).

2.3.3 Craigieburn Valley avalanche terrain

McNulty (1984) carried out an analysis of the avalanche hazard faced within the Craigieburn Valley. As a result of his study, McNulty identified 28 avalanche paths which lie within the current ski area boundary. The starting zone elevations of these paths were found to range between 1,400 m a.s.l. and 1,870 m a.s.l. Starting zone slope angles ranged between 29° and 43°, and aspects ranged from north-easterly to south-westerly. Whilst providing a detailed identification of avalanche paths within the Craigieburn Valley ski area boundary, McNulty’s (1984) analysis of backcountry avalanche terrain is not quite so detailed. Five broad avalanche paths are defined; although it is clear that multiple avalanche paths are present within those identified by the author. Characteristics of the backcountry avalanche paths identified by McNulty (1984) are not provided. Instead, characteristics encompassing the entire backcountry are provided. Specifically, the altitude of backcountry avalanche start zones ranged between 1,400 m a.s.l. and 1,800 m a.s.l., slope angle ranged between 33° and 37°, and slope aspects were easterly, south-easterly, southerly, and south-westerly.
Despite valuable analysis of the Craigieburn Range and Craigieburn Valley avalanche terrain garnered in the mid- to late-1980’s, the information obtained remains somewhat ambiguous. Information regarding specific avalanche paths has been described, yet there is little context of the results provided. For example, it remains unknown what proportion of terrain in the Craigieburn Valley is prone to avalanches. Thus, the opportunity is presented to carry out a more detailed analysis of the Craigieburn Valley avalanche terrain, to obtain an enhanced understanding of the potential avalanche hazard of the area. This opportunity is supported by the development of cartographically-derived digital elevation models (DEMs) and geographic information systems (GIS) software. Areas of potential avalanche initiation can be identified given a reasonable DEM resolution of less than 30 m (Schweizer et al, 2003), and GIS software enables the calculation of complex avalanche terrain characteristics, beyond that which has been presented for Craigieburn Valley to date.

2.4 Weather

2.4.1 Implications of weather on snowpack stability

Meteorological factors have a critical role to play in the evolution of snowpack stability. Weather forms snowpacks, and weather creates snowpack stability concerns (Tremper, 2008). Weather influences the type of snow climate observed at a given location. Maritime snow climates may be characterised by relatively heavy snowfall (and associated relatively deep snowpacks), relatively high temperatures, and the occurrence of midwinter rainfall events (McClung and Schaerer, 2006; Tremper, 2008). In contrast, continental snow climates may be characterised by relatively low snowfall (and associated relatively thin snowpacks), relatively low temperatures, and midwinter rainfall events are extremely rare (McClung and Schaerer, 2006; Tremper, 2008). Persistent weak layers (Section 2.5.1) are a feature of continental snowpacks, meaning avalanches may occur quite some time after the passage of a storm. In contrast, avalanche occurrences in maritime snowpacks tend to occur as “direct action” events (Tremper, 2008); during or immediately after the passage of a storm. The total depth and water equivalent of new snowfall during a storm are important variables to consider, as they represent the direct addition of weight to a snowpack which may contain a weak layer, thus adding stress to that weak layer (McClung...
and Schaerer, 2006). New snowfall depths of 30 cm - 50 cm are considered sufficient for avalanches to release naturally (Schweizer et al., 2003). With respect to new snowfall, the significance of wind must be accounted for. Anecdotal evidence suggests that around 15 cm of new snowfall accompanied by wind is sufficient for avalanches to release naturally, due to the re-deposition of snow onto leeward slopes. The rate of snow depth increase over time (to which snowfall intensity contributes) is also an important consideration. Schweizer et al. (2003) note a rate of greater than or equal to 2.5 cm h$^{-1}$ can contribute to instability, as weak layers below storm snow are unable to gain strength sufficiently quickly under such circumstances. Air temperatures during a storm can have implications on the stability of a snowpack, due to their influence on the temperature of the snow that falls. Relatively low air temperatures result in new snow that also has a relatively low temperature, which slows bond formation between snow crystals and allows weaknesses within the new snow to persist (McClung and Schaerer, 2006). As such, the opposite is also true; relatively high temperatures during snowfall enhance bond formation between snow crystals (McClung and Schaerer, 2006). The air temperature trend during a storm also has interesting implications. Specifically, rising temperatures during a storm can contribute to instability (Schweizer, et al. 2003). This is because the initial snow that falls is relatively low in temperature, promoting the persistence of weaknesses within the storm snow initially deposited. Subsequent higher temperature snowfall may bond well, forming a slab layer on top of the weaker snow below, potentially creating highly unstable conditions (McClung and Schaerer, 2006; Tremper, 2008).

### 2.4.2 New Zealand weather and snowpack stability

Previous studies have investigated the contribution of weather to avalanche occurrences in New Zealand, particularly with respect to direct action avalanches (e.g. Fitzharris, 1976; Moore and Marcus, 1983). Fitzharris (1976) described the importance of fluctuating freezing levels typical of New Zealand storms, and the associated implications for snowpack stability. For example, snow often falls at air temperatures near 0°C in the mountains of New Zealand, which supports the potential for deposition of cohesive slabs of snow (McNulty and Fitzharris, 1980). Unstable conditions may then result if these slabs
form above a weak layer, such as a melt-freeze crust. McNulty and Fitzharris (1980) noted the development of melt-freeze crusts on slopes exposed to solar radiation, and also observed loose snow avalanches occurring on such slopes. Such instability on solar slopes arises frequently in New Zealand. This occurs as a result of daytime warming, enhanced by the reception of solar radiation, which reduces cohesion in the uppermost layers of the snowpack. McNulty and Fitzharris (1980) highlight the important role of wind regarding snowpack stability, and observed snow being stripped from wind exposed slopes and deposited onto lee slopes. Furthermore, the authors observed the presence of persistent weak layers, which are of considerable concern with respect to snowpack stability (Section 2.5.1). These developed during an extended period of clear weather and low air temperatures on southerly aspects which had relatively low snow depths. Further studies have observed the development of persistent weak layers in the seasonal snowpack of the Craigieburn Range (e.g. Prowse and Owens, 1984; McGregor, 1990). Thus, persistent weak layers emerge as a snowpack weakness that contributes to stability concerns, and the associated avalanche hazard, of the Craigieburn Range.

2.5 Snowpack stability

2.5.1 Snowpack structure and associated stability

Factors contributing to snowpack stability are complex, yet well understood. Textbooks by McClung and Schaerer (2006) and Tremper (2008) provide a comprehensive analysis of such factors, and as such are the salient sources of literature for recreationalists and practitioners alike. In order to determine snowpack stability, the aforementioned complexity must be unravelled. Observations of avalanches provide indisputable evidence that the snowpack is unstable. However, in lieu of actual avalanche observations, data obtained from the field provides the most pertinent indication of snowpack stability (McClung, 2000; McClung & Schaerer 2006). A full snow profile is one method which provides insight into the stability of a snowpack, and it enables detailed information about the snowpack to be obtained. In order to carry out a full snow profile, a snowpit must be dug in the snowpack. Snowpack variables that are typically obtained from a full profile include total snow depth, snowpack structure (e.g. layer identification), layer hardness,
snow crystal types, snow crystal size, and snowpack temperature profiles (a description of the full snow profile methodology is provided in Section 3.3.1). Through characterising the snowpack structure, it is possible to identify potential weak layers and/or interfaces within the snowpack. The presence of persistent weak layers within a snowpack is of significant importance regarding the snowpack stability. This is because persistent weak layers have been shown to be the most prominent weak layer type upon which skier-triggered avalanches occur (e.g. Jamieson & Johnston, 1992; Birkeland et al., 1998; Schweizer & Jamieson, 2001; Schweizer & Lütschg, 2001; Schweizer & Wiesinger, 2001). Specifically, persistent weak layers comprise surface hoar, depth hoar or faceted crystals (Schweizer and Wiesinger, 2001). It is beyond the scope of this review to provide a detailed discussion of the development of persistent grain types. However, most notably, faceted crystals tend to develop in relatively thin snowpacks (Jamieson and Johnston, 1992), where temperature gradients are relatively high (Colbeck, 1982; Birkeland, 1998; Birkeland et al., 1998; Kronholm and Schweizer, 2003). Faceted crystals also have a propensity to develop adjacent to crusts (Colbeck and Jamieson, 2001; Jamieson et al., 2001; Hägeli and McClung, 2003).

McCammon and Schweizer (2002) sought to identify specific structural characteristics which are typical of an unstable snowpack. To achieve this, the full snow profiles undertaken at the crown wall of 145 skier-triggered avalanches were analysed. As a result of their study, the authors attributed threshold values to five weak layer variables associated with the 145 skier-triggered avalanche events (Table 2.2). McCammon and Schweizer (2002) show that the weak layer variable observed most often in the snowpack where skier-triggered avalanches have occurred is a weak layer depth of less than or equal to 1 m. In addition, persistent weak layers were observed in 86% of the snow profiles undertaken at the site of skier-triggered avalanches. Overall, the five variables identified are known colloquially as ‘lemons’. The authors note that in isolation, each variable is not a reliable predictor of snowpack instability. However, unstable conditions were shown to correlate well with a greater number of ‘lemons’ identified within the snowpack (McCammon and Schweizer, 2002). Each of the 145 full snow profiles analysed were obtained from skier-triggered avalanche occurrences in Switzerland (95) and Canada (50). As of yet, no such study has been carried out in New Zealand. Therefore, the level of
The correlation between the weak layer variables identified (Table 2.2) and skier-triggered avalanches in New Zealand are unknown.

Table 2.2 Weak layer variables, identified from full snow profiles carried out at the crown wall of 145 skier-triggered avalanches. The percentage prevalence on unstable slopes refers to the percentage of the 145 profiles within which each weak layer variable threshold was met. Table adapted from McCammon and Schweizer (2002).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Threshold</th>
<th>Prevalence on unstable slopes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak layer depth</td>
<td>≤ 1 m</td>
<td>96</td>
</tr>
<tr>
<td>Weak layer thickness</td>
<td>≤ 10 cm</td>
<td>78</td>
</tr>
<tr>
<td>Hardness difference</td>
<td>≥ 1 step</td>
<td>90</td>
</tr>
<tr>
<td>Weak layer grain type</td>
<td>Persistent (SH, DH, FC)</td>
<td>86</td>
</tr>
<tr>
<td>Grain size difference</td>
<td>≥ 1 mm</td>
<td>65</td>
</tr>
</tbody>
</table>

2.5.2 Stability tests utilised to determine snowpack stability

Once a snowpit has been excavated, a range of tests may be carried out which allow the stability of the snowpack to be assessed. Stability tests are widely employed, as they enable weak layers to be located, and fracture characteristics to be observed (van Herwijnen and Jamieson, 2007). Two such tests are the compression and extended column tests (CT and ECT, respectively). The CT is noted as a quick stability test (Jamieson and Johnston, 1996), and as such it is widely utilised as an indicator of snow stability (Stewart and Jamieson, 2002; Winkler and Schweizer, 2009). Section 3.3.1.1 provides a detailed description of the CT procedure. Research has shown that human triggered avalanches are more likely when an ‘easy’ CT result has occurred, as opposed to a ‘hard’ test result (Jamieson, 1999). If a fracture occurs during a CT, its character should also be noted. Broadly, fracture character may be either sudden, resistant or break. As the name suggests, a sudden fracture character represents the most unstable character, and it involves a fracture propagating across the entire column in a single loading step (strike). Notably, sudden fractures are the
most common fracture character associated with slab avalanche occurrences (van Herwijnen and Jamieson, 2007).

Despite the prominent use of the CT, studies have determined that the ECT is generally a more reliable indicator of slope stability (Winkler and Schweizer, 2009; Simenhois and Birkeland, 2009; Schweizer and Jamieson, 2010). The ECT was first developed and performed in field studies by Simenhois and Birkeland (2006, 2007); Section 3.3.1.1 provides a description of the ECT procedure. The ECT differs from the CT in that if a fracture does initiate, the fracture propagation propensity may also be observed. This is possible due to the larger size of the isolated column in an ECT (90 cm x 30 cm) compared to the CT (30 cm x 30 cm). The ability to observe fracture propagation potential is valuable, as avalanche release results from both the initiation and propagation of a fracture across a weak layer (Hendrikx et al., 2009).

Currently, no criteria have been set regarding the stability test score and its relevance to snowpack stability. This may be due in part to the variability inherent in carrying out stability tests, e.g. different practitioners unintentionally applying different levels of force during stability testing. Furthermore, it must be noted that the number of taps per level of force, and the total number of taps per test, are arbitrary. CTs and ECTs may stop at 30 taps, yet a fracture could have occurred on tap 31. Nevertheless, as previously inferred, the lower the stability score, the more unstable a slope is likely to be. In a study comparing stability tests, Schweizer and Jamieson (2010) created a CT score stability threshold; CT scores < 14 were indicative of instability, and CT scores ≥ 14 were indicative of stability. Schweizer and Bellaire (2010) created a CT score stability threshold with additional complexity. Specifically, CT scores ≤ 13 were indicative of poor stability, 14 ≤ x ≤ 20 were indicative of fair stability, and 20 ≤ x ≤ 30 were indicative of good stability. Again, these numbers are arbitrary. ECT results may provide a clearer indication of slope stability compared to CT, due to fracture propagation potential being observed. If a fracture initiates and propagates across the entire ECT column, then the result may be deemed indicative of instability (Simenhois and Birkeland, 2009; Schweizer and Jamieson, 2010). If a fracture does not propagate across the entire ECT column, then the result may be deemed indicative of stability (Simenhois and Birkeland, 2009; Schweizer and Jamieson, 2010).
2.5.3 The three-component model of stability

In the absence of stability test scores providing a definitive indication of slope stability, a recent study by McCammon and Sharaf (2005) sought to combine a range of evidence to provide a more comprehensive indication of snowpack stability. To achieve this, the authors propose a three-component model of stability combining strength, energy and structure. The strength component of the model is obtained from stability test results, and infers snowpack stability based on lower test scores being representative of greater snowpack instability. The energy component is based on the fracture character observed when undertaking stability tests. Here, fracture characters that are sudden (sudden planar and sudden collapse) are indicative of snowpack instability, whereas the remaining fracture characters (resistant planar, progressive compression and break) are indicative of snowpack stability. The final component is structure, and utilises the classification of ‘lemons’ described by McCammon and Schweizer (2002). Again, the greater the number of ‘lemons’ observed, the greater the snowpack instability. It appears that accounting for each of the three components of stability enables a more comprehensive and holistic view of stability to be obtained. If all three components suggest snowpack stability, then greater confidence can be placed on that conclusion than if the decision was based upon only one component. As such, the three-component model of stability emerges as an effective method of characterising snowpack stability. It must be noted that this model of characterising snowpack stability is largely qualitative. This reflects the fact that despite stability assessments being based in part on quantitative data, overall stability assessments are qualitative. This can present challenges in making meaningful comparisons of stability ratings, due to the fact that there exists a certain level of ambiguity in qualitative assessments of snowpack stability. The present study attempts to address this challenge, by formulating a qualitative method of defining snowpack stability, based upon the three-component model of stability (Section 3.4.1.1).

2.6 Spatial and temporal variability of snowpack stability

The spatial variability of factors contributing to snowpack stability has been the topic of significant contemporary focus (Schweizer et al., 2008). This trend may be partly attributed
to the critical role spatial variability plays when considering avalanche formation. Currently, it is a source of considerable uncertainty in avalanche forecasting due to the multiple levels of scale involved (Schweizer et al., 2003b; Hägeli and McClung, 2004), ranging from micro-scale (e.g. snow crystal) to macro-scale (e.g. mountain range). Conway and Abrahamson (1984) produced a landmark paper regarding the spatial variability of snowpack stability. Their fieldwork was carried out in the Tasman Saddle area of New Zealand, and compared shear strength measurements (which indicates snowpack stability) from slopes that had recently avalanched, to slopes that hadn’t avalanched. The authors identified areas of pinning (strength) and deficit (weakness), which were spatially discontinuous, and concluded that the likelihood of avalanche release would increase as the measured value of shear strength decreased, or the areas of deficit increased. This paper triggered an interest in the spatial variability of a range of factors contributing to snowpack stability, including persistent weak layer distribution (e.g. Schweizer and Kronholm, 2007; Guy and Birkeland, 2010; Lutz and Birkeland, 2011) and snow hardness (e.g. Birkeland et al., 1995; Birkeland et al., 2004; Kronholm et al., 2004; Schweizer et al., 2008b; Bellaire and Schweizer, 2008, 2011). Furthermore, a number of studies have utilised modelling to address the issue (e.g. Fyffe and Zaiser, 2004; Kronholm and Birkeland, 2004, 2005; Schirmer et al., 2010).

2.6.1 Spatial variability at the mountain range scale

Spatial variability of snowpack stability occurs over a range of scales. Birkeland (2001) sought to test spatial variability at the mountain range scale, recognising that avalanche forecasts are usually based on limited field data, which is then extrapolated to similar terrain. The author demonstrated links between terrain and stability, with greater instability observed at higher elevations and more shaded aspects. This conformed to common observations in the area, such as shaded aspects being more unstable as a result of a relatively colder snowpack, within which weak layers persist for longer periods of time. Schweizer et al. (2002) also demonstrated spatial variability at the mountain range scale, and showed that the amount of variability observed remained the same across different forecasted levels avalanche danger. An issue with both studies is that a minimum of 12
different individuals collected stability test data. For reliability of results, it would be preferable for stability tests to be carried out by a single experienced observer. Nonetheless, it must be acknowledged that the use of multiple observers is the only way such a large spatial scale study could be undertaken in a single day. Whilst mountain scale variability remains as an important consideration for many avalanche forecasting operations, it is smaller, slope scale variability which has received more scholarly attention. This is reflective of larger scale variability of stability, as influenced by elevation, slope aspect, and exposure to wind, being relatively well understood. Slope scale variability of stability has proven more perplexing, as evidenced by examples of avalanches being triggered by not the first, but a subsequent skier on a slope (Harvey and Signorell, 2002; Schweizer and Bellaire, 2010). Because avalanche formation is a process occurring primarily at the slope scale (Schweizer et al., 2008), the remainder of this review will focus on studies carried out at this scale.

2.6.2 Spatial variability at the slope scale

Both low and high stability test results have been obtained from the same slope when testing is carried out on the same day (e.g. Kronholm and Schweizer, 2003). Föhn (1988) tested two avalanche slopes extensively, and found one and two zones of instability on each slope, respectively. However, the vast majority of test results indicated that the slopes were stable. Subsequent bombing and “intensive” skiing of the slopes confirmed the finding that the slopes were stable. The author concluded that in order for an avalanche to have occurred on these slopes, either the total number, or the size of instability zones, needed to be larger. Due to the overwhelming predominance of stability tests showing high stability, no discernible spatial pattern of stability was observed. In contrast, Simenhois and Birkeland (2007, 2009) observed a clustering of stability scores at the slope scale (Figure 2.5). The slope tested was convex, with slope angles ranging from 27° at the top of the slope to 33° at the bottom. The authors attributed the spatial variability observed to the variability of the slab overlying the weak layer. Low stability test scores were obtained were the slab was relatively hard, whereas high stability test scores occurred where the slab was relatively soft. Stewart and Jamieson (2002) also observed a clustering
of low and high stability test scores at the slope scale. However, the clustering observed in both studies was based on a visual assessment by the authors. Therefore, no statistical significance can be placed on these findings. Slab variability was also suggested by Campbell and Jamieson (2004) as a factor contributing to spatial variability. These authors found that areas of relatively thin slabs tended to have a lower stability score than areas of relatively thick slabs. Varying slope angle was another reason provided, as relatively high slope angles tended to have lower stability scores. Notably, a limited slope angle range of 30° to 36° were tested in this study. Furthermore, the conclusion was based on the aforementioned observation being obtained in only 7 out of the 29 arrays in the study, which doesn’t constitute conclusive evidence. In fact, 3 arrays showed the opposite relationship, with lower slope angles having lower stability scores.

![Figure 2.5](image.png)

**Figure 2.5** Results of 24 ECTs obtained from a single slope by Simenhois and Birkeland (2007, 2009), demonstrating a clustering of ECTP results. a) The spatial context for the location of stability sampling, with the curved black line drawn to indicate the lowest extent of the hard slab observed in the field. b) Close-up of the gridded pattern of stability sampling, with the ECT result attributed to each of the associated 24 snowpits. The letter ‘P’ represents an ECTP result (indicative of relatively low stability), and the letter ‘N’ represents an ECTN result (indicative of relatively high stability). Images obtained from Simenhois and Birkeland (2009).

In order to remove slope angle as a potential contributor to slope scale spatial variability of snowpack stability, studies have been carried out on slopes which are uniform. Simenhois and Birkeland (2006) tested the spatial variability of a 32° slope classified as stable at Mt Hutt, New Zealand. The ECT was used, and with respect to fracture propagation, spatial uniformity was observed. Specifically, of 21 ECTs, no fracture propagations were
observed. Spatial variability of fracture initiation scores were observed, with tap scores of the 21 tests ranging between 11 taps and 18 taps. Landry et al. (2002, 2004) tested seven slopes, which were undisturbed by artificial activity, and had uniform slope angles ranging between 25° and 30°. This study addressed whether or not testing from within a single snowpit can reliably represent the snowpack strength and stability of an entire slope. Of 54 total snowpits, the stability obtained from only 26 snowpits were representative of the associated slope stability. Thus, the authors acknowledge the potential unreliability of using stability tests alone when assessing the stability of a slope. This conclusion is supported by Birkeland and Chabot (2006), who reported a 13% “false-stable” (i.e. stability test result was stable when in fact the tested slope was unstable) ratio overall from 289 stability tests on unstable slopes. This data comprised a number of different stability tests, with the “false-stable” ratio of CTs found to be 14%. Such results suggest, quite simply, that one stability test is insufficient to reliably determine the stability of a slope (Kronholm et al., 2004). As a result, Birkeland and Chabot (2006) suggest undertaking more than one stability test on a given slope, in order to reduce the likelihood of classifying a slope as stable when in fact it is unstable. Importantly, the authors recommend that a well placed testing site, which is representative of the slope in question, is vital in order to enhance the likelihood of correctly determining the stability of the slope in question. In order for a testing site to be representative of the slope in question, it should be of comparable aspect, slope angle, and share the same snowpack structure as the majority of the slope in question.

Evidently, the potential exists to incorrectly classify slope stability due to spatial variability. Thus, a comprehensive classification approach, such as the three-component model of stability (McCammon and Sharaf, 2005) outlined in Section 2.3, is clearly a valuable method to follow. A recent study by Birkeland et al. (2010) sought to identify what spacing between stability tests would optimise slope stability assessments. As such, the authors addressed the issue of spatial autocorrelation, that is, how correlated are stability test results to adjacent stability test results within a slope. In order to more accurately assess the stability of a slope, it has been suggested that two stability tests should be carried out beyond the correlation length of the slope. Previous studies have reported a range of correlation length values (e.g. Kronholm et al., 2004b), and as a result, the correlation length remains unknown (Schweizer and Bellaire, 2010). Nevertheless, a contemporary proposal
suggests independent stability tests should be spaced at least 10 m apart (Schweizer et al., 2008). The results of the Birkeland et al. (2010) study regarding the optimal spacing of stability tests were inconclusive, with a range of optimal spacing distances reported. As such, the aforementioned recommendation of Birkeland and Chabot (2006) regarding the importance of representative site selection of stability tests remains most pertinent.

Schweizer and Bellaire (2010) provide further evidence regarding the unreliability of determining slope stability from a single snowpit. This study was based in the Swiss Alps, near Davos. 22 small slopes were analysed, and the average slope angle of these slopes was 25°. Four pairs of CTs were performed within four snowpits on each slope, and each snowpit was evenly spaced apart from each other (Figure 2.6). Due to a pair of CTs being undertaken at each snowpit location, analysis of both small scale (less than one metre) and larger scale (up to 15 m on each slope) variability could be made. The authors found that within a single snowpit, the two stability test results were similar for 61% (75%) of the cases, with respect to the CT score (fracture character).

![Figure 2.6](image)

**Figure 2.6** Stability sampling strategy of Schweizer and Bellaire (2010). Four evenly spaced snowpits were dug, with two CTs performed in each snowpit, enabling pit-scale and slope scale variability to be observed. Figure obtained from Schweizer and Bellaire (2010).

Using an average test score obtained from the two tests in each pit, the authors were able to carry out a slope scale analysis of spatial variability between each pit. At the slope scale,
59% (75%) of stability test results were similar with respect to the CT score (fracture character). As such, it may be inferred from this study that the spatial variability of CT scores is greater than it is when considering fracture character. This is supported by Campbell and Jamieson (2007), who found fracture character results were less spatially variable than stability test results. Based on further analysis of their results, Schweizer and Bellaire (2010) make an interesting suggestion. The authors believe that it is not always necessary to dig more than one snowpit in order to judge the stability of a slope. Specifically, if low CT scores coupled with sudden fracture occur in both tests within a snowpit, then it is indicative of highly unstable conditions. The practical application of such a result is that slopes where such results are located should be avoided, as it indicates avalanche activity is rather more likely. This suggestion is linked to the authors finding that small scale variability was more prominent on slopes rated as having good stability. Examination of the literature shows that this finding is not unique. For example, Conway and Abrahamson (1984) and Schweizer and Bellaire (2010) also found such a result. This raises an important thought, whereby spatial variability (specifically at small sub-slope scales) may result in a more stable slope, through counteraction of fracture propagation (avalanche formation). Such findings make an implicit link to temporal variability. Specifically, slope stability may become more spatially variable as overall stability increases over time (Birkeland and Landry, 2002).

2.6.3 Temporal variability at the slope scale

Studies have addressed the temporal variability of snowpack stability at the slope scale. Logan et al. (2007) demonstrated a strengthening of buried surface hoar layers (a form of persistent weak layer) over time, although the rate of strengthening decreased. Furthermore, the authors found that weaker areas of the snowpack tend to remain relatively weak, despite overall strengthening at the slope scale. Birkeland and Landry (2002) also examined the temporal variability of snowpack stability. The authors tested one slope on three different days, with a 30 m x 30 m plot of slope tested each time. The slope angle of slope tested ranged between 25° and 28°. Testing was carried out over the course of about three weeks. On day one of testing, the snowpack stability ratings obtained from
each of the five pits were representative of the plot-wide stability rating. On day two, this decreased to three, therefore increasing spatial variability was observed between day one and day two. On day three, the stability rating obtained from four of five pits were representative of the plot. As a result, the initial temporal variability trend was reversed, and spatial variability at the plot scale decreased. The authors identified that the most hazardous situation for an observer exists when pit (small) scale variability is low (promoting a sense of conviction for an observer regarding their stability rating) but the plot (larger) scale variability is high. Once again, the representativeness of an individual pit observation with respect to an entire slope is questioned. The method of sampling undertaken by Birkeland and Landry (2002) was destructive, meaning each area of the slope could only be tested once. Therefore, in order to assess temporal variability, it had to be assumed that the stability within each section of the slope was relatively similar at the beginning of the study, and would undergo similar temporal changes over the course of the study. Given significant evidence of spatial variability existing within a slope, and no evidence of how to account for this without in-situ testing, this assumption is dubious. As such, it raises an important issue; how can the same area of a single slope be tested in order to carry out a reliable temporal variability analysis?

This issue was successfully addressed by Hendrikx and Birkeland (2008) and Hendrikx et al. (2009). The authors developed a gridded sampling strategy, with snowpits spaced apart evenly by 10 m (Figure 2.7). This enabled subsequent sampling of the same area of slope, through offsetting the gridded pattern of sampling by five metres. The focus of these studies was on the spatial and temporal variability of fracture propagation (as determined by the ECT). Fieldwork was carried out at three locations; two in Montana USA, and one at Broken River Ski Area, New Zealand. The slope angle at one of the USA sites averaged 30°, but decreased to 26° near the top of the slope. At the second USA site, slope angle averaged 29°. No slope angle information was provided for the New Zealand site. At both USA locations, fracture propagation results were randomly distributed on the first day of testing (as determined by statistical analysis). At both sites, evidence of a temporal change to increased clustering of fracture propagation results on day two of testing was obtained. Furthermore, ECTP scores increased from day one to day two at both sites. However, at only one site was the increase statistically significant.
At the New Zealand location, non-spatially variable ECTP results were observed. Specifically, only one ECTP result out of 24 ECT was recorded over the two days of testing. CTs were also carried out at one of the USA locations and at the NZ location. At the USA location, the average CT tap score increased from an average of 8.9 taps to 13 taps, however this increase was not statistically significant. At the New Zealand location, the average CT tap score increased from an average of 13.8 taps to 19 taps, and the increase was statistically significant. The standard deviation of the CT scores at the New Zealand study site also increased. This is further evidence of a snowpack that has increased in stability, yet become more spatially variable.

![Figure 2.7](image)

**Figure 2.7** ECT results obtained in a study by Hendrikx et al. (2009) at one of their two USA study sites. The left represents ECT scores obtained on the first day of stability sampling, and the right represents ECT scores obtained on the second day of stability sampling. Only ECTP results are shown, with the number representing the number of taps required for an ECTP result. 16 ECTs were performed on each day, and were evenly spaced 10 m apart from each other. The gridded stability sampling scheme was offset 5 m in both the upslope and across slope direction from day one of stability sampling to day two of stability sampling, in order to enable the same area of slope to be tested. Figure obtained from Hendrikx et al. (2009).

The strategy employed by the authors meant that snowpits which were dug on the second day were five metres away from the snowpits which were dug on the first day. It is assumed that once measurements were made on the first day, the snowpits were filled back in, although this concern isn’t addressed in the paper. Nevertheless, snowpits are an intrusive method of examining a snowpack. As one of the slopes tested had a solar aspect, and testing appeared to be undertaken on fine weather days, a certain amount of extra solar
energy (warmth) may have been added to the snowpack of that slope, which otherwise wouldn’t have occurred. The potential implications of this are yet to be fully explored. However, as noted by Hendrikx et al. (2009), a perfect technique for undertaking such temporal analyses has yet to be developed. Thus, this sampling strategy currently appears to be the most effective way in which temporal variability of snowpack stability can be tested.

### 2.6.4 Stability sampling methodological issues

Throughout this review, it is apparent that studies have been undertaken on a wide range of slope angles. Many studies either haven’t specified the slope angle of slopes tested (e.g. Föhn, 1988), or carried out testing on slopes which had an angle of less than 30° (e.g. Birkeland and Landry, 2002; Simenhois and Birkeland, 2009; Hendrikx et al., 2009; Schweizer and Bellaire, 2010). This is critical, because avalanches primarily initiate on slope angles between 30° and 45° (Perla, 1977; Schweizer and Jamieson, 2001; Schweizer and Lütschg, 2001). A recent study showed evidence that slope angle had little effect on ECTP results, so long as the snowpack structure showed little spatial variability (Birkeland et al., 2010b). The implication of this is that there is potential to garner comparable stability test results from safe terrain to that which would be obtained in avalanche terrain. The results of this study are encouraging. However, testing was only carried out at two locations (Montana and Alaska, USA), only one stability test was used, and the specific weak layer tested was buried surface hoar. Therefore, it remains inappropriate to consider the results of the study as a general rule, at least until further studies are carried out. Furthermore, it stands to reason that the most pertinent information regarding snowpack stability will always be that which is collected from primary avalanche terrain. A further issue regarding stability sampling studies pertains to the large number of differing stability tests and sampling designs used (Schweizer et al., 2008). Such discrepancy between studies impacts on the comparability of their results (Hendrikx and Birkeland, 2008). Clearly then, consistent methods between studies should be used where possible, in order to maximise the comparability of results.
2.6.5 Implications for avalanche hazard

The spatial variability of snowpack stability provides a challenge for snow safety practitioners, and ski area management alike. In order to make reliable interpretations of snowpack stability, and to ensure the safe operation of a skifield, the spatial and temporal variability must be accounted for. At the Craigieburn Valley Ski Club, snow safety practitioners are guided by a comprehensive snow safety plan, which details typical stability concerns observed in the area, and methods to deal with such concerns. Snow safety practitioners seek to control the snowpack stability (and inherently, the spatial variability of snowpack stability) of ski areas, and reduce the potential avalanche hazard. This is achieved by a ‘hands-on’ approach, whereby slopes may be stabilised by, for instance, bombing, ski-cutting or boot-packing techniques. Generally, such a ‘hands-on’ approach is limited to terrain within ski area boundaries only. As such, this can result in considerable discrepancy in snowpack stability between a ski area and the adjacent backcountry, despite the close proximity of the two locations. This may also result in considerable discrepancy in the potential avalanche hazard of the two locations.

2.7 Summary and research opportunities

Through a comprehensive review of pertinent literature, a number of key ideas and issues have been identified. Slope angle is of critical importance, as avalanches primarily initiate on terrain with a slope angle between 30° and 45°. Despite this distinction, numerous snowpack stability studies have been undertaken on terrain which doesn’t meet this threshold. Determining stability is a complex task, which can be achieved with higher reliability by combining snowpack strength, energy and structural observations. Spatial variability of snowpack stability appears to be higher on more stable slopes, which introduces a temporal variability aspect to spatial variability. Specifically, it may be inferred that as a slope becomes more stable, the spatial variability of stability within that slope will increase. A difference in sampling strategies between studies has emerged as a key issue. As such, studies should employ similar sampling strategies in order to maximise the comparability of results obtained. Further exploration of the literature has exposed a number of gaps in the current state of knowledge. Firstly, there is room for improvement
regarding the current state of avalanche terrain analysis for the Craigieburn Valley, particularly for the backcountry. As such, the present study aims to carry out an analysis of the avalanche terrain of the Craigieburn Valley, and in doing so, will address the first objective of this study. Secondly, whilst a number of studies regarding the spatial variability of snowpack stability exist, few of such studies have been undertaken in New Zealand. The need exists to carry out a New Zealand based study, in order to provide insight into the spatial and temporal variability of snowpack stability in the New Zealand setting, and to determine whether snowpack stability relationships are comparable to those demonstrated in North America and Europe.
Chapter 3

Methods

3.1 Introduction

This chapter outlines the data collection and processing methods used to investigate the spatial variability of snowpack stability at the slope scale, and how that spatial variability changes over time, in the Craigieburn Valley, New Zealand. Section 3.2 describes the physical setting of Craigieburn Valley, and justifies why it was a suitable location to carry out the present study. Data collection methods are presented in Section 3.3, and data processing methods are explained in Section 3.4. As such, the following chapter will clarify how the research objectives of this study (Section 1.3) were achieved.

3.2 Research location

3.2.1 Physical setting of Craigieburn Valley

Craigieburn Valley is located towards the northern end of the Craigieburn Range of the South Island, New Zealand. The Craigieburn Range lies broadly north-south in orientation, and is approximately 26 km in length. Situated 25 km east of the Main Divide of the Southern Alps, Craigieburn Valley is around 100 km inland from both the Tasman Sea to the west, and the Pacific Ocean to the east (Figure 3.1). Craigieburn Valley in its entirety has a relative relief 1,189 m, ranging from a minimum elevation of 733 metres above sea level (m a.s.l.), to a maximum elevation of 1,922 m a.s.l. (Hamilton Peak). The lower elevations of the valley are predominantly covered by mountain beech forest. In contrast,
higher elevations comprise a combination of snow tussock, scree, and outcrops of bedrock (McNulty, 1984), typical of that which is observed along the remainder of the Craigieburn Range (Prowse and Owens, 1984).

Figure 3.1 Map of the Craigieburn Valley. Each ‘X’ indicates the location of stability testing performed in this study. Inset: location of study area within the central South Island, New Zealand (modified from Geographx). Aerial photograph SN8584 obtained from NZ Aerial Mapping Limited, topographic data sourced from the LINZ Topo50 database.
As the present study is focused on avalanche terrain, snowpack stability and the associated avalanche hazard, further clarification of the physical setting of the research is required. Due to factors including ease of access, and typical elevation extent of seasonal snow accumulation, winter recreation within the Craigieburn Valley is predominantly undertaken at elevations above 1,200 m a. s. l. As such, the most significant hazard associated with avalanche activity is similarly located above 1,200 m a. s. l. Therefore, elevations below 1,200 m a. s. l. have been disregarded from analysis for the remainder of the present study. This gives rise to the following definitions of physical settings for the present study’s research:

- **Craigieburn Valley ski area** – this encompasses all terrain which is bound by the current Craigieburn Valley Ski Club ski area boundary (Figure 3.2). The Craigieburn Valley ski area has a relative relief of 722 m (1,200 m a.s.l. – 1,922 m a.s.l.), and an area of 151.9 ha.

- **Craigieburn Valley backcountry** – this encompasses terrain within the Craigieburn Valley to the north of the current ski area boundary, above 1,200 m a.s.l., within an area known as Middle Basin (Figure 3.2). The Craigieburn Valley backcountry has a relative relief of 626 m (1,200 m a.s.l. – 1,826 m a.s.l.), and an area of 99.1 ha.

- **Craigieburn Valley** – this will hereby refer to the terrain of both the Craigieburn Valley ski area and the Craigieburn Valley backcountry as defined above. As such, the Craigieburn Valley has a relative relief of 722 m (1,200 m a.s.l. – 1,922 m a.s.l.) and an area of 251 ha.
Figure 3.2 West-northwest facing view of Craigieburn Valley, subdivided into the current ski area boundary (red) and the backcountry terrain of Middle Basin (blue). The black lines within the ski area represent the approximate location of rope-tows used to access Craigieburn Valley terrain. Each ‘x’ on the image shows the location where stability testing was performed for the present study.

3.2.2 Climate setting

The Craigieburn Range receives approximately 1,800 mm of precipitation annually. Precipitation primarily comes from north-westerly airflows (Morris and O’Loughlin, 1965), with over 80% of total annual precipitation received from north-westerly to south-westerly airflows (Prowse and Owens, 1984; McGregor 1990). Snow may fall along the Craigieburn Range at any time of year, yet there are no perennial snowfields. The seasonal snowpack of the range usually begins accumulating above 1,200 m a.s.l. in May or June, and typically reaches a peak in depth in September (McNulty, 1984). Air temperatures may fluctuate above and below freezing point during any month of the year (Table 3.1). Specifically, air temperatures can vary considerably on a diurnal or day-to-day basis (Prowse and Owens, 1984), as a result of the advection of air masses with relatively high (low) temperatures, typically associated with north-westerly (southerly) airflows. The lowest monthly mean air
temperature of -1.7°C is experienced in July, yet air temperatures of up to 9.1°C have been recorded at 1,554 m a.s.l. during this month (Table 3.1). The mean air temperature appears to rise above freezing during August or September, with the highest monthly mean air temperature of 9.5°C recorded in February. The seasonal variation in air temperatures of the Craigieburn Range is not as pronounced as those observed in continental climates (Prowse and Owens, 1984).

McNulty (1984) suggests a low pressure system moving eastwards across the south of the South Island is the most common meteorological condition which results in heavy snowfall during the winter months for the Craigieburn Valley. As the associated trough of low pressure passes over Craigieburn Valley, airflow generally shifts from the north-westerly quarter to the southerly quarter. During the north-westerly phase, air temperatures are relatively high, and precipitation may initially fall as rain to ridge-top. As the airflow shifts to the south, air temperatures progressively decrease. Such progression of air temperatures over the course of a storm has important implications for snowpack stability of Craigieburn Valley. Relatively high temperatures at the onset of a storm promote bonding between the former snowpack surface and the new snowfall, which may enhance the stability of the old snow – new snow interface. However, this benefit to snowpack stability is often offset by Craigieburn Valley’s location to the lee of the airflow of such storm events. This may result in significant redistribution of snow, and windslab formation throughout Craigieburn Valley terrain.
Table 3.1 Craigieburn Range monthly air temperature data. Data measured at 1,554 m a.s.l., in the valley immediately adjacent to the south of Craigieburn Valley (Figure 3.8), from July 1966 to September 1986. Data modified from NIWA (2012).

<table>
<thead>
<tr>
<th>Month</th>
<th>Absolute min.</th>
<th>Mean min.</th>
<th>Mean</th>
<th>Mean max.</th>
<th>Absolute max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>-6.7</td>
<td>5.0</td>
<td>8.8</td>
<td>12.9</td>
<td>24.0</td>
</tr>
<tr>
<td>February</td>
<td>-5.8</td>
<td>5.3</td>
<td>9.5</td>
<td>13.6</td>
<td>25.0</td>
</tr>
<tr>
<td>March</td>
<td>-7.0</td>
<td>4.1</td>
<td>7.7</td>
<td>11.3</td>
<td>22.4</td>
</tr>
<tr>
<td>April</td>
<td>-8.6</td>
<td>1.6</td>
<td>4.9</td>
<td>8.1</td>
<td>18.2</td>
</tr>
<tr>
<td>May</td>
<td>-10.2</td>
<td>-1.1</td>
<td>1.8</td>
<td>4.7</td>
<td>13.3</td>
</tr>
<tr>
<td>June</td>
<td>-11.5</td>
<td>-3.3</td>
<td>-0.5</td>
<td>2.2</td>
<td>11.1</td>
</tr>
<tr>
<td>July</td>
<td>-12.2</td>
<td>-4.3</td>
<td>-1.7</td>
<td>1.0</td>
<td>9.1</td>
</tr>
<tr>
<td>August</td>
<td>-14.5</td>
<td>-4.0</td>
<td>-1.1</td>
<td>1.7</td>
<td>13.5</td>
</tr>
<tr>
<td>September</td>
<td>-11.4</td>
<td>-2.6</td>
<td>0.4</td>
<td>3.3</td>
<td>14.6</td>
</tr>
<tr>
<td>October</td>
<td>-10.3</td>
<td>-0.8</td>
<td>2.6</td>
<td>6.0</td>
<td>15.0</td>
</tr>
<tr>
<td>November</td>
<td>-9.0</td>
<td>1.1</td>
<td>4.8</td>
<td>8.5</td>
<td>22.5</td>
</tr>
<tr>
<td>December</td>
<td>-5.7</td>
<td>3.4</td>
<td>7.5</td>
<td>11.5</td>
<td>20.2</td>
</tr>
</tbody>
</table>

Snowfall and snowpack structure information has been utilised to deduce that the Craigieburn Range snow climate displays characteristics of both continental and maritime locations (Prowse and Owens, 1984). This observation is supported by McGregor (1990). The author notes that both temperature-gradient metamorphism, which is typical within continental snowpacks and results in persistent weak layer formation, and melt-freeze processes, typical of maritime snowpacks, create weak layers in the Craigieburn Range that may contribute to avalanche release (McGregor, 1990). Therefore, the snow climate of Craigieburn Valley may be most accurately defined as transitional.
3.2.3 Research location justification

Craigieburn Valley was an ideal location to carry out the present study for a number of reasons. Anecdotal evidence, supported by previous studies (e.g. McNulty, 1984) suggested that there was considerable avalanche terrain within Craigieburn Valley. Therefore, the potential for avalanche hazard exists in the area. In order to achieve research objective (2), it was necessary to carry out stability testing on a slope that had not been disturbed by artificial activity. For logistical purposes, such a slope had to be easily accessible. The presence of a skifield within Craigieburn Valley facilitated easy access to undisturbed backcountry terrain. As such, the skifield also facilitates recreation, and exposure of recreationalists to avalanche terrain. In addition, due to the ease of access to the backcountry, backcountry recreation is popular within Craigieburn Valley. As a result, the aforementioned potential for avalanche hazard is realised. An important component of hazard mitigation is hazard identification. Therefore, carrying out a snowpack stability study in the Craigieburn Valley has inherent value. The results of the present study highlight issues associated with avalanche hazard in the area, allowing practical implications to be drawn for both recreationalists and Craigieburn Valley Ski Club management (Section 5.5.2).

3.3 Data collection

The fieldwork campaign for the present study encompassed 35 consecutive days, from 22 June to 26 July, in the Austral winter of 2012. The author remained ‘on-mountain’ for the entire duration of the campaign. This enabled a continuous, detailed observation of the weather and snowpack in the lead-up to stability testing being performed. As such, a depth of understanding to the results obtained was achieved, which would not have been possible without spending an extended period of time ‘on-mountain’. Furthermore, this allowed a study slope to be roped-off in the backcountry prior to public access of the area (Craigieburn Valley ski area opened to the public for the 2012 Austral winter season on 30 June), ensuring the backcountry test slope remained undisturbed from artificial activity.
3.3.1 Stability testing sampling strategy

One issue of previous studies examining snowpack stability pertains to the disparity in methodology employed. As established in Section 2.6.4, studies of snowpack stability should employ consistent sampling strategies in order to maximise the comparability of the results obtained. Thus, the current study employed almost identical sampling strategies to those employed by two contemporary snowpack stability studies (Hendrikx et al. 2009; Schweizer and Bellaire, 2010). Significantly, Hendrikx et al. (2008, 2009) were the first to develop and utilise a sampling strategy which enabled the temporal variability of the same section of a slope to be observed. Use of this sampling strategy in the present study enabled research objective (2) to be achieved. In order to maintain consistency in stability testing technique and sampling strategy, the author of the current study carried out all stability sampling described herein.

3.3.1.1 Craigieburn Valley backcountry sampling strategy

A suitable section of slope was selected for carrying out stability testing in the Craigieburn Valley backcountry. The section of slope was deemed suitable as it appeared uniform, and was representative of the Craigieburn Valley backcountry terrain in general (Section 4.2). It was important to carry out stability testing in the backcountry, as the snowpack in this location is uncontrolled by snow safety practitioners. Therefore, the natural spatial variability of snowpack stability could be observed. The section of slope chosen had an elevation of 1,650 m a.s.l., a slope angle of 37°, and a southerly aspect. The section of the slope to be tested was roped off, to ensure it wasn’t disturbed by artificial activity. Approximately 65 m by 45 m of the slope was roped off, using bamboo sticks and hot-tape (Figure 3.3). Within the roped off section of the slope, 15 snowpits were dug on the first day of stability testing (7 July 2012). It would have been preferable to dig an even greater number of snowpits, however 15 snowpits represented the maximum number the author could achieve during daylight hours, whilst ensuring accuracy of sampling procedure and reliability of the results obtained. In any case, 15 snowpits proved a sufficient number to address research objective (2). The 15 snowpits were spaced evenly in a gridded pattern, with 10 m spacing between adjacent snowpits (Figure 3.4). Three snowpits were dug in the
upslope direction, and five snowpits were dug in the across slope direction. The second
day of stability testing (11 July 2012) was carried out four days after the first day of testing.
This is in accordance with two of the three study sites tested by Hendrikx et al. (2008),
including their New Zealand site. On day two of testing, a further 15 snowpits were dug
within the roped off section of the slope, and the same gridded pattern of sampling that
was used on the first day of testing was employed. These snowpits were offset five metres
in the upslope direction, and five metres in the across slope direction, in order to allow
sampling of the slope which had been unaffected by artificial activity (Figure 3.4). It must
be noted that the intrusive nature of the sampling strategy on day one of testing may have
affected the snowpack stability results on day two of testing; this concern is addressed in
Section 5.6. Each snowpit was wide enough to allow stability testing to be carried out, and
the snowpits were fully excavated to the ground surface below the snowpack.

Figure 3.3 Location of the section of slope where stability testing was performed in the
Craigieburn Valley backcountry (highlighted in blue). This section of slope had a southerly
aspect, a slope angle of 37°, and an elevation of 1,650 m a.s.l.
Figure 3.4 Gridded sampling methodology for the Craigieburn Valley backcountry study slope. Snowpits were evenly spaced by 10 m on each day of testing. Fifteen snowpits were examined on the first day of testing (7 July), and are represented by the solid squares. On the second day of testing (11 July), the gridded sampling methodology was offset five metres in both the upslope and across slope direction (represented by the dashed boxes). This enabled the examination of a further 15 snowpits on a second day of testing (11 July) within areas of the slope which remained undisturbed by sampling that was carried out on the first day of testing.

Within each snowpit, two compression tests (CTs) and one extended column test (ECT) were performed. The following description outlines the CT procedure, which follows the standard procedure of the CT prescribed by the New Zealand Mountain Safety Council (2011):

The procedure for this test first involves isolating a 30 cm by 30 cm column of snow, which must be deep enough to expose potential near surface weak layers. A shovel blade is then placed atop the column, and is struck 10 times per level of force, of which there are three (known as loading steps). The first level of force involves tapping the shovel blade with the hand, hinging the hand from the wrist. The second level of force involves hitting the shovel blade with the hand, hinging the forearm from the elbow. Finally, the third level of force involves striking the shovel blade with the hand, hinging the arm from the shoulder. If a fracture occurs during the process of striking, it may be termed an easy (CTE),
moderate (CTM) or hard (CTH) result, depending on whether the fracture occurred during the first, second or third level of force (loading step), respectively. If the snowpack is particularly unstable, a fracture may initiate in the column of snow whilst the column is being isolated. This is the most unstable result that may be obtained from a CT, as no taps are required to initiate a fracture. Such a result is termed very easy (CTV). As such, fracture initiation results may vary from 0 taps (CTV) to 30 taps (CTH). If no fracture occurs during the CT, then it is termed a no result (CTN). Table 3.2 outlines the CT classification scheme. Fracture character observed during the CT should also be recorded. Table 3.3 outlines the classification of fracture character. As highlighted in Section 2.5.2, sudden fracture characters represent the most unstable fracture character. The depth of the fracture from the snow surface was recorded, as was the snow crystal size and snow crystal form of the weak layer that the fracture occurred on.

Table 3.2  Compression test classification scheme, adapted from the New Zealand Mountain Safety Council (2011).

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
<th>Data Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very easy</td>
<td>Fracture occurs during column isolation</td>
<td>CTV</td>
</tr>
<tr>
<td>Easy</td>
<td>Fracture occurs within 10 light taps hinging hand from wrist</td>
<td>CTE</td>
</tr>
<tr>
<td>Moderate</td>
<td>Fracture occurs within 10 moderate taps hinging forearm from elbow</td>
<td>CTM</td>
</tr>
<tr>
<td>Hard</td>
<td>Fracture occurs within 10 firm taps hinging arm from shoulder</td>
<td>CTH</td>
</tr>
<tr>
<td>No fracture</td>
<td>Fracture does not occur as a result of the previous loading steps</td>
<td>CTN</td>
</tr>
</tbody>
</table>
Table 3.3 Fracture character classification scheme, adapted from the New Zealand Mountain Safety Council (2011).

<table>
<thead>
<tr>
<th>Major Class</th>
<th>Sub class</th>
<th>Description</th>
<th>Data code</th>
<th>Typical shear quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sudden</td>
<td>Sudden planar</td>
<td>Thin planar fracture crosses entire column suddenly in one loading step, and block slides easily on the weak layer</td>
<td>SP</td>
<td>Q1</td>
</tr>
<tr>
<td>Sudden</td>
<td>Sudden collapse</td>
<td>Fracture crosses entire column in single loading step, associated with a noticeable collapse of the weak layer</td>
<td>SC</td>
<td>Q1</td>
</tr>
<tr>
<td>Resistant</td>
<td>Resistant planar</td>
<td>Planar or mostly planar fracture requiring more than one loading step to cross entire column and/or block does not slide easily on weak layer</td>
<td>RP</td>
<td>Q2</td>
</tr>
<tr>
<td></td>
<td>Progressive compression</td>
<td>A fracture of noticeable thickness, usually crossing the entire column in one loading step, followed by step-by-step compression of the layer with subsequent loading steps</td>
<td>PC</td>
<td>Q2 or Q3</td>
</tr>
<tr>
<td>Break</td>
<td>Non-planar break</td>
<td>Non-planar, irregular fracture</td>
<td>BRK</td>
<td>Q3</td>
</tr>
</tbody>
</table>

Along with the two CTs per snowpit, one ECT was performed in each snowpit. As with the CT, the ECTs carried out in the present study followed the standard procedures prescribed by the New Zealand Mountain Safety Council (2011). The primary difference between the ECT and the CT is that the isolated column of snow in an ECT is 90 cm in the across slope direction (Figure 3.5). The shovel blade is placed on top of the column, at either the left or
right outer edge. The ECT employs the same loading steps as employed in the CT. If a fracture initiates and propagates throughout the entire column on a single loading step, or the very next loading step after a fracture initiates, then the result is termed an ECTP. If a fracture initiates but does not propagate throughout the entire column, then it is termed an ECTN. A fracture which initiates and propagates during column isolation is termed an ECTPV, and if no fracture initiates, then it is termed ECTN. The number of taps required for a given fracture occurrence is also recorded. Table 3.4 outlines the ECT score classification scheme. Fracture character (Table 3.3) is observed and recorded. The fracture depth from the snow surface was also recorded, along with the snow crystal size and snow crystal type of the weak layer that the fracture occurred on.

Table 3.4  Extended column test (ECT) classification scheme, adapted from Simenhois and Birkeland (2009) and the New Zealand Mountain Safety Council (2011).

<table>
<thead>
<tr>
<th>Description</th>
<th>Data Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture initiates and propagates across entire column through the weak</td>
<td>ECTPV</td>
</tr>
<tr>
<td>layer or interface during column isolation</td>
<td></td>
</tr>
<tr>
<td>Fracture initiates and propagates across the entire column through the weak</td>
<td>ECTP ##</td>
</tr>
<tr>
<td>layer or interface on the ‘##’ tap, or the fracture initiates on the ‘##’</td>
<td></td>
</tr>
<tr>
<td>tap and propagates across the entire column on the ‘## + 1’ tap</td>
<td></td>
</tr>
<tr>
<td>Fracture initiates on the ‘##’ tap, but does not propagate across the entire</td>
<td>ECTN ##</td>
</tr>
<tr>
<td>column through the weak layer on the ‘##’ or ‘## + 1’ tap</td>
<td></td>
</tr>
<tr>
<td>No fracture initiation occurs during the test</td>
<td>ECTX</td>
</tr>
</tbody>
</table>
On each day of testing (7 July 2012 and 11 July 2012), one full snow profile was carried out in the bottom left snowpit (when looking upslope) of the 15 snowpits performed each day, respectively. Each snow profile was carried out according to the procedures outlined in the New Zealand Mountain Safety Council Guidelines (2011). Carrying out a full snow profile enables a comprehensive understanding of the snowpack to be obtained. Firstly, layers were identified within the snowpack. This was primarily achieved by running a snow crystal card along the face of the exposed snowpack, and noting where changes in resistance were observed. The location of each layer within the snowpack was measured with a ruler, with the distance to ground surface and layer thickness noted. The resistance of each layer was tested using the hand hardness test. Recording standards for the hand hardness test are provided in Table 3.5. Next, the snow crystals of each layer were examined, using a 10 x magnification lens and a snow crystal card. Snow crystal type was defined according to the classification scheme provided by the New Zealand Mountain Safety Council (2011), and snow crystal size was also recorded. Snow temperatures were recorded at 10 cm intervals with a calibrated digital thermometer. Snow densities of individual layers were measured where possible, using a Snowmetrics snow density
sampling kit (1000 cc Model; Rip1). In order to enhance the reliability of procedures carried out during a full snow profile, gloves are worn at all times.

Table 3.5 Hand hardness test recording standards, adapted from the New Zealand Mountain Safety Council (2011). The test is used to indicate the hardness of the snow. It is suggested that no more than 1 to 1.5 kg of force is applied during the test (New Zealand Mountain Safety Council, 2011). Each “hand test” is performed on each layer identified within the snowpack, to observe the minimum “hand test” (with respect to hardness term) required to push into the snow on an exposed wall of a snowpit.

<table>
<thead>
<tr>
<th>Hand test</th>
<th>Term</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fist in glove</td>
<td>Very low</td>
<td>F</td>
</tr>
<tr>
<td>Four fingers in glove</td>
<td>Low</td>
<td>4F</td>
</tr>
<tr>
<td>One finger in glove</td>
<td>Medium</td>
<td>1F</td>
</tr>
<tr>
<td>Blunt end of pencil</td>
<td>High</td>
<td>P</td>
</tr>
<tr>
<td>Knife blade</td>
<td>Very high</td>
<td>K</td>
</tr>
<tr>
<td>Too hard to insert knife</td>
<td>Ice</td>
<td>I</td>
</tr>
</tbody>
</table>

Whilst only one full snow profile was carried out for each day of testing, the remaining 14 snowpits on each day were closely examined to determine whether the snowpack structure was comparable to that which was observed in the associated full snow profile. Each snowpit location was marked using a handheld GPS unit. Once all stability testing and observations in each snowpit had been completed, the snowpits were re-filled with the snow which had been excavated.

3.3.1.2 Craigieburn Valley ski area sampling strategy

Whilst research objective (2) was achieved through the sampling strategy employed in Section 3.3.1.1, further value to the current study was achieved by carrying out snowpack stability testing in the Craigieburn Valley ski area. The section of slope chosen for study was representative of a small proportion of the Craigieburn Valley ski area (Section 4.2). Specifically, the section of slope chosen had an average elevation of 1,810 m a.s.l., a slope angle of 36°, and an easterly aspect (Figure 3.6). However, the section of slope chosen for
study was of interest because some of the largest avalanches observed in the Craigieburn Valley have initiated from this slope (Jarmin, pers. comm. 2012). Furthermore, the slope had been affected by relatively little artificial activity (e.g. skier compaction) up until the point stability testing was carried out for the present study. As such, despite discrepancy in slope elevation and aspect compared to that of the Craigieburn Valley backcountry, results obtained from this slope would provide an interesting comparison to the results obtained from the Craigieburn Valley backcountry.

Figure 3.6 Locations of stability testing within the Craigieburn Valley ski area. The area, known as Hamilton Face, is divided into four zones by McNulty (1984). The approximate boundary of three of those zones has been indicated in red (Zone 4, partially obscured, is situated adjacent to the right of Zone 3). The positioning of the Zone numbers is approximately representative of the section of each Zone where stability testing was carried out on 9 July 2012.

Due to the spatial extent of the slope, a different sampling strategy was employed compared to that which was employed in the Craigieburn Valley backcountry. Specifically, the sampling strategy used by Schweizer and Bellaire (2010) was employed in the current
study. This sampling strategy involves digging four evenly spaced snowpits in a square pattern, and then digging a fifth snowpit in the centre of the four snowpits which had previously been dug. In the present study, the original four snowpits were spaced 13 m apart (Figure 3.7). The five snowpit sampling strategy was employed three times on the same day, with five snowpits being excavated within each of Zone 1, Zone 2 and Zone 3. As a result, 15 total snowpits were dug in the Craigieburn Valley ski area, and the locations of these snowpits were marked with a handheld GPS unit. Testing was carried out on 9 July 2012, which was in the middle of the two days of testing for the Craigieburn Valley backcountry. This was so as to enhance the value of any comparison of results made between Craigieburn Valley ski area and the Craigieburn Valley backcountry. Again, two CTs and one ECT were performed in each snowpit (procedures described in Section 3.3.1.1). Two full snow profiles were performed in the centre of the five-snowpit array; one full snow profile was performed in Zone 1 and the other in Zone 3.

Figure 3.7 Sampling methodology for the Craigieburn Valley ski area study slope. Each square represents a snowpit. This five-snowpit array was performed three times on 9 July, resulting in 15 total snowpits being dug, 5 in each of Zone 1, Zone 2 and Zone 3, respectively.
3.3.2 Meteorological variables and stability forecasts

The Craigieburn Valley Ski Club has established a weather observation plot on a flat site at 1,265 m a. s. l. (Figure 3.8). Standard daily observations were carried out, usually at 0530 hours. Variables recorded and obtained for the present study included daily maximum and minimum air temperature, rainfall, total snow depth, and new snowfall depth. An automatic weather station (AWS) currently exists at 914 m a. s. l. in an adjacent valley to the south of Craigieburn Valley (Figure 3.8), and has been operational since June 1964. The station name of this AWS is Craigieburn Forest. Another AWS was located in the same adjacent valley, at 1,554 m elevation (Figure 3.8). The station name of this AWS is Ski Basin. However, for clarification purposes, it will hereby be referred to as the Broken River AWS. This weather station was operational between July 1966 and September 1986. Air temperature data from both of these weather stations were obtained online from New Zealand’s national climate database (CliFlo), provided by New Zealand’s National Institute of Water and Atmospheric Research (NIWA, 2012).
Forecasted freezing levels were obtained from regional weather forecasts provided by the Meteorological Service of New Zealand Ltd. Weather maps and infrared satellite images were also provided by the Meteorological Service of New Zealand Ltd. Regional snowpack stability and avalanche forecasts for the Craigieburn Range were obtained from the New Zealand Avalanche Centre (2012). Avalanche occurrences within the Craigieburn Valley over the course of the fieldwork campaign were recorded. Key descriptive variables associated with the avalanches were noted, comprising avalanche type, size, trigger, and the aspect and elevation of the avalanche.
3.3.3 Rain event case study

As highlighted in Section 4.5, a significant rainfall event (the second of the 2012 Austral winter season) occurred from 13 July 2012 to 15 July 2012. Further stability testing was carried out subsequent to this rainfall event. Within the roped off section of the Craigieburn Valley backcountry, the upper section of the slope, approximately 10 m in the upslope direction and 65 m in the across slope direction, remained undisturbed by artificial activity. In this section of the slope, two snowpits spaced 10 m apart were dug on 22 July 2012. Two CTs and one ECT were performed in each snowpit (procedures described in Section 3.3.1.1), and one full snow profile was performed in one of the snowpits. At the Craigieburn Valley ski area, seven snowpits spaced at least 10 m apart from each other were dug on 23 July 2012. Five snowpits were dug in Zone 3 of Hamilton Face, and two snowpits were dug in Zone 2. Again, two CTs and one ECT were performed in each snowpit, and one full snow profile was performed in one of the snowpits.

3.4 Data treatment

3.4.1 Stability testing observations

Descriptive statistics were calculated from stability sampling results obtained from Craigieburn Valley ski area and Craigieburn Valley backcountry, comprising the mean, standard deviation and range of CT and ECT scores. Regression analyses of stability test tap scores against slab thickness were undertaken to demonstrate whether or not any relationship existed between these variables in the present study. For the Craigieburn Valley backcountry data, Mann-Whitney tests were carried out between the respective stability test scores from day one and day two of testing. This demonstrated whether or not temporal changes in the spatial variability of snowpack stability were statistically significant.

Further analysis of the spatial variability of stability test results (CT and ECT) was undertaken. Specifically, the median, upper quartile and lower quartile of stability test results were calculated. This provides further representation of the spatial variability of snowpack stability observed at the slope scale.
3.4.1.1 Three-component model of stability

As established in Section 2.5.3, the three-component model of stability is an effective method of characterising snowpack stability. However, it is largely a qualitative method of determining snowpack stability. As such, the present study attributed number ratings to the indication of stability obtained from each component of the model, in order to provide additional meaning to the stability results obtained from a single snowpit, and to promote ease of interpretation of the results (Table 3.6). Lower stability indications were allocated lower number ratings, and higher stability indications were allocated higher number ratings (Table 3.6). For example, a stability indication of poor received a number rating of 1, whereas a stability rating of good received a number rating of 3.

With respect to the strength component of the model, the stability indication was obtained from the stability test tap score required for a fracture to initiate. The thresholds set for indication of stability are shown in Table 3.6. These are based on the thresholds defined by Schweizer and Bellaire (2010), who created tap number thresholds with respect to the indication of stability for the CT. Note, that in addition to the thresholds set by the aforementioned authors, two further stability thresholds were defined in the present study. Namely, a very poor stability threshold was set for stability test tap scores of 0, and a very good stability threshold for stability test tap scores > 30 (i.e. no fracture initiation occurred during testing). Because two CTs were performed in each snowpit, the two CT tap scores were averaged to provide the tap score value to be assessed by the tap score stability threshold.

With respect to the energy component of the model, the stability indication was obtained from the stability test fracture character. The thresholds set for indication of stability are shown in Table 3.6. These are based on the observation of van Herwijnen and Jamieson (2007); that sudden (shear quality 1; Q1) fractures are the most common fracture character associated with slab avalanche occurrences. Regarding the CTs undertaken in a single snowpit; if both CT fracture characters were sudden then the stability was rated as poor, if only one CT had a sudden fracture character then the stability was rated as fair, and if no sudden fracture character was observed for either of the two CTs then the stability was rated as good. If both CT results were CTN, then no fracture character could be observed. In this case, the stability was rated as very good. Thresholds set for the stability indication
of the energy component obtained from ECTs were based on the observation of Simenhois and Birkeland (2009). That is, ECTV and ECTP results are indicative of instability, and all other ECT results are indicative of stability. Thus, the energy component of ECTPV and ECTP results were rated poor, the energy component of ECTN results that had a sudden fracture character were rated fair, the energy component of ECTN results that did not have a sudden fracture character were rated good, and the energy component of ECTX results were rated very good.

With respect to the structure component of the model, the stability indication was obtained from the number of ‘lemons’ observed in the snowpack (as defined by thresholds described in Table 2.2). The thresholds set for indication of stability are shown in Table 3.6. These are based on the findings presented by McCammon and Schweizer (2002), who demonstrate that unstable conditions correlate well with a greater number of ‘lemons’ identified in the snowpack. As such, a greater number of ‘lemons’ observed in the snowpack resulted in a lower stability indication. For example, if 5 ‘lemons’ were observed in the snowpack, then the structure component was rated very poor, whereas if no ‘lemons’ were observed in the snowpack, the structure was rated very good.
Table 3.6 Stability indication thresholds developed for the present study, which attribute a number rating (bracketed) to the associated stability indication. Results from stability testing (CTs and ECTs) enable the stability indication of the strength and energy components to be assessed. The strength component is determined from the stability test score, and the energy component is determined from the fracture character. Note that the stability indication thresholds provided for the CT reflect the fact that two CTs were carried out in each snowpit. The stability indication obtained from the structure component was attributed to the number of ‘lemons’ observed in the snowpack, which was determined by carrying out a full snow profile. The stability indication score from each of the three stability components is tallied, in order to provide an overall stability rating obtained from each snowpit.

<table>
<thead>
<tr>
<th>Stability indication</th>
<th>Stability component</th>
<th>Structure # of 'lemons'</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength CT ECT</td>
<td>Energy CT ECT</td>
</tr>
<tr>
<td>Very poor (0)</td>
<td>CTV ECTV</td>
<td>~ ~</td>
</tr>
<tr>
<td>Poor (1)</td>
<td>1 ≤ x ≤ 13</td>
<td>2 x Q1 ECTV or ECTP</td>
</tr>
<tr>
<td>Fair (2)</td>
<td>13 &lt; x ≤ 19</td>
<td>1 x Q1 ECTN; Q1</td>
</tr>
<tr>
<td>Good (3)</td>
<td>19 &lt; x ≤ 30</td>
<td>0 x Q1 ECTN; Q2, Q3</td>
</tr>
<tr>
<td>Very good (4)</td>
<td>CTN ECTX</td>
<td>2 x CTN ECTX</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overall stability rating</th>
<th>Very poor</th>
<th>Poor</th>
<th>Fair</th>
<th>Good</th>
<th>Very good</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤ 2</td>
<td>3</td>
<td>4 ≤ x ≤ 6</td>
<td>7 ≤ x ≤ 9</td>
<td>&gt; 9</td>
</tr>
</tbody>
</table>

3.4.1.2 Intra- and inter-pit variability

Carrying out two CTs in each snowpit enabled the variability of stability test results at both the pit scale (intra-pit variability) and slope scale (inter-pit variability) to be observed. The method used to characterise such variability followed those outlined by Schweizer and Bellaire (2010). The methods employed by these authors sought to determine both intra-pit and inter-pit similarity (and inherently, variability) of CT scores and CT fracture character. The criteria set by Schweizer and Bellaire (2010) were utilised in the current study, and are presented in Table 3.7. In order for a pair of intra-pit CTs to be deemed similar regarding their CT score, the CT score had to be ≤ 2 taps for medium CT scores (11 – 20 taps), and the fracture had to occur on the same weak layer. For easy (0 – 10 taps) and hard (21 – 30 taps)
scores, the CT score had to be ≤ 4 taps for similarity to be achieved, and the fracture had to occur on the same weak layer. In order for a pair of intra-pit CTs to be deemed similar regarding their fracture character, the fracture character of the two CTs had to be either sudden (SP or SC); or RP, PC or BRK, and the fracture had to occur on the same weak layer.

Inter-pit (slope scale) similarity was calculated following comparable criteria (Table 3.7). In order for two individual pits to be deemed similar regarding their CT score, the two CT scores for each pit were averaged, and that averaged score had to be ≤ 2 for medium CT scores, or ≤ 4 for easy or hard CT scores. Furthermore, the fracture had to occur on the same weak layer. When observing whether the same weak layer fractured in each pit, similarity was achieved if the same weak layer failed in at least one of the two CTs in the second pit when compared to the first pit. When calculating inter-pit similarity regarding the fracture character, both fractures in both pits had to have the same fracture character (either sudden (one of SP or SC); or one of RP, PC or BRK), and the same weak layer failed in at least one of the two CTs in the second pit when compared to the first pit.
### Table 3.7 Criteria used to determine intra-pit (pit scale) and inter-pit (slope scale) similarity, with respect to the compression test score and fracture character.

<table>
<thead>
<tr>
<th>Intra-pit similarity</th>
<th>Inter-pit similarity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compression test</strong></td>
<td>Based on pit avg. score</td>
</tr>
<tr>
<td>CTE: ≤ 4</td>
<td>CTE: ≤ 4</td>
</tr>
<tr>
<td>CTM: ≤ 2</td>
<td>CTM: ≤ 2</td>
</tr>
<tr>
<td>CTH: ≤ 4</td>
<td>CTH: ≤ 4</td>
</tr>
<tr>
<td>Both fractures had to</td>
<td>Sufficient if one fracture in each pit occurred on the same weak layer</td>
</tr>
<tr>
<td>occur on same weak layer</td>
<td></td>
</tr>
</tbody>
</table>

#### Fracture character

Both FCs one of either:
- SP / SC
  - or
- RP / PC / BRK

Both fractures had to occur on same weak layer

All four FCs had to 1 of either:
- SP / SC
  - or
- RP / PC / BRK

Sufficient if one fracture in each pit occurred on the same weak layer

The data from three snowpits performed within the Craigieburn Valley ski area were removed from the intra-pit (pit-scale) and inter-pit (slope-scale) analyses of snowpit similarity in order to ensure comparability of results with Schweizer and Bellaire (2010), whose study this analysis was based on. As such, the data from three snowpits, each located within the centre of their respective five snowpit array, were removed; Schweizer and Bellaire (2010) had also not included the data obtained from their correlating snowpits in their study. The reason Schweizer and Bellaire (2010) had not included the data from these snowpits is because the snowpits fall within the recommended snowpit spacing with respect to the correlation length of stability results. In other words, the central snowpit of
the five snowpit array is closer than 10 m from neighbouring snowpits. However, the
correlation length has been shown to vary by previous authors (Schweizer et al., 2008), and
remains unknown (Section 2.6.2). Therefore, the data obtained from the central snowpit of
the five snowpit array was only removed from the pit-scale and slope-scale similarity
analyses, to ensure the comparability of results from the current study to those presented
by Schweizer and Bellaire (2010). For all remaining spatial variability analyses within the
present study, data from the central snowpit of the five snowpit array was included.

3.4.1.3 Moran’s I analyses

Moran’s I analysis was undertaken in order to determine whether a coherent spatial pattern
was present in the Craigieburn Valley backcountry, with respect to the CT and ECT scores.
The stability scores examined using the Moran’s I analysis were; each of the first CTs
carried out in each snowpit (two CTs were performed in each snowpit); each of the second
CTs carried out in each snowpit; the ECTN scores; and the ECTP scores. Note that the first
CT score and the second CT score from each pit for each day of testing were examined
separately using the Moran’s I analysis, due to being recorded as having the same location
in the field. Only one location was marked with a GPS per snowpit that was dug, and a
Moran’s I analysis could not be undertaken when two stability test scores were provided
for the same location. Thus, the first CT scores obtained from each pit were tested against
each other, and then the second CT scores obtained from each pit were tested against each
other.

The Spatial Autocorrelation (Morans I) tool in the ArcToolbox of ArcGIS 10.0 was utilised in
the present analysis. The Moran’s I statistic (Moran, 1948, 1950) is a widely used index for
determining spatial autocorrelation (Rogerson, 2001). The index cannot be interpreted
directly; it may only be interpreted within the context of the null hypothesis. The null
hypothesis for the present analysis was that stability test scores were randomly distributed
in the Craigieburn Valley backcountry study slope. The Moran’s I index value may be
interpreted as follows (Rogerson, 2001); values approaching +1 indicate a strengthening
spatial pattern, whereby high values tend to be located near other high values, and low
values tend to be located near other low values. Conversely, values approaching −1
indicate a strengthening negative spatial pattern, whereby higher values tend to be located beside lower values. A Z score and p-value are calculated, which enable significance to be attributed to the Moran’s I index value. Z score (p-value) thresholds of > 1.65 (< 0.10) and > 1.96 (< 0.05) allow the null hypothesis to be rejected at the 90% and 95% level of confidence, respectively.

3.4.2 Weather and snowpack observations

The results of all snow profiles obtained were plotted visually (e.g. Section 4.3.4), using SnowPilot; computer software developed by Chabot et al. (2004). Data from full snow profiles were examined to determine whether weak layer variable thresholds (i.e. structural lemons, described in Section 2.5) were met. Basic statistical analyses were performed on the air temperature data obtained from the Craigieburn Forest AWS and the Broken River AWS, in order to provide a comparison, and context, to the data obtained from the Craigieburn Valley Ski Club weather observation plot. Over the period of time encompassing stability testing, freezing levels specific to Craigieburn Valley were calculated based on temperatures recorded at the Craigieburn Valley Ski Club weather observation plot (Table 4.2; Figure 4.21). The daily maximum temperature was combined with an adiabatic lapse rate of 0.7°C / 100 m (Sturman and Tapper, 2002) to provide a calculated freezing level.

3.4.3 Craigieburn Valley avalanche terrain

Analysis of the avalanche terrain of Craigieburn Valley was carried out in ArcGIS 10.0, utilising a cartographically-derived digital elevation model (DEM). The DEM (NZDEM_SoS_v1.0), created by Columbus et al. (2011), has a spatial resolution of 15 m. This represents a finer spatial resolution, and is of greater accuracy, than that of previous New Zealand-wide DEMs (Columbus, 2011). The DEM was created in 2011, although it is based upon the LINZ Topo50 database, which was created in 1987. The area analysed in the present study falls within NZTopo50-BV21 and NZTopo50-BW21.
3.5 Summary

Due to the ease of access into backcountry terrain, and the associated potential avalanche hazard, Craigieburn Valley represented a suitable location to carry out the present study. Thirty-five consecutive days were spent ‘on-mountain’, enabling a detailed observation of the weather and snowpack leading up to snowpack stability testing being performed. A combination of stability tests and snowpack observations were performed in order to achieve research objective (2) of this study (Section 1.3), and analyses of the data obtained addressed the two research questions which guide this study (Section 2.7.1). A contemporary, relatively fine spatial resolution DEM was examined in ArcGIS 10.0, allowing research objective (1) of this study to be achieved. By addressing research objectives (1) and (2), an examination of the implications of the results obtained from this study with respect to the potential avalanche hazard of Craigieburn Valley is enabled (Section 5.5.2).
Chapter 4

Results

4.1 Introduction

Before assessing snowpack stability, it is pertinent to recall the three fundamental components of the avalanche hazard triangle; terrain, weather and snowpack. It is these three variables which provide the foundation for this chapter. As such, the following chapter is divided into four main sections. In Section 4.2, a detailed hypsometry of Craigieburn Valley is presented. This enables the first objective of this study to be achieved; namely, to utilise a geographic information system in order to analyse the avalanche terrain of Craigieburn Valley. In Section 4.3, an analysis of the snowpack is presented alongside weather conditions prior to and during the fieldwork campaign. Section 4.4 presents the data obtained from fieldwork, which satisfies the research objective (2) of this study; to investigate the spatial and temporal variability of snowpack stability within Craigieburn Valley. Section 4.5 presents the results of a case study involving a significant mid-winter rainfall event for the Craigieburn Valley.

4.2 Craigieburn Valley avalanche terrain

This section will provide a detailed examination of specific avalanche terrain within Craigieburn Valley. As introduced in Section 2.3.1, avalanches primarily initiate on terrain with a slope angle between 30° and 45° inclusive. In addition, avalanches can initiate on terrain with a minimum slope angle of 15° and a maximum of 60°. As such, it is these critical slope angle values which form the basis of the following examination of avalanche
terrain within Craigieburn Valley. Figures 4.1 and 4.2 demonstrate the distribution of avalanche terrain within the Craigieburn Valley ski area and of the Craigieburn Valley Backcountry respectively. 61% of Craigieburn Valley ski area is primary avalanche terrain, and overall, avalanches could possibly initiate upon 95% of Craigieburn Valley ski area terrain. In comparison, 51% of Craigieburn Valley backcountry terrain is primary avalanche terrain, and avalanches could possibly initiate upon 97% of Craigieburn Valley backcountry terrain. Figures 4.3 and 4.4 show the spatial distribution of avalanche terrain within the Craigieburn Valley ski area, and the Craigieburn Valley backcountry, respectively.

Figure 4.1 Proportions of avalanche terrain within the Craigieburn Valley Ski Area. Primary avalanche terrain represents the proportion of terrain with a slope angle of between 30° and 45° inclusive. Secondary avalanche terrain represents the proportion of terrain with a slope angle between 15° and 30° or 45° and 60°. Tertiary avalanche terrain represents the remainder of terrain, with slope angles < 15° or > 60°.
Figure 4.2  Proportions of avalanche terrain of the Craigieburn Valley Backcountry. Primary avalanche terrain represents the proportion of terrain with a slope angle of between 30° and 45° inclusive. Secondary avalanche terrain represents the proportion of terrain with a slope angle between 15° and 30° or 45° and 60°. Tertiary avalanche terrain represents the remainder of terrain, with slope angles < 15° or > 60°.

Figure 4.3  Spatial distribution of avalanche terrain within the Craigieburn Valley ski area.
Figures 4.5 and 4.6 display the distribution of primary avalanche terrain (slope angle between 30° and 45° inclusive) between different elevation bands for the Craigieburn Valley ski area and Craigieburn Valley backcountry, respectively. With regard to the Craigieburn Valley ski area, 16% of primary avalanche terrain is located between 1,200 m a.s.l. and 1,399 m a.s.l., 36% between 1,400 m a.s.l. and 1,599 m a.s.l., 42% between 1,600 m a.s.l. and 1,799 m a.s.l., and 6% above 1,800 m a.s.l. The Craigieburn Valley backcountry shows a similar distribution at lower elevations. In contrast to the ski area, 48% of primary avalanche terrain is located between 1,600 m a.s.l. and 1,799 m a.s.l, and just 0.2 of primary avalanche initiation terrain is located above 1,800 m a.s.l.

**Figure 4.4** Spatial distribution of avalanche terrain within the Craigieburn Valley backcountry.
Figure 4.5 Distribution of primary avalanche initiation terrain (slope angle between $30^\circ$ and $45^\circ$) between different elevation bands within the Craigieburn Valley ski area.

Figure 4.6 Distribution of primary avalanche initiation terrain (slope angle between $30^\circ$ and $45^\circ$) between different elevation bands of the Craigieburn Valley backcountry.
Figures 4.7 and 4.8 display the distribution of primary avalanche terrain (slope angle between 30° and 45° inclusive) between different slope aspects for the Craigieburn Valley ski area and Craigieburn Valley backcountry, respectively. For the Craigieburn Valley ski area, a clear majority of primary avalanche terrain is located on slopes with an easterly (41%) or north-easterly (33%) aspect. 25% of primary avalanche terrain is located on slopes with a southerly component, whilst the remaining 1% is located on slopes with a westerly, north-westerly or northerly aspect. The distribution of primary avalanche terrain between different slope aspects for the Craigieburn Valley backcountry is considerably different to that of the Craigieburn Valley ski area. The majority of Craigieburn Valley backcountry primary avalanche terrain is located on slope aspects of a southerly component. Specifically, 41% is located on slopes with a south-westerly aspect, 30% on slopes with a southerly aspect and 23% with a south-easterly aspect. Four percent (4%) of primary avalanche terrain is located on slopes with a westerly aspect, and 2% is located on slopes with an easterly aspect. No primary avalanche terrain is located on the remaining northerly, north-easterly and north-westerly aspects. Figures 4.9 and 4.10 show the spatial distribution of slope aspect for the Craigieburn Valley ski area and the Craigieburn Valley backcountry, respectively.
**Figure 4.7** Distribution of primary avalanche initiation terrain (slope angle between 30° and 45°) between different slope aspects within the Craigieburn Valley ski area.

**Figure 4.8** Distribution of primary avalanche initiation terrain (slope angle between 30° and 45°) between different slope aspects of the Craigieburn Valley backcountry.
Figure 4.9 Spatial distribution of slope aspect within the Craigieburn Valley ski area.

Figure 4.10 Spatial distribution of slope aspect within the Craigieburn Valley backcountry.
4.3 Weather and Snowpack

4.3.1 Early winter 2012 in context

In order to provide context to the weather observed in the Craigieburn Valley over the course of the present study, historical meteorological data obtained from the nearby Craigieburn Forest AWS (914 m a.s.l., Figure 3.8) has been analysed, and compared to the measurements of June and July 2012 (Table 4.1). Daily maximum air temperatures were consistently above freezing during both months (Figure 4.11). Table 4.1 shows that higher air temperatures were observed during the month of July than the month of June. This contrasts to the 30-year (1981 – 2010) average measured at that location. Whilst the mean daily maximum air temperature of June 2012 was similar to the 30-year average, the mean and the mean daily minimum air temperatures were considerably lower. Air temperatures of July 2012 were higher than the 30-year average. The mean daily maximum air temperature of July 2012 was 8.9°C; 1.6°C higher than the 30-year average. The mean July 2012 air temperature of 3.5°C was 1.0°C higher than the 30-year average. Precipitation recorded at the Craigieburn Forest AWS was also analysed. Rainfall totals recorded for June 2012 and July 2012 were considerably higher than the 30-year average for those months, respectively. A total of 217.4 mm of precipitation was recorded in June 2012; 58.6 mm more than the 30-year average. Notably, 88.8 mm of precipitation was recorded on 23 June 2012 (Figure 4.11; Julian Day 175). This coincides with 70 mm of rainfall that was recorded at the Craigieburn Valley Ski Club weather observation plot, which fell as rain to ridge-top (Section 4.3.2). 186.1 mm of precipitation was recorded in July 2012 at the Craigieburn Forest AWS. Notably, 125 mm was recorded on July 14 2012 (Figure 4.7; Julian Day 196), which represents 87% of the 30-year average total rainfall for the month of July. This coincides with the significant rain event that was observed within the Craigieburn Valley (Section 4.5).
Table 4.1 Meteorological variables measured at the Craigieburn Forest AWS (C.F., 914 m a.s.l.), which is located in the adjacent valley immediately south of the Craigieburn Valley. Air temperature and precipitation data that was recorded in the Austral winter of 2012 is provided, along with the 1981 – 2010 mean for each variable. Data obtained from NIWA (2012).

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Air temperature (°C)</th>
<th>Precipitation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean daily min.</td>
<td>Mean</td>
</tr>
<tr>
<td>C.F.</td>
<td>2012</td>
<td>-3.6</td>
<td>-1.9</td>
</tr>
<tr>
<td></td>
<td>1981 – 2010</td>
<td>-1.5</td>
<td>-2.3</td>
</tr>
</tbody>
</table>
Figure 4.11  Daily minimum and maximum air temperatures, and rainfall, measured at the Craigieburn Forest AWS (914 m a. s. l.), over the course of June 1 (Julian day 153) to July 31 (Julian Day 213). Considerable rainfall was recorded on 23 June (Julian Day 175) and 14 July (Julian Day 196). Data obtained from NIWA (2012).
4.3.2 Weather preceding snowpack stability testing

This section describes the significant weather events which occurred prior to snow stability testing at Craigieburn Valley (Table 4.2). Due to the seasonality of snowfall accumulation in the region, only weather events pertinent to the 2012 Austral winter snowpack of the region are described. On 5 June, a complex low pressure system with a central pressure of 972 hPa approached the South Island from the Tasman Sea. Its passage south was preceded by a moist airmass, which combined with polar air arriving from south of the South Island resulting in heavy snowfall at Craigieburn Valley (Figure 4.12). A total of 125 cm of snow accumulated at 1,265 m a.s.l. as a result of the storm, with snowfall rates averaging 10 cm h\(^{-1}\) between 0800 hours and 1500 hours on 6 June. Note that snow depths provided are measured in centimetres, as snow densities of new snow were not always obtained, meaning millimetres water equivalent could not be reliably calculated.

![Mean sea level isobar map](image)

**Figure 4.12** a) Mean sea level isobar map, valid at 1200 hours NZST on 6 June 2012 (provided by the Meteorological Service of New Zealand Ltd), and b) the Craigieburn Valley Ski Club Manager stands beside the 1.25 m of fresh snowfall that occurred as a result of the single storm.

The next significant weather event of the winter commenced on 23 June, when a strong north-westerly airflow resulted in spillover of pre-frontal orographic rainfall from the Main Divide. In total, 70 mm of rain was recorded at the Craigieburn Valley weather observation plot. This rain was associated with a relatively high freezing level, which was estimated to
be 2,000 m throughout the rainfall event, thus it was likely no snowfall occurred on the Craigieburn Valley terrain. Rain turned to snow overnight, and by 0730 hours on 24 June, 5 cm of snow had accumulated at the Craigieburn Valley Ski Club weather observation plot, associated with the passing of a cold front. After a brief clearance on 25 June, 25 cm of snow accumulated at the Craigieburn Valley Ski Club weather observation plot on 26 June, associated with the passage of a cold front and troughs embedded in a south-westerly airflow over the South Island (Figure 4.13). Air temperatures lowered gradually over the course of this snowfall, which was demonstrated by snow densities measured during the course of the snowfall. The first 16 cm of snow to settle had a density of 115 kg m$^{-3}$, whereas the final 6 cm to settle had a density of 88 kg m$^{-3}$.

**Figure 4.13** a) Infrared satellite image, valid at 0000 hours NZST 26 June 2012, and b) mean sea level isobar map, valid at 1200 hours NZST on 26 June 2012 (provided by the Meteorological Service of New Zealand Ltd). Snowfall densities measured during the passage of this weather system at Craigieburn Valley progressively lowered, due to the airmass of the system becoming progressively colder. This is symbolised by the trough located off the south-westerly coast of the South Island, and can be distinguished by ‘speckled’ cloud forms present in the infrared satellite image.

Following the 26 June snowfall, a period of clear and calm conditions prevailed from 27 June through to 3 July. This was associated with a slow moving high pressure system, the central pressure of which peaked at 1030 hPa on 30 June. On 4 July, 1 cm of snow settled at the Craigieburn Valley Ski Club weather observation plot, with similar totals observed
across all Craigieburn Valley terrain. This was followed on 5 July by light drizzle up to an elevation of 1,700 m a.s.l. throughout the day, associated with an easterly airflow carrying a moist airmass off the Pacific Ocean. Cloud cleared in the early hours of 6 July, prior to sunrise, resulting in a thin crust forming on the snowpack surface over the majority of the ski area.

Table 4.2 Significant weather events occurring in the Austral winter of 2012, pertinent to the Craigieburn Valley snowpack, and prior to snow stability testing.

<table>
<thead>
<tr>
<th>Date</th>
<th>Weather events of significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 June – 6 June</td>
<td>125 cm snowfall.</td>
</tr>
<tr>
<td>23 June</td>
<td>70 mm rainfall.</td>
</tr>
<tr>
<td>24 June</td>
<td>5 cm snowfall.</td>
</tr>
<tr>
<td>26 June</td>
<td>25 cm snowfall.</td>
</tr>
<tr>
<td>27 June – 3 July</td>
<td>Slow moving high pressure system. Clear, calm conditions.</td>
</tr>
<tr>
<td>4 July</td>
<td>1 cm snowfall.</td>
</tr>
<tr>
<td>5 July</td>
<td>Occasional light drizzle to 1,700 m.</td>
</tr>
<tr>
<td>6 July</td>
<td>Pre-dawn cloud clearance</td>
</tr>
</tbody>
</table>

4.3.3 Weather during snowpack stability testing

Over the 5 days from 7 July to 11 July 2012, an anticyclone was the dominant weather system over Craigieburn Valley (Figure 4.14). As a result, clear and calm conditions prevailed over the course of the 5 days (Figure 4.15).
Figure 4.14 Mean sea level isobar maps (left column) and infrared satellite images (right column), valid at 1200 hours NZST, for: a) 7 July 2012; b) 9 July 2012; and c) 11 July 2012. Images provided by the Meteorological Service of New Zealand Ltd.

Figure 4.15 0900 hours on 7 July 2012, looking north from the western ridgeline of Craigieburn Valley, showing the predominant weather observed at Craigieburn Valley from 7 July to 11 July 2012.
Air temperatures recorded at the Craigieburn Valley Ski Club weather observation plot during the five day snowpack stability testing period displayed a diurnal signal (Table 4.3). Daily maximum temperatures were recorded during daylight hours, and daily minimum temperatures were recorded at night. Forecasts provided by the Meteorological Service of New Zealand for the Canterbury High Country (which includes the Craigieburn Valley), called for a rising freezing level over the course of the five day snow stability testing period (Table 4.3), and calculated freezing levels were similar to those forecasted for Craigieburn Valley.

Table 4.3 Daily maximum and minimum temperatures recorded at the Craigieburn Valley weather observation plot (1,265 m a.s.l.) over the course of the snow stability testing period. Forecasted and calculated freezing levels (F.L.) are also provided for the same time frame.

<table>
<thead>
<tr>
<th>Date</th>
<th>7 July</th>
<th>8 July</th>
<th>9 July</th>
<th>10 July</th>
<th>11 July</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Min. Temp. (°C)</strong></td>
<td>0.0</td>
<td>-2.0</td>
<td>-1.5</td>
<td>-1.0</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Max. Temp. (°C)</strong></td>
<td>3.0</td>
<td>4.0</td>
<td>2.4</td>
<td>3.6</td>
<td>5.5</td>
</tr>
<tr>
<td><strong>Forecasted F.L. (m)</strong></td>
<td>1,200</td>
<td>1,600</td>
<td>1,600</td>
<td>1,800</td>
<td>2,000</td>
</tr>
<tr>
<td><strong>Calculated F.L. (m)</strong></td>
<td>1,693</td>
<td>1,803</td>
<td>1,608</td>
<td>1,779</td>
<td>2,051</td>
</tr>
</tbody>
</table>

4.3.4 Craigieburn Valley backcountry snowpack observations

This section describes the snowpack structure and characteristics observed in the Craigieburn Valley backcountry for both day one (7 July) and day two (11 July) of stability testing. Snow profiles obtained from each day of testing are presented in Figure 4.16 and Figure 4.17. A description regarding the interpretation of snow profiles is provided in Appendix A.

Clear links can be made between the snow profiles obtained from the Craigieburn Valley backcountry and the significant weather events leading up to snow stability testing (Table 4.2). On both days of testing, the snowpack structure can be broadly characterised by three main components. The most notable component is the rain-crust that exists mid-snowpack; observed between 38 cm and 52 cm on 7 July, and between 39 cm and 50 cm on 11 July.
This rain-crust formed as a result of the 70 mm rainfall event which occurred on 23 June 2012; the rainfall saturated portion of the upper snowpack re-froze, creating a relatively thick crust layer. The second component of snowpack structure present on both days of testing is the snowpack immediately below the rain-crust through to the ground surface; observed between 0 cm and 38 cm on 7 July, and 0 cm and 39 cm on 11 July. This component represents the portion of the snowpack that could be distinguished from the rain-crust due to a hardness that was a minimum of one step lower. The third component of the snowpack structure evident is the uppermost portion which was deposited atop the rain-crust; observed between 52 cm and 83 cm on 7 July, and 50 cm and 70 cm on 11 July. On both days of stability testing, the surface of the snowpack was capped by a thin layer of rime crust, which formed as a result of the relatively moist easterly airflow which affected the Craigieburn Valley on 5 July 2012, and the subsequent pre-dawn cloud clearance on 6 July 2012.
Figure 4.16 Snow profile obtained at the Craigieburn Valley backcountry on day one of testing, 7 July 2012 at 0900 hours.

Relatively large temperature gradients were observed within the snowpack on both days of stability testing. The largest temperature gradient observed on 7 July occurred between 60 cm and 73 cm, where the temperature decreased from -4.7°C to -8.1°C; a temperature gradient of 2.6°C per 10 cm. A similarly high temperature gradient of 2.0°C per 10 cm was observed between 30 cm and 40 cm. The highest temperature gradient observed on 11 July occurred between 30 cm and 50 cm, where the temperature decreased from -3.1°C to -6.0°C; a temperature gradient of 1.45°C per 10 cm.
Figure 4.17 Snow profile obtained at the Craigieburn Valley backcountry on day two of testing, 11 July 2012 at 0900 hours.

Slab thickness (defined here as the depth of snowpack above the uppermost limit of the rain-crust) was spatially variable (Table 4.4). Further spatial variability of the snowpack was observed with respect to snow depth (Table 4.4). Possible reasons for the variable snow depths measured are explored in Section 5.3.1.
### Table 4.4
Descriptive statistics pertaining to the Craigieburn Valley backcountry on each day of testing, showing the variability of snow depth and slab thickness observed during snowpack stability testing.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Day of testing</th>
<th>Avg.</th>
<th>Std. Dev.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow depth (cm)</td>
<td>7 July</td>
<td>79.3</td>
<td>8.5</td>
<td>55 - 90</td>
</tr>
<tr>
<td></td>
<td>11 July</td>
<td>83.0</td>
<td>18.4</td>
<td>65 - 115</td>
</tr>
<tr>
<td>Slab thickness (cm)</td>
<td>7 July</td>
<td>25.2</td>
<td>3.9</td>
<td>17 - 31</td>
</tr>
<tr>
<td></td>
<td>11 July</td>
<td>26.9</td>
<td>8.7</td>
<td>17 - 40</td>
</tr>
</tbody>
</table>

Some discrepancy was observed regarding the snow crystal forms and their size between the two days of testing. Specifically, there had been ongoing development of faceted crystals within the snowpack from 7 July to 11 July. This was observed both above the rain-crust, and immediately below the rain-crust. For example, a 7 cm thick layer of 0.5 mm rounded crystals was observed above the rain-crust on 7 July. On 11 July, there was no evidence of such a layer. Instead, almost the entire snowpack above the rain-crust showed evidence of faceting, and there was an associated increase in crystal size to 1 mm. Furthermore, on 7 July, a 16 cm layer of 1 mm faceting rounded crystals was observed immediately below the snowpack. On 11 July, a 10 cm layer of 1.5 mm faceted crystals was observed immediately below the rain-crust. Such changes in snow crystal type and size highlights the temporal evolution of snowpack structure, despite relatively benign weather conditions observed over the duration of the snowpack stability testing period.

Further inspection of the snow profiles demonstrates the presence of ‘lemons’ (Section 2.5.1) within the Craigieburn Valley backcountry snowpack (Table 4.5). On both days of stability testing, four thresholds for weak layer variables were met; in other words, four ‘lemons’ were present in the snow pack. This suggests that, according to the snowpack structure, the snowpack had relatively low stability.
Table 4.5  Weak layer variables (structural ‘lemons’) observed within the Craigieburn Valley backcountry snowpack on 7 July and 11 July 2012. The weak layer variable thresholds were applied to the weak layer upon which fracture initiation and propagation occurred during stability testing, and the layers immediately adjacent to that weak layer.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Threshold</th>
<th>7 July</th>
<th>11 July</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak layer depth</td>
<td>≤ 1 m</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Weak layer thickness</td>
<td>≤ 10 cm</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Hardness difference</td>
<td>≥ 1 step</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Weak layer grain type</td>
<td>Persistent (SH, DH, FC)</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Grain size difference</td>
<td>≥ 1 mm</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

4.3.5 Craigieburn Valley ski area snowpack observations

This section describes the snowpack structure and characteristics observed at the Craigieburn Valley ski area when testing was carried out on 9 July 2012. Similarities could be drawn between the snowpack structure observed at the Craigieburn Valley ski area, and the snowpack structure observed at the Craigieburn Valley backcountry. Despite considerable complexity of snowpack structure observed, the Craigieburn Valley ski area snowpack could also be characterised by the three main components observed in the Craigieburn Valley backcountry (Figure 4.18). Most notably, the rain-crust was observed within the snowpack, between 25 cm and 43 cm. Below the rain-crust, layers of faceted crystals and rounded crystals were observed. Above the rain-crust, layers of faceted crystals, rounded crystals, and faceting rounded crystals were observed, capped by a thin rime-crust. The highest temperature gradient within the snowpack was observed between 20 cm and 30 cm, where the temperature decreased from -2.2°C to -3.7°C; a temperature gradient of 1.5°C per 10 cm.
Figure 4.18 Snow profile obtained at the Craigieburn Valley ski area, 9 July 2012 at 1200 hours.

The Craigieburn Valley ski area slope tested received direct solar radiation during the morning, due to the easterly aspect of the slope. This contrasts to the Craigieburn Valley backcountry slope tested, which did not receive any direct sunlight over the course of the fieldwork campaign, due to the southerly aspect of that slope. As such, a second full profile was carried out later in the day (1730 hours, with the first snow profile carried out at 1200 hours) at the Craigieburn Valley ski area, in an attempt to observe changes in the temperature gradient of the snowpack (Figure 4.19). Indeed, snowpack temperatures measured were considerably different in the upper portion of the snowpack. This was
especially apparent at the surface of the snowpack, where the temperature had decreased from -5.2°C at 1200 hours to -11.7°C at 1730 hours. Resultantly, a relatively high temperature gradient was established in the upper portion of the snowpack, which contrasts to the lack of temperature gradient observed in the uppermost portion of the snowpack that was observed at 1200 hours. At 1730 hours, a temperature decrease of 6.3°C was observed between 70 cm and 95 cm, where the temperature decreased from -5.4°C to -11.7°C; a temperature gradient of 2.52°C per 10 cm.

Figure 4.19 Snow profile obtained at the Craigieburn Valley ski area, 9 July 2012 at 1730 hours.
Spatial variability of snow depth and slab thickness was observed within the Craigieburn Valley ski area when stability testing was carried out on 9 July 2012 (Table 4.6). Again, possible reasons for the variability in snow thickness are outlined in Section 5.3.1.

**Table 4.6** Descriptive statistics pertaining to the Craigieburn Valley ski area snowpack, showing the variability of snow depth and slab thickness observed during stability testing on 9 July 2012.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Avg.</th>
<th>Std. Dev.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow depth (cm)</td>
<td>85.4</td>
<td>9.9</td>
<td>65 - 100</td>
</tr>
<tr>
<td>Slab thickness (cm)</td>
<td>23.4</td>
<td>7.9</td>
<td>7 - 41</td>
</tr>
</tbody>
</table>

Structural ‘lemons’ were observed in the Craigieburn Valley ski area snowpack (Table 4.7). Four thresholds for weak layer variables were met, which suggests the snowpack was structurally unstable.

**Table 4.7** Weak layer variables (structural ‘lemons’) observed within the Craigieburn Valley ski area snowpack on 9 July 2012. The weak layer variable thresholds were applied to the weak layer upon which fracture initiation and propagation occurred during stability testing, and the layers immediately adjacent to that weak layer.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Threshold</th>
<th>Threshold met?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak layer depth</td>
<td>≤ 1 m</td>
<td>Yes</td>
</tr>
<tr>
<td>Weak layer thickness</td>
<td>≤ 10 cm</td>
<td>Yes</td>
</tr>
<tr>
<td>Hardness difference</td>
<td>≥ 1 step</td>
<td>Yes</td>
</tr>
<tr>
<td>Weak layer grain type</td>
<td>Persistent (SH, DH, FC)</td>
<td>Yes</td>
</tr>
<tr>
<td>Grain size difference</td>
<td>≥ 1 mm</td>
<td>No</td>
</tr>
</tbody>
</table>
4.3.6 Avalanche observations

As demonstrated in Section 2.4 and 2.5, weather and snowpack structure have an implicit role in the snowpack stability observed. As such, it is pertinent to describe the avalanche occurrences observed at Craigieburn Valley over the course of the field work campaign of the present study. Two skier-triggered loose snow avalanches occurred in early July (Table 4.8). On 2 July, the avalanche event resulted from instability in association with solar radiation, which reduced the cohesion of the uppermost portion of the snowpack (Figure 4.20). The 5 July avalanche event occurred on a day when thin low cloud was present. As such, it is thought that a ‘greenhouse effect’ occurred, which reduced the cohesion of the uppermost portion of the snowpack. Widespread avalanche activity occurred between 13 July and 14 July 2012, associated with the passage of a rain event.

Table 4.8 Avalanche observed within Craigieburn Valley that occurred between 22 June and 26 July, 2012. Note that the avalanche size, and the slope angle/aspect where the avalanche occurred have been estimated.

<table>
<thead>
<tr>
<th>Date</th>
<th>Avalanche type</th>
<th>Size</th>
<th>Slope angle/aspect</th>
<th>Trigger</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 July</td>
<td>Loose snow</td>
<td>1.5</td>
<td>39° / NE</td>
<td>Skier</td>
<td>Within ski area</td>
</tr>
<tr>
<td>5 July</td>
<td>Loose snow</td>
<td>1</td>
<td>35° / SE</td>
<td>Skier</td>
<td>Within ski area</td>
</tr>
<tr>
<td>13 – 14 July</td>
<td>Loose snow</td>
<td>≤ 2</td>
<td>35° - 39° / southerly half</td>
<td>Natural</td>
<td>Backcountry</td>
</tr>
</tbody>
</table>
Figure 4.20  A skier-triggered loose snow avalanche, which occurred on 2 July 2012. The avalanche debris runs from near the upper-right corner towards the lower left corner of the picture. This avalanche occurred in an area within the Craigieburn Valley ski area known as the “Remarkables”, and occurred on a slope with a north-easterly aspect, and initiated on a slope angle of approximately 39°.

4.4 Spatial and temporal variability of snowpack stability

This section presents the snowpack stability results obtained from testing that was carried out over a period of five days at Craigieburn Valley, from 7 July 2012 to 11 July 2012. Results from the Craigieburn Valley backcountry study slope are described first (Section 4.4.1). Testing was carried out on two days at the Craigieburn Valley backcountry study slope; 7 July and 11 July. Each day of testing enabled the spatial variability snowpack stability to be observed, and any difference in results between the two days of testing enabled observations of temporal variability to be made. Snow stability results obtained from the Craigieburn Valley ski area on 9 July will be presented (Section 4.4.2) following the Craigieburn Valley backcountry results. Note that detailed records of the stability test results obtained for the present study are provided in Appendix B.
4.4.1 Craigieburn Valley backcountry

Thirty CT and 15 ECT results from the Craigieburn Valley backcountry were obtained on each day of stability testing (Figures 4.21 and 4.22). A fracture initiated on all 30 CTs on both day one (7 July) and day two (11 July) of testing. The average tap score required for a fracture to initiate on 7 July was 14.8 taps, and on 11 July the average tap score was 19.2 taps (Table 4.9). On 7 July, 26 of 30 CT results fractured with a sudden fracture character, with 2 of the remaining 4 fractures having a resistant planar fracture character, and 2 fractures having a non-planar break fracture character. In 13 of the 15 day one snowpits, both CT fracture results were of sudden fracture character. On 11 July, 26 of 30 CT results fractured with a sudden fracture character, with the remaining 4 fractures having a non-planar break fracture character. In 12 of the 15 day two snowpits, both CT fracture results were of a sudden fracture character. On 7 July, the CT result which indicated the highest instability occurred twice in snowpit A3. In this snowpit, both CTs had a very easy tap score of 0 and a sudden planar fracture character. The highest CT tap score observed on 7 July occurred in snowpit C3. Within this snowpit, a hard tap score of 25 along with a sudden collapse fracture character was observed. On 11 July, the CT result which indicated the highest instability occurred in pit DD3.5. The result comprised an easy tap score of 1 and a sudden planar fracture character. The day two CT result which indicated the highest stability occurred in pit AA3.5. The result comprised a hard tap score of 28 and a break fracture character.
Figure 4.21 Compression test (CT) results obtained from the Craigieburn Valley backcountry. Note that two CTs were performed in each snowpit (Section 3.3.1). The upper plot represents results obtained from stability testing on day one; 7 July, and the lower plot represents results obtained from stability testing on day two; 11 July. Each of the 30 small boxes represents a snowpit which was dug within the Craigieburn Valley backcountry study slope. Numbers within the small boxes represent the number of taps required for a fracture to initiate, and the associated letters represent the type of fracture that occurred. Boxes which have been highlighted light grey indicate snowpits within which a sudden fracture character occurred in both compression tests. The letters and numbers along the outside of the plots have been provided in order to enable identification of individual snowpits.
A fracture initiated in all 15 ECTs on 7 July, whereas on 11 July this occurred in 13 of 15 ECTs (Figure 4.22). Fracture propagation occurred in 8 of the 15 ECTs on 7 July, and in 5 of the 15 ECTs on 11 July. The average tap score required for an ECT to propagate on 7 July was 16.3 taps, and on 11 July the average was 17.8 taps (Table 4.9). On 7 July, all 8 ECTP results comprised a sudden fracture character. On 11 July, 4 of the 5 ECTP results comprised a sudden fracture character. The remaining ECTP result (pit CC2.5) had a resistant planar fracture character. On 7 July, the ECT result which indicated the highest instability occurred in pit C2. Here, a very easy tap score of 0 was required for fracture propagation (i.e., the fracture initiated and propagated along the entire length of the column whilst the column was being isolated), with a sudden planar fracture character observed. The 7 July ECT result which indicated the highest stability occurred in pit E3, where a hard result of 28 taps was required for a fracture to initiate. A break fracture character was observed in association with this tap score. On 11 July, the ECT result which indicated the highest instability occurred in pit DD3.5. Here, a very easy tap score of 0 resulted in fracture propagation, and a sudden collapse fracture character was observed. The 7 July ECT result which indicated the highest stability occurred in pits BB3.5 and EE1.5. No fracture initiation occurred during these two ECTs.
Figure 4.22  Extended column test results obtained from the Craigieburn Valley backcountry. The upper plot represents results obtained from testing on day one; 7 July, and the lower plot represents results obtained from testing on day two; 11 July. Each of the 30 small boxes represents a snowpit that was dug within the Craigieburn Valley backcountry study slope. Numbers within the small boxes represent the number of taps required for a fracture to initiate, and the associated letters represent the type of fracture that occurred. The letter ‘X’ indicates that no fracture initiated. Boxes which have been highlighted light grey indicate snowpits within which a fracture both initiated and propagated along the entire length of the isolated column. The letters and numbers along the outside of the plots have been provided in order to enable identification of individual snowpits.
Table 4.9 Descriptive statistics of compression test (CT) and extended column test fracture propagation (ECTP) results obtained from the Craigieburn Valley backcountry on 7 July and 11 July 2012.

<table>
<thead>
<tr>
<th>Day</th>
<th>CT Count</th>
<th>Avg. CT Score (Taps)</th>
<th>Std.Dev. CT Score</th>
<th>ECTP Count</th>
<th>Avg. ECTP Score (Taps)</th>
<th>Std.Dev. ECTP Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 July</td>
<td>30 of 30</td>
<td>14.8</td>
<td>5.9</td>
<td>8 of 15</td>
<td>16.3</td>
<td>9.2</td>
</tr>
<tr>
<td>11 July</td>
<td>30 of 30</td>
<td>19.2</td>
<td>6.5</td>
<td>5 of 15</td>
<td>17.8</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Due to the spatial variability of slab thickness observed on both days of testing (Table 4.6), regression analyses were performed to determine whether a relationship could be detected between this variable and the CT scores obtained (Table 4.10). The null hypothesis was that there was no relationship between the predictor variable (slab thickness), and the CT score. On 7 July, \( p = 0.761 \) (which is greater than 0.05); thus, the null hypothesis could not be rejected. On 11 July, \( p = 0.775 \ (> 0.05) \); again, the null hypothesis could not be rejected. As such, in the Craigieburn Valley backcountry study slope, there was no statistically significant relationship between slab thickness and the CT score.

Table 4.10 Regression analyses testing the relationship between slab thickness \((y)\) and compression test (CT) score \((x)\). The null hypothesis \((H_0)\) stated that there is no relationship between slab thickness and CT score.

<table>
<thead>
<tr>
<th>Date of testing</th>
<th>Linear regression equation</th>
<th>( R^2 )</th>
<th>( p )-value</th>
<th>Reject ( H_0 )?</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 July</td>
<td>( x = 28.13 - 0.1682 \ y )</td>
<td>0.3%</td>
<td>0.761</td>
<td>No</td>
</tr>
<tr>
<td>11 July</td>
<td>( x = 20.4 - 0.043 \ y )</td>
<td>0.3%</td>
<td>0.775</td>
<td>No</td>
</tr>
</tbody>
</table>

Further statistical analyses were carried out in order to characterise the temporal variability of snowpack stability at the Craigieburn Valley backcountry slope (Table 4.11). As already identified, the mean CT score increased from 14.8 taps on 7 July, to 19.2 taps on 11 July. The Mann-Whitney test was used to compare these data, and found the temporal change in
CT results to be statistically significant at the 99% level of confidence ($p = 0.008$, $N = 30$). With respect to the ECTP score, the temporal change in scores observed from 7 July to 11 July was not statistically significant ($p = 0.7697$, $N = 8$ and 5, note the small sample size). Regarding ECT fracture initiation results, no statistically significant temporal change in score was observed ($p = 0.1600$, $N = 30$ and 28).

**Table 4.11** Statistical significance in the temporal change of compression (CT), extended column test fracture propagation (ECTP) and extended column test fracture initiation (ECTN) test scores, calculated using the Mann-Whitney test. Note that the ECTN scores include the tap scores obtained from ECTP results, as a fracture must firstly initiate in an ECTP result. Change in median CT, ECTP and ECTN scores are shown, as well as the Mann-Whitney test $p$-value, demonstrating whether the observed temporal change was statistically significant. Bracketed numbers represent the sample size ($N$) of each stability test result obtained on each day of testing.

<table>
<thead>
<tr>
<th>Stability test</th>
<th>Median score 7 July (N)</th>
<th>Median score 11 July (N)</th>
<th>$p$-value</th>
<th>Statistically significant temporal change</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>14 (30)</td>
<td>21 (30)</td>
<td>0.008</td>
<td>Yes</td>
</tr>
<tr>
<td>ECTP</td>
<td>17.5 (8)</td>
<td>20 (5)</td>
<td>0.7697</td>
<td>No</td>
</tr>
<tr>
<td>ECTN</td>
<td>18 (30)</td>
<td>25 (28)</td>
<td>0.1600</td>
<td>No</td>
</tr>
</tbody>
</table>

Carrying out two CTs per snowpit enabled the observation of snowpack stability for both small scale variability within a pit (intra-pit variability) and larger slope scale variability (inter-pit variability), respectively (Table 4.12). The greatest intra-pit range of CT tap score was 12 (1 – 13), observed on 11 July. The largest inter-pit range of CT tap score of 27 (1 – 28) was also observed on 11 July. Both intra-pit and inter-pit similarity of CT scores and CT fracture character were calculated (criteria outlined in Section 3.4.1.2), providing a detailed measure of small and larger scale variability (Table 4.12). The results show that fracture character was generally less spatially variable than the compression test score, and greater variability was observed at the inter-pit (slope-) scale compared to the intra-pit (pit-) scale.
Table 4.12 Spatial variability of compression test (CT) scores and fracture character (FC) obtained from the Craigieburn Valley backcountry on each day of testing, showing the maximum intra-pit (pit scale) and inter-pit (slope scale) range of CT tap scores. Percentage of similar pairs at the pit scale (a measure of pit scale variability), and percentage of similar pits within slope (a measure of slope scale variability) with respect to the compression test tap score (CT) and compression test fracture character (FC) are shown.

<table>
<thead>
<tr>
<th>Day</th>
<th>CT Score Range (Intra- &amp; Inter- pit)</th>
<th>% of similar pairs at pit scale</th>
<th>% of similar pits within slope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intra-</td>
<td>Inter-</td>
<td>CT</td>
</tr>
<tr>
<td>7 July</td>
<td>7 - 17</td>
<td>0 - 25</td>
<td>73</td>
</tr>
<tr>
<td>11 July</td>
<td>1 - 13</td>
<td>1 - 28</td>
<td>66</td>
</tr>
</tbody>
</table>

Figures 4.23 - 4.25 highlight the variability of CT scores, ECT fracture initiation scores and ECT fracture propagation scores, respectively. The median, upper quartile and lower quartile stability test scores for each of the CT, ECTN, and ECTP results are shown. Whilst the number of ECTP results were relatively few, Figure 4.25 demonstrates that there was considerable discrepancy in the ECTP score observed within the Craigieburn Valley backcountry slope on each day of testing.

7 July

```
0 | | | | 12 | 14 | 19 | | | | | | | | 30
```

11 July

```
0 | | | | 15 | | 21 | 23 | | | | | | | 30
```

**Figure 4.23** Compression test (CT) results obtained from the Craigieburn Valley backcountry study slope on each day of testing. Numbers represent the tap score. Highlighted in dark yellow is the median tap score obtained from the slope, and the extent of the yellow highlighted bar represents the lower quartile and upper quartile of CT results, respectively.
Moran’s \( I \) analysis was undertaken in order to determine whether a coherent spatial pattern was present in the snow study plot, with respect to a number of snowpack stability variables (Table 4.13). The variables which were tested comprised the tap score of the first compression test carried out in each pit (CT1 score), the tap score of the second compression test carried out in each pit (CT2 score), extended column test fracture initiation score (ECTN score), and the extended column test fracture propagation score (ECTP score). Note that the CT scores from each pit on each day of testing were treated separately due to having the same location – only one location was marked with a GPS per snowpit that was dug. Thus, the first CT scores from each pit were tested against each other, and then the second CT scores from each pit were tested against each other. Results from the Moran’s \( I \) analysis on day one show that for each of the four variables tested, there
is no spatial clustering of the values. Thus, the pattern observed may be defined as random. Despite being separated for analysis purposes, the Z score of both the first and second CT scores obtained from each snowpit on day two of testing indicates that there is less than a 10% likelihood that the clustered pattern of each is the result of random chance. This is due to the ‘CT1 score’ $Z = 1.71$, and the ‘CT2 score’ $Z = 1.66$, which are both greater than the 10% Z score threshold of 1.65 (Section 3.4.1.3). These results indicate a discernible temporal change in the spatial variability of CT scores, from a random pattern on day one of testing to a more spatially clustered pattern on day two of testing. A temporal change is also apparent for the ECTP results. The day two ‘ECTP score’ $Z$ of 2.38 exceeds the 5% Z score threshold of 1.96 (Section 3.4.1.3). This indicates that there is less than 5% likelihood that the clustered pattern observed is the result of random chance. As such, a discernible temporal change in ECTP results is demonstrated, from a random pattern on day one of testing to a more spatially clustered pattern on day two of testing.
Table 4.13  Moran’s I analyses undertaken on data obtained from the Craigieburn Valley backcountry study slope. Seven snowpack stability variables were tested; the initial compression test carried out in each pit (CT1 score), the second compression test carried out in each pit (CT2 score), extended column test fracture initiation score (ECTN score), and extended column test fracture propagation score (ECTP score). ‘Day’ represents the day of testing in the Craigieburn Valley backcountry from which the snowpack stability variables were obtained.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Day</th>
<th>Moran’s I</th>
<th>Z score</th>
<th>Moran’s I summary comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT1 score</td>
<td>7 July</td>
<td>-0.03</td>
<td>0.87</td>
<td>Pattern is not clustered (i.e. random).</td>
</tr>
<tr>
<td></td>
<td>11 July</td>
<td>0.25</td>
<td>1.71</td>
<td>There is less than 10% likelihood that this clustered pattern is the result of random chance. Note that P = 0.088.</td>
</tr>
<tr>
<td>CT2 score</td>
<td>7 July</td>
<td>-0.08</td>
<td>-0.13</td>
<td>Pattern is not clustered (i.e. random).</td>
</tr>
<tr>
<td></td>
<td>11 July</td>
<td>0.23</td>
<td>1.66</td>
<td>There is less than 10% likelihood that this clustered pattern is the result of random chance. Note that P = 0.097.</td>
</tr>
<tr>
<td>ECTN score</td>
<td>7 July</td>
<td>-0.07</td>
<td>-0.04</td>
<td>Pattern is not clustered (i.e. random).</td>
</tr>
<tr>
<td></td>
<td>11 July</td>
<td>~</td>
<td>~</td>
<td>Unable to carry out analysis due to presence of ECTX results.</td>
</tr>
<tr>
<td>ECTP score</td>
<td>7 July</td>
<td>0.02</td>
<td>0.94</td>
<td>Pattern is not clustered (i.e. random).</td>
</tr>
<tr>
<td></td>
<td>11 July</td>
<td>0.40</td>
<td>2.38</td>
<td>There is less than 5% likelihood that this clustered pattern is the result of random chance. Note that P = 0.017.</td>
</tr>
</tbody>
</table>

4.4.1.1 Three-component model of stability

Section 3.4.1.1 describes how stability ratings for individual snowpits were calculated, with respect to the CT and ECT stability tests, utilising a stability rating scheme developed for the present study based on the three-component model of stability. Figure 4.26 shows the avalanche forecast for the region. Table 4.14 and Figure 4.27 highlight the results of the aforementioned analysis, with specific individual snowpit stability ratings obtained for each stability test on each day of testing provided in Appendix B. In order to provide
context to the stability ratings calculated, Figure 4.26 shows a portion of the regional avalanche forecast, representative of all the forecasts which were provided over the course of snow stability testing carried out from 7 July to 11 July 2012. The highest avalanche danger rating forecasted was low, with the primary avalanche danger expected to be loose wet avalanches on northerly, north-easterly and easterly aspects. The Craigieburn Range avalanche forecast stated that the snowpack stability across the range was relatively good. In addition to the forecast stating that the highest avalanche danger was low, it may be inferred that the snowpack stability throughout the Craigieburn Range was relatively high (i.e. good stability). The avalanche forecast noted that isolated areas of persistent weak layers were present on high elevations (which was defined as 1,800 m a.s.l.) of the southerly quarter. The forecast stated, somewhat ambiguously, that a wide range of stability results had been obtained, with no information provided as to the stability scores obtained, nor the aspect or elevation of the location where stability tests were carried out. Because the area of slope tested in the Craigieburn Valley backcountry had an average elevation of 1,650 m a.s.l., there was no specific indication that persistent weak layers would be present. Furthermore, there were no obvious signs of instability on the slope, or on similar slopes. The combination of information obtained from the avalanche forecast and stability interpretations justifies an expectation of good stability for the Craigieburn Valley backcountry slope which was tested in the present study.
Figure 4.26 Public avalanche advisory for the Craigieburn Range, issued at 2209 hours on 8 July 2012, valid till 1800 hours on 9 July 2012. This advisory is representative of all avalanche advisories that were provided for the Craigieburn Range for the period of 7 July to 11 July. Avalanche danger was rated as low, and the primary avalanche concern was for loose snow avalanches occurring on solar aspects. Advisory obtained from the New Zealand Avalanche Centre (2012).
Table 4.14 further illustrates the spatial variability of snowpack stability observed within the Craigieburn Valley backcountry study slope. Notably, three very poor stability ratings, and nine poor stability ratings were obtained from individual snowpits, respectively. These results contrast considerably to the expected stability of the slope. As such, the expected slope stability was good, yet overall slope stability ratings calculated by combining individual snowpit stability ratings rated the slope as having fair stability.

Table 4.14  Snowpack stability ratings of individual snowpits, and the overall stability of the Craigieburn Valley backcountry slope tested. The overall stability rating averages the 15 individual snowpit stability scores obtained on each day of testing, for each of the compression (CT) and extended column (ECT) stability tests (Appendix B). These snowpit stability ratings were calculated according to the stability rating scheme developed for the present study, which is based on the three-component model of stability. With regard to the distribution of snowpits ratings, “VP” is very poor stability, “P” is poor stability, “F” is fair stability, “G” is good stability, and “VG” is very good stability. Note that the snowpack stability ratings obtained from individual snowpits with respect to the ECT results are also demonstrated pictorially in Figure 4.27.

<table>
<thead>
<tr>
<th>Stability test</th>
<th>Date</th>
<th>Distribution of snowpit stability ratings</th>
<th>Overall slope stability rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>VP</td>
<td>P</td>
</tr>
<tr>
<td>CT</td>
<td>7 July</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>11 July</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>ECT</td>
<td>7 July</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>11 July</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 4.27 Individual snowpit stability ratings with respect to the extended column test (ECT) scores, utilising the three-component model of stability, obtained from the Craigieburn Valley backcountry study slope on 7 July and 11 July 2012. The spatial variability of individual snowpit stability ratings is demonstrated. Despite an increase in the overall stability rating of the slope between 7 July and 11 July, areas of very poor and poor stability were observed on 11 July.

4.4.2 Craigieburn Valley ski area

A total of 15 snowpits were dug within the Craigieburn Valley ski area on 9 July 2012. Within each snowpit, two compression tests (CTs) and one extended column test (ECT) were performed, providing 30 CT and 15 ECT results (Figures 4.28 and 4.29). With respect to the CT, a fracture occurred on 26 out of the 30 tests performed. The average tap score required for a fracture to occur was 18.9 taps (Table 4.15). Twenty-two of the 26 CT fractures had a sudden fracture character. Two of the remaining four fractures had a resistant planar fracture character (snowpit D3), and two non-planar break fracture characters were observed (snowpits A1 and C3). In 10 of the 15 pits, both CT fracture
character results were sudden. The CT result which indicated the highest instability occurred in snowpit G3. Within this snowpit, an easy tap score of 7 and an associated sudden collapse fracture character was observed. The CT result which indicated the highest stability occurred four times; twice in snowpit F1 and twice in snowpit F3. No fracture occurred as a result of performing the CT within each of these snowpits.

![Diagram](image)

**Figure 4.28** Compression test results obtained from the Craigieburn Valley ski area on 9 July. Each of the 15 boxes represents a snowpit which was dug during stability testing. Numbers within the small boxes represent the number of taps required for a fracture to initiate, and the associated letters represent the fracture character that was observed. The letter ‘X’ indicates that no fracture initiated during stability testing. Boxes which have been highlighted light grey indicate snowpits within which a sudden fracture character was observed in both compression tests.

With respect to the ECTs carried out within the Craigieburn Valley ski area on 9 July 2012, a fracture initiated (ECTN) on six of the 15 ECTs (Figure 4.29). Fracture propagation (ECTP) occurred on only one of the 15 ECTs (Table 4.14). This ECTP result (pit G3) was indicative of the highest instability observed throughout the slope tested, with a hard tap score of 28. The ECTP consisted of a sudden collapse fracture character. The highest stability observed occurred in seven pits (indicated by an ‘X’ in Figure 4.29), where no fracture initiation or propagation occurred as a result of the respective ECTs.
Figure 4.29 Extended column test results obtained from the Craigieburn Valley ski area on 9 July 2012. Each of the 15 small boxes represents a snowpit which was dug during stability testing. Numbers within the small boxes represent the number of taps required for a fracture to initiate, and the associated letters represent the type of fracture that occurred. The letter ‘X’ indicates that no fracture initiated. Boxes which have been highlighted light grey indicate snowpits within which a fracture both initiated and propagated (ECTP) along the entire length of the isolated column.

Table 4.15 Descriptive statistics of stability test results obtained from the Craigieburn Valley ski area on 9 July 2012.

<table>
<thead>
<tr>
<th>CT Count</th>
<th>Avg. CT Score (Taps)</th>
<th>Std.Dev. CT Score</th>
<th>ECTP Count</th>
<th>Avg. ECTP Score (Taps)</th>
<th>Std.Dev. ECTP Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 of 30</td>
<td>18.9</td>
<td>7.1</td>
<td>1 of 15</td>
<td>28</td>
<td>~</td>
</tr>
</tbody>
</table>

Detailed information regarding both intra-pit (pit scale) and inter-pit (slope scale) variability of snowpack stability could be obtained due to undertaking two CTs per snowpit. Table 4.16 shows the results obtained from the data treatment steps outlined in Section 3.4.1.2. CT scores ranged between 7 and CTN across the study slope, and greater variability was observed at the inter-pit (slope-) scale compared to the intra-pit (pit-) scale.
Table 4.16  Spatial variability of compression test (CT) scores and fracture character (FC) obtained from the Craigieburn Valley ski area on 9 July 2012, showing the maximum intra-pit (pit scale) and inter-pit (slope scale) range of CT tap scores. Percentage of similar pairs at the pit scale (a measure of pit scale variability), and percentage of similar pits within slope (a measure of slope scale variability) with respect to the compression test tap score (CT) and compression test fracture character (FC) are shown. Note that the results from three snowpits have not been included as they fell within the recommended distance of snowpit spacing (Sections 2.6.2 and 3.4.1.2). The letter ‘X’ represents a CT where no fracture occurred.

<table>
<thead>
<tr>
<th>CT Results (out of 24)</th>
<th>CT Score Range (Intra- &amp; Inter-pit)</th>
<th>% of similar pairs at pit scale</th>
<th>% of similar pits within slope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intra- 7 - 23</td>
<td>Inter- 7 - X</td>
<td>CT 60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CT 14</td>
</tr>
</tbody>
</table>

Figures 4.30 and 4.31 provide a further illustration of the spatial variability snowpack stability, highlighting the median, upper quartile and lower quartile of CT and ECTN scores obtained from the Craigieburn Valley ski area, respectively.

**Figure 4.30** Median (dark yellow) and lower and upper quartiles (light yellow) of compression test (CT) results obtained from the Craigieburn Valley ski area on 9 July 2012.

**Figure 4.31** Median (dark yellow) and lower and upper quartiles of extended column test fracture initiation (ECTN) results obtained from the Craigieburn Valley ski area on 9 July 2012.

4.4.2.1 Three-component model of stability

Given the regional avalanche forecast (Figure 4.26), combined with no pertinent observations of instability within the Craigieburn Valley ski area, the stability of the
Craigieburn Valley ski area slope tested was expected to be good. Section 3.4.1.1 describes how stability ratings for individual snowpits were calculated, with respect to the CT and ECT stability tests. Table 4.17 highlights the overall results of this analysis, with specific individual snowpit stability ratings obtained for each stability test provided in Appendix C. The expected slope stability was good, and the overall slope stability rating obtained from ECT results was good. In contrast, the overall slope stability rating obtained from CT results was fair, and the results from three individual snowpits rated the slope stability as poor.

Table 4.17 Snowpack stability ratings of individual snowpits, and the overall stability of the Craigieburn Valley ski area slope tested on 9 July 2012. The overall stability rating averages the 15 individual snowpit stability scores obtained for each of the compression (CT) and extended column (ECT) stability tests (Appendix C). Snowpit stability ratings were calculated according to the stability rating scheme developed for the present study, which is based on the three-component model of stability. With regard to the distribution of snowpits ratings, “VP” is very poor stability, “P” is poor stability, “F” is fair stability, “G” is good stability, and “VG” is very good stability.

<table>
<thead>
<tr>
<th>Stability Test</th>
<th>Distribution of snowpit ratings</th>
<th>Overall slope stability rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VP</td>
<td>P</td>
</tr>
<tr>
<td><strong>CT</strong></td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td><strong>ECT</strong></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

4.5 Rain event case study

A significant rainfall event occurred at Craigieburn Valley, starting in earnest on the morning of 13 July 2012 and ending in the afternoon of 15 July 2012. A warm, moist northwesterly airflow with a number of warm fronts embedded within became established over New Zealand (Figure 4.32). As a result of this weather system, Craigieburn Valley received a total of 106 mm of rain at 1,265 m a.s.l., with rain falling to ridge-top for the duration of the weather event due to high freezing levels (Table 4.18).
Table 4.18 Minimum temperature, maximum temperature, and 24 hr rainfall totals at the Craigieburn Valley Ski Club weather observation plot (1,265 m a.s.l.), as well as forecasted and calculated freezing levels (F.L.), over the course of the 13 July – 15 July rain event.

<table>
<thead>
<tr>
<th>Date</th>
<th>July 12</th>
<th>July 13</th>
<th>July 14</th>
<th>July 15</th>
<th>July 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Temp. (°C)</td>
<td>1.5</td>
<td>3.0</td>
<td>2.5</td>
<td>4.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>Max. Temp. (°C)</td>
<td>6.5</td>
<td>5.0</td>
<td>8.0</td>
<td>8.0</td>
<td>6.5</td>
</tr>
<tr>
<td>Forecasted F.L. (m)</td>
<td>2,000</td>
<td>2,200</td>
<td>2,600</td>
<td>2,400</td>
<td>1,800</td>
</tr>
<tr>
<td>Calculated F.L. (m)</td>
<td>2,193</td>
<td>1,979</td>
<td>2,407</td>
<td>2,407</td>
<td>2,193</td>
</tr>
<tr>
<td>24 hr rainfall (mm)</td>
<td>1</td>
<td>27</td>
<td>54.5</td>
<td>23.5</td>
<td>0</td>
</tr>
</tbody>
</table>

The rainfall event had a considerable impact on the snowpack structure at both the Craigieburn Valley ski area and Craigieburn Valley backcountry locations. A full snow profile was carried out at the Craigieburn Valley backcountry study slope on 21 July 2012, and at the Craigieburn Valley ski area study slope on 22 July 2012 (Figures 4.33 and 4.34, respectively). As shown in Figure 4.33, the snowpack depth had reduced significantly within the Craigieburn Valley backcountry study slope as a result of the rainfall event. At the location of the associated full snow profile, a snowpack depth of 38 cm was measured. Probing around the area revealed snow depths between 35 cm and 40 cm, considerably less than the approximately 80 cm average snow depth of the area observed prior to the rain event (Table 4.4). Of note was the apparent development of a new persistent weak layer,
between 25 cm and 27 cm in the snowpack. As a result of this layer, the snowpack was observed to meet the threshold of three weak layer variables, therefore three ‘lemons’ were observed in the snowpack (Table 4.19). The presence of three ‘lemons’ meant the snowpack structure was indicative of fair stability. A relatively high temperature gradient was observed between 20 cm and 25 cm in the snowpack. At this location, the temperature decreased from -3.5°C to -4.8°C; a temperature gradient of 2.6°C per 10 cm.

Figure 4.33 Snow profile obtained at the Craigieburn Valley backcountry on 21 July 2012 at 1000 hours.
A reduction in snow depth as a result of the rain event was also observed at the Craigieburn Valley ski area study slope, although it was not as considerable as that observed within the Craigieburn Valley backcountry study slope. Measurements from seven snowpits performed in the Craigieburn Valley ski area revealed an average snow depth of 72.9 cm, compared to an 85.4 cm average observed prior to the rain event (Table 4.6). Figure 4.34 demonstrates a considerable change in snowpack structure of the Craigieburn Valley ski area compared to that which was observed prior to the rain event (Figures 4.18 and 4.19). Most notably, no persistent weak layers were observed, and there were no longer any structural ‘lemons’ within the snowpack (Table 4.19). As such, the snowpack stability was very good with respect to the structure. The full snow profile shows that the snowpack had been somewhat homogenised by the rain event, with the majority of layers observed comprising either rain crust or thin ice layers. Between 0 cm and 35 cm, a layer of rounded grains was observed, which contained some liquid water. As such, the temperatures measured within this portion of the snowpack were close to 0°C. For example, the temperature of the snowpack at 30 cm was -0.4°C, and at 10 cm the temperature was -0.2°C.
Figure 4.34 Snow profile obtained at the Craigieburn Valley ski area on 22 July 2012 at 1100 hours.
Table 4.19  Weak layer variable (structural ‘lemons’) thresholds, and whether or not they were observed within the Craigieburn Valley backcountry, and Craigieburn Valley ski area, when stability testing was carried out on 21 July and 22 July 2012, respectively.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Threshold</th>
<th>Backcountry</th>
<th>Ski area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak layer depth</td>
<td>≤ 1 m</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Weak layer thickness</td>
<td>≤ 10 cm</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Hardness difference</td>
<td>≥ 1 step</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Weak layer grain type</td>
<td>Persistent (SH, DH, FC)</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Grain size difference</td>
<td>≥ 1 mm</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

A limited number of stability tests were carried out at both the Craigieburn Valley ski area and Craigieburn Valley backcountry locations after the rain event. Two snowpits were dug within the Craigieburn Valley backcountry on 21 July 2012, and seven snowpits were dug within the Craigieburn Valley ski area on 22 July 2012. Within each snowpit, two CTs and one ECT were performed. No fractures occurred in the Craigieburn Valley backcountry for either the CTs or the ECTs (Table 4.19). Regarding the Craigieburn Valley ski area, no fractures occurred as a result of the ECTs. However, in three out of 14 CTs, a fracture occurred. The average tap score of these fractures was 15.7 taps, comprising an 11 tap, 15 tap and 21 tap result. The fracture character of each of these results was non-planar break. Each fracture occurred at a depth of 4 cm from the snow surface. Here, a melt-freeze crust fractured atop a three centimetre thick layer of large rounded particles, which sat atop the uppermost rain-crust. Thus, the uppermost section of the snowpack in these locations differed from that observed when the full profile was carried out (Figure 4.34). However, beneath this discrepancy the snowpack structure was comparable to that observed at the location of the full snow profile. These fracture initiation results did not represent a significant stability concern. Firstly, this was due to the close proximity of the fracture to the surface; only a very thin slab was involved. Secondly, the snowpack structure observed at the location of the fracture initiation results was relatively isolated at the slope scale.
Table 4.20 Descriptive statistics of stability test results (compression test; CT, and extended column test; ECT) obtained from the Craigieburn Valley backcountry on 21 July 2012, and from the Craigieburn Valley ski area on 22 July 2012.

<table>
<thead>
<tr>
<th>Location</th>
<th>CT Count</th>
<th>Avg. CT Score (Taps)</th>
<th>Std.Dev. CT Score</th>
<th>ECTP Count</th>
<th>Avg. ECTP Score (Taps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backcountry</td>
<td>0 of 4</td>
<td>~</td>
<td>~</td>
<td>0 of 2</td>
<td>~</td>
</tr>
<tr>
<td>Ski area</td>
<td>3 of 14</td>
<td>15.7</td>
<td>5.0</td>
<td>0 of 7</td>
<td>~</td>
</tr>
</tbody>
</table>

An analysis of the stability ratings obtained from individual snowpits was also carried out (Table 4.21). Section 3.4.1.1 describes how stability ratings for individual snowpits were calculated, with respect to the CT and ECT stability tests. Very good overall slope stability was demonstrated at both the Craigieburn Valley ski area and Craigieburn Valley backcountry locations. Of the nine total snowpits dug subsequent to the rain event, all but one snowpit indicated very good stability.
Table 4.21  Snowpack stability ratings of individual snowpits, and the associated overall stability rating of the Craigieburn Valley ski area and Craigieburn Valley backcountry, as a result of stability testing carried out subsequent to the July 13 – July 15 rain event. The Craigieburn Valley ski area location was tested on 22 July, and the Craigieburn Valley backcountry location was tested on 21 July. The overall stability rating averages the individual snowpit stability scores obtained for each of the compression (CT) and extended column (ECT) stability tests obtained for each location (Appendix C). Snowpit stability ratings were calculated according to the stability rating scheme developed for the present study, which is based on the three-component model of stability. With regard to the distribution of snowpits ratings, “VP” is very poor stability, “P” is poor stability, “F” is fair stability, “G” is good stability, and “VG” is very good stability.

<table>
<thead>
<tr>
<th>Location</th>
<th>Stability Test</th>
<th>Distribution of snowpit ratings</th>
<th>Overall slope stability rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>VP</td>
<td>P</td>
</tr>
<tr>
<td>Backcountry</td>
<td>CT</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>ECT</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ski area</td>
<td>CT</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>ECT</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

4.6 Summary

The results presented in this study have shown that 61% of Craigieburn Valley ski area terrain and 51% of Craigieburn Valley backcountry terrain may be classified as primary avalanche terrain. Terrain analyses carried out highlight a notable discrepancy in proportions of slope aspect between the Craigieburn Valley ski area and the Craigieburn Valley backcountry. The vast majority of backcountry terrain (94%, or 93 ha) has an aspect with a southerly component, compared to 25% (38 ha) of the ski area terrain. Snowpack analyses demonstrated the presence of persistent weak layers within the Craigieburn Valley snowpack, and considerable spatial variability of snowpack stability results were
obtained from stability testing, ranging from very poor to good indications of stability within the same slope. Very poor stability results were obtained despite an expected slope stability of good, highlighting the disparity that may be observed between regional forecasts and snowpack stability observed at a smaller scale. Temporal changes in snowpack stability were also observed. An increase in stability at the slope scale was observed over time, although areas of considerable instability were still observed. Furthermore, spatial variability of snowpack stability appeared to increase over time, and snowpack stability results became increasingly clustered. The following chapter will compare the results obtained from the present study to previous studies, highlighting both similarities and dissimilarities observed. In addition, an in-depth analysis of the implications of the results obtained will be offered, in order to assess the pertinence of the results obtained with respect to the management of avalanche hazard in the Craigieburn Valley.
Chapter 5

Discussion

5.1 Introduction

The following discussion will highlight both the relevance and implications of the results presented in Chapter 4. As such, a detailed appraisal of the results with respect to the research objectives of this study is presented. Section 5.2 examines the weather and snowpack observations made over the course of the fieldwork campaign. This is necessary, as it provides an important framework within which the remainder of the discussion is situated. Section 5.3 compares the spatial variability of snowpack stability results obtained to those of previous studies. Section 5.4 examines the temporal variability results of the present study in the context of previous studies, and provides a comprehensive analysis of the rain event case study. Section 5.5 evaluates the implications of the discrepancy observed between the Craigieburn Valley ski area avalanche terrain and the Craigieburn Valley backcountry avalanche terrain. Additionally, by spending 35 consecutive days at Craigieburn Valley, the author of this study was afforded a unique insight into the practical implications of the results obtained, with respect to the potential avalanche hazard of the area. These implications are presented in Section 5.5.2. Caveats of the research carried out in this study are described in Section 5.6. As a result of this discussion, the reader will be aware of the key findings, which distinguish this study from previous research, and highlight this study’s valuable contribution to the current state of snowpack stability knowledge in New Zealand.
5.2 Weather and snowpack

As evidenced in Section 4.3, Craigieburn Valley experienced conditions typical of a transitional snow climate. This supports similar observations outlined in previous studies based in the Craigieburn Range (e.g. Prowse and Owens, 1984). The weaknesses of interest identified in this study were layers of faceted crystals within the snowpack. These were primarily the layers upon which fractures initiated and propagated during snow stability testing. The development of faceted crystals within the Craigieburn Valley snowpack occurred due to three key conditions (outlined in Section 2.5.1) being met; firstly, the snowpack was relatively thin (Jamieson and Johnston, 1992), and secondly, temperature gradients were relatively high (e.g. Birkeland, 1998). Finally, the facet layers identified in the Craigieburn Valley snowpack were located immediately above, below and within the rain-crust. This is in accordance with previous studies (e.g. Hägeli and McClung, 2003), which demonstrate the propensity of faceted crystals to develop in association with crusts.

Studies have shown persistent weak layers to be the layer primarily associated with skier triggered avalanches (e.g. Schweizer and Jamieson, 2001). Such studies, which are based on data obtained in North America and Europe, demonstrate the potential hazard associated with persistent weak layers. Over the course of the fieldwork campaign, the aforementioned association wasn’t observed at Craigieburn Valley. Two skier triggered avalanches occurred, and both of these were loose snow avalanches involving the uppermost layer of the snowpack. Snowpack analyses undertaken at the location of each avalanche showed that fracture initiation and propagation did not occur on persistent weak layers. Despite this, the development and subsequent observation of faceted crystal layers within the Craigieburn Valley snowpack is concerning. This is because such layers stabilise relatively slowly, and facilitate potential avalanche activity for a relatively long period of time (Hägeli and McClung, 2003). As a result, these weak layers may prove troublesome for snow safety practitioners for an extended period of time. Given that air temperatures are projected to increase in New Zealand throughout the 21st century (Sturman and Tapper, 2006; IPCC, 2007), it can be expected that rain events will continue to affect the seasonal snow cover of Craigieburn Valley. Furthermore, a recent study (Hendrikx et al., 2012) suggests that the mean maximum snow accumulation at elevations encompassing Craigieburn Valley will decrease throughout the next century. As a result, a combination
of relatively thin snowpacks, and crusts associated with rainfall, can continue to be expected. It was this combination, along with relatively high temperature gradients, which supported the observed development of persistent weak layers in the Craigieburn Valley snowpack during snow stability testing. Therefore, it is likely that snowpack stability concerns associated with the development of persistent weak layers will remain prevalent into the foreseeable future at Craigieburn Valley. This has important implications, given the difference in the proportions of terrain aspect between the Craigieburn Valley ski area and the backcountry. These implications are explored in Section 5.5.

Similar snowpack structure was observed at the Craigieburn Valley ski area and the Craigieburn Valley backcountry (Section 4.3). Despite this, the stability of the Craigieburn Valley ski area was observed to be considerably higher than that of the Craigieburn Valley backcountry (Section 4.4). The different aspect of each area is likely to have contributed to this observation. The Craigieburn Valley ski area location tested had an easterly aspect, and received direct solar radiation during the day, which would add heat to the snowpack. This is highlighted by the Craigieburn Valley ski area snow profiles shown in Section 4.3.5. These snow profiles demonstrate a diurnal signal, whereby the temperature gradient of the upper snowpack varies considerably between times of solar radiation being received and times when the slope is shaded. As a result, the temperature gradient in the upper snowpack was reduced during solar radiation reception, which may have reduced the rate of faceting occurring, and enhanced sintering between snow crystals (Colbeck, 1982). In contrast, the Craigieburn Valley backcountry location tested had a southerly aspect, and did not receive any direct solar radiation, perhaps supporting a higher rate of faceting compared to the Craigieburn Valley ski area location. In further contrast to the backcountry study slope, the ski area study slope was not completely undisturbed by skier compaction. As such, and along with the discrepancy in slope aspect and elevation, it is difficult to make direct comparisons between the snowpack stability of the ski area and the backcountry. Nevertheless, the difference in stability observed between the Craigieburn Valley ski area and the Craigieburn Valley backcountry, despite similar snowpack structures at each location, has a number of implications for local snow safety practitioners and recreationalists alike. These implications are explored in Section 5.5.2. An important consideration to take from the analysis of weather and snowpack presented in this study is
that conditions observed pertained to early winter, when air temperatures are generally at their lowest and snowpack depths are generally relatively low. This provides the overall framework within which the remaining discussion is based.

5.3 Spatial variability of snowpack stability at Craigieburn Valley

Research objective (2) is addressed by considering the results provided in Section 4.4, which analyse the spatial variability of snowpack stability at Craigieburn Valley. These results demonstrate that stability testing from a single snowpit cannot reliably represent the snowpack stability of an entire slope. This finding is not unexpected, as it mirrors that of a number of previous spatial variability of snowpack stability studies (e.g. Landry et al., 2002, 2004). What was unexpected, however, was the absolute discrepancy between the forecasted snowpack stability and the observed snowpack stability. Specifically, areas of significant instability were observed despite a forecasted highest avalanche danger rating of low. A low avalanche danger rating suggested the snowpack stability was good, yet areas of very poor stability were present. As far as the author is aware, this is the first time such discrepancy has been demonstrated.

5.3.1 Craigieburn Valley backcountry

Considerable spatial variability of snowpack stability was observed in the Craigieburn Valley backcountry on day one of testing, 7 July 2012. This study revealed spatial variability in CT and ECT scores, which has previously been demonstrated at a number of Northern Hemisphere locations, including North America (e.g. Hendrikx et al., 2009) and Switzerland (e.g. Schweizer and Bellaire, 2010). According to the Moran’s I analysis (Table 4.13), both CT and ECT scores showed a non-clustered (random) pattern of snowpack stability at the slope scale on 7 July. Similar results were previously demonstrated by Föhn (1988) and Hendrikx et al. (2009). These results contrast to those presented by Stewart and Jamieson (2002) and Simenhois and Birkeland (2007, 2009), which demonstrate a clustering of stability scores at the slope scale. In each of these studies, the authors were able to attribute the clustering of stability scores to the variability of the slab overlying the weak
layers present. Campbell and Jamieson (2004) demonstrated a clustering of low (high) stability scores were associated with areas of lower (higher) slab thickness, whilst Simenhois and Birkeland (2007, 2009) attributed clusters of low (high) stability with a relatively hard (soft) slab. No relationship between slab thickness and stability test scores was observed in the present study. However, slab hardness did appear to influence the snowpack stability observed in the present study, with a link noted between relatively hard (rather more cohesive) slabs and lower snowpack stability. This link between fracture character and slab cohesion alludes to a spatial variability of fracture character being observed in the present study.

The aforementioned spatial variability of fracture character is worthy of further exploration. Previous studies have demonstrated that the fracture character observed in stability tests is less spatially variable than the stability test score (Campbell and Jamieson, 2007; Schweizer and Bellaire, 2010). Tables 4.12 and 4.16 demonstrate the same observation, as obtained from testing of the Craigieburn Valley backcountry on 7 July 2012 and the Craigieburn Valley ski area on 9 July 2012, respectively. Nevertheless, spatial variability in stability test fracture character was demonstrated in the present study. Observations made during stability testing of the Craigieburn Valley backcountry study slope suggest that this result may have been linked to the overlying slab properties. Sudden fracture characters (shear quality 1) tended to occur when the overlying slab was relatively cohesive, whereas non-planar break fracture characters (shear quality 3) were observed when the overlying slab had relatively low cohesion. It is thought that a relatively cohesive slab supported the transfer of energy applied during stability testing through to the weak layer, which resulted in the release of a sudden fracture character, due to the strength of that weak layer being exceeded by the stress being applied on it (McClung and Schaerer, 2006). In contrast, lower energy (shear quality 3) fracture characters were associated with slabs of lower cohesion, where the transfer of energy may have been relatively inefficient. Given the supposed uniformity of the slope (e.g. the slope was of the same elevation, aspect, and slope angle, and did not receive direct solar radiation), the discrepancy of slab cohesion is an interesting observation. The backcountry slope tested is wind exposed, which may have affected the slab properties observed. Furthermore, the ground surface of the area is a mix of scree and outcrops of rock. As such,
it is likely the underlying ground surface roughness contributed to the variability in snow depth observed within the slope (Schweizer et al., 2003). This is notable, given different snow temperature gradients may have existed between areas of different snow depths. Snow temperature gradients contribute to the sintering of snow crystals, and also to the metamorphism of snow crystals (Colbeck, 1982). Therefore, it appears that the underlying ground surface has an inherent contribution to the spatial variability of snowpack characteristics, and implicitly, the spatial variability of snowpack stability, that was observed in the present study.

Results obtained from this study show that the stability test results from one snowpit cannot reliably represent the snowpack stability of an entire slope. At the time of testing, the highest avalanche danger rating provided by the regional forecast was low. This suggested that the snowpack stability was good. Furthermore, no obvious signs of instability (e.g. recent avalanches on slopes with similar aspect and elevation) supported the suggestion that snowpack stability of the slope was indeed good. A relatively comprehensive characterisation of stability for individual snowpits was carried out for this study, which encompassed measures of snowpack strength, energy and structure, for both CTs and ECTs. The value of combining these measures to obtain a stability rating is outlined in Section 2.5.3. According to these data, zero of 30 snowpits indicated good stability with respect to the CT results in the Craigieburn Valley backcountry study slope, despite the expectation that the snowpack stability was good. The stability rating obtained from ECT results showed greater reliability of representing the expected slope stability compared to the CT results. This is in accordance with previous studies, which have demonstrated the ECT as a more reliable indicator of stability (e.g. Simenhois and Birkeland, 2009). Despite a higher reliability of stability ratings obtained from the ECT, the stability ratings were still unable to reliably represent the expected snowpack stability of the slope. Specifically, just nine (30%) of the snowpits indicated good stability. One reason for the discrepancy observed could be that the slope was inaccurately predicted as having good stability. Certainly, stability test results obtained suggest the distribution of stability test results was more representative of a slope which had a moderate avalanche danger rating (Figure 5.1). However, this only became apparent after stability testing was performed. Given the regional avalanche forecast of low avalanche hazard, and a lack of
signs of instability on the backcountry test slope (as well as other representative slopes), the slope was justifiably characterised as having good stability.

![Diagram of point stability observations](image.png)

**Figure 5.1** Distribution of point stability observations (i.e. stability ratings obtained from stability testing at a single location) with respect to the associated regional avalanche danger level forecast, based on fieldwork carried out by Schweizer et al. (2003b) in Switzerland. Interestingly, fieldwork for the Schweizer et al. (2003b) study was performed on a snowpack which had been subject to early winter rainfall, and included both rain-crusts and facet layers; comparable to the snowpack observed in the present study. Figure obtained from Schweizer et al. (2008).

Whilst previous studies have demonstrated that stability ratings obtained from one snowpit cannot reliably represent the stability of an entire slope, the results obtained from the Craigieburn Valley backcountry are at the lower end of the reliability scale. Specifically, previous studies have shown that between 48.1% and 87% of stability ratings obtained from individual snowpits were representative of the slope stability (Birkeland and Landry, 2002; Landry et al., 2002, 2004; Birkeland and Chabot, 2006). Again, just 0% (CT) and 30% (ECT) of snowpits were representative of the slope stability of the Craigieburn Valley backcountry. Utilising the overall slope stability rating calculated from individual snowpit stability ratings, it is likely that the slope stability rating would be more accurately characterised as fair, as opposed to the expectation that the slope stability was good. Given this more accurate slope stability rating, individual snowpits were still an unreliable indicator of the slope stability. With respect to the CT (ECT), 77% (53%) of snowpits are now representative of the slope stability, which remains relatively low compared to previous studies.
As described in Section 2.6.4, there is difficulty in making meaningful comparisons with previous studies, due to the variety of sampling strategies and stability tests used. Nevertheless, this study may be distinguished from previous studies due to the absolute discrepancy between the expected snowpack stability and the observed snowpack stability of individual snowpits. Two CTV and two ECTPV results were obtained, which are both indicative of highly unstable conditions. To the author’s knowledge, this is the first time such highly unstable results, within a slope rated as having good stability, have been demonstrated. In addition, fieldwork carried out by Schweizer et al. (2003b, Figure 5.1) illustrated that given a highest regional avalanche danger of low, around 90% of point stability observations rated the stability as good or very good. No poor or very poor point stability observations were made. The discrepancy observed may at least in part be attributed to the limited reliability of the regional avalanche forecast (in this instance covering the entire Craigieburn Range) at relatively small spatial scales (e.g. the Craigieburn Valley backcountry study slope). Indeed, such scale issues with respect to avalanche forecasting were highlighted by Hägeli and McClung (2004). The Craigieburn Range avalanche forecasts are partly based on snowpack and stability data obtained from the field. It follows then, that the reliability of the forecast would be linked to the number of observations contributed to the forecast, as well as the spatial extent of those observations. In addition, it appears that snowpack observations provided for the regional avalanche forecast are primarily obtained from testing carried out within ski area boundaries along the Craigieburn Range. As such, the snowpack is less likely to be undisturbed. Therefore, the reliability of information garnered from within ski areas at accurately representing backcountry conditions is questionable (Figure 5.2).
Results obtained from the present study demonstrate that areas of considerable snowpack instability may be observed despite a ‘low’ avalanche danger rating.

5.3.2 Craigieburn Valley ski area

Spatial variability of snowpack stability was also observed in the Craigieburn Valley ski area, when testing was carried out on 9 July 2012. Spatial variability of CT scores was observed, although in contrast to the Craigieburn Valley backcountry, no spatial variability of ECTP scores was observed. Specifically, only one of 15 ECTs resulted in an ECTP. The slope stability of this location was rated as good, and results obtained from stability testing were more reflective of this when compared to the results obtained from the Craigieburn Valley backcountry. For the ski area, three (20%) of 15 individual snowpit stability ratings were representative of the slope stability, when CTs were considered. When ECTs were considered, 11 (73%) of 15 individual snowpit stability ratings were representative of the slope stability. Despite being more favourable than the backcountry, these ski area results still support the notion that stability testing from one snowpit cannot reliably represent the snowpack stability of an entire slope. The stability test fracture character of the ski area was also shown to be less spatially variable than the stability test score, which reflects such findings demonstrated by Campbell and Jamieson (2007) and Schweizer and Bellaire (2010).
5.3.3 Comparisons with New Zealand case studies

As established in Section 2.6, there is a relative paucity of spatial variability of snowpack stability studies conducted in New Zealand. In fact, just two such studies (Simenhois and Birkeland, 2006; Hendrikx and Birkeland, 2008) have followed the landmark spatial variability of snowpack stability study produced by Conway and Abrahamson (1984, which was based on fieldwork carried out in New Zealand). The results from the two most contemporary of the aforementioned studies will be utilised for comparison, as they are most pertinent to the current study. It should be noted that Simenhois and Birkeland (2009) produced another paper which included data from New Zealand based field work; however, these data wasn’t explicitly provided by the authors.

Hendrikx and Birkeland (2008) based their study in the Craigieburn Range, and tested the spatial variability of snowpack stability on two separate days. Little information was specified regarding the study slope. It appears the slope tested had a south-westerly aspect, and was approximately 1,550 m a.s.l. No slope angle information could be garnered. The authors dug 12 evenly spaced snowpits on each day, and a CT and ECT was performed in each snowpit. Spatial variability of CT scores was demonstrated on both days of testing, with the standard deviation of CT scores being 2.5 and 3.7, respectively. The standard deviations of CT scores observed in the present study were 5.9 for the Craigieburn Valley backcountry (on day one of testing, 7 July 2012), and 7.1 for the Craigieburn Valley ski area. Thus, greater spatial variability of snowpack stability with respect to the CT score was observed in the present study, than that observed by Hendrikx and Birkeland (2008).

With respect to the ECT, Hendrikx and Birkeland (2008) reported spatially uniform ECTP results, with only one of the 24 total ECTs resulting in an ECTP result (which was 22 taps). Simenhois and Birkeland (2006) also observed spatially uniform ECTP results. These authors tested a 32° slope at Mt Hutt on 27 June (early Austral winter). No slope aspect information was specified, although a photo of the slope shortly after testing showed it in sunshine. Zero of the 21 ECT tests performed resulted in an ECTP. ECT results from the Craigieburn Valley ski area showed similar results, with only one of 15 ECTs resulting in an ECTP result (which was 28 taps). In contrast, ECT results from the Craigieburn Valley
backcountry showed considerable spatial variability. At the backcountry location, 13 of 30 ECTs resulted in an ECTP result. Consequently, the present study may be distinguished as the first to demonstrate spatial variability of ECTP results at the slope scale in New Zealand.

5.3.4 Implications of observed spatial variability of snowpack stability

A number of implications result from the spatial variability of snowpack stability demonstrated in this study. Perhaps most significantly, areas of very poor stability were observed within a slope rated as having good snowpack stability. Furthermore, this study is the first to demonstrate spatial variability of ECTP results at the slope scale in New Zealand. Nevertheless, it is imperative to attribute some meaning to the results obtained.

Avalanche forecasting is a valuable practice, as it aims to minimise the uncertainty of spatial and temporal variability of snowpack stability (McClung, 2000). An important component of regional avalanche forecasts is the inclusion of information collected from the field. As such, the reliability of these forecasts may be affected by the resolution and the volume of information obtained from the field. The need for accurate forecasts increases as the spatial scale decreases (McClung, 2000), which is exemplified when regional forecasts differ from the local stability observed by a backcountry recreationalist (Jamieson et al., 2009). The results of this study have shown that local stability can be considerably different to that which is forecasted. As such, this reinforces the obligation of backcountry recreationalists to be equipped with the necessary skills and equipment if travelling in the backcountry. Backcountry recreationalists should be able to make their own stability assessments, as regional forecasts aren’t necessarily entirely accurate. Given that an avalanche did not occur during testing, it must be acknowledged that the forecasted avalanche danger rating of low was likely to be suitable. However, an avalanche danger rating of low infers that the snowpack stability is good, and the results of this study showed considerable disparity from this inference. As such, the onus must be placed on recreationalists to be able to make their own stability decisions, and not base their decisions solely on avalanche forecasts.
The physical processes controlling the spatial variability of snowpack stability observed in the present study are difficult to determine. A qualitative correlation between slab cohesion and snowpack stability was observed, although the sampling methodology employed in this study did not enable this correlation to be examined in depth. With respect to slab thickness and the stability test scores obtained at each snowpit, no relationship was observed in the present study. Furthermore, slopes tested were uniform, and there was no considerable change in synoptic scale weather over the course of stability testing. In the case of the Craigieburn Valley backcountry, the slope tested was additionally undisturbed, and did not receive direct solar radiation. As a result, and as introduced in Section 5.3.1, it appears the underlying ground cover characteristics may contribute to the spatial variability of snowpack stability observed within Craigieburn Valley.

5.4 Temporal variability of snowpack stability at Craigieburn Valley

As shown in Section 4.3.3, snow stability testing for the Craigieburn Valley backcountry was carried out during an extended period of fine weather. Such a ‘weather window’ was actively sought, because unsettled weather (such as new snowfall, or strong winds resulting in wind-loading of snow onto the Craigieburn Valley slopes) would have resulted in spatial variability of stability patterns which would be attributed to such weather events. This study aimed to test for changes in spatial variability of snowpack stability that could not be attributed to unsettled weather events. In other words, how does the spatial variability of slope-scale stability change over time, in the absence of considerable changes to synoptic scale weather? An investigation of the results provided in Section 4.4 enables this question to be answered. Furthermore, comparing the spatial variability results obtained from day one of testing (7 July 2012) and day two of testing (11 July 2012) for the Craigieburn Valley backcountry allow research objective (2) to be comprehensively addressed.
5.4.1 Craigieburn Valley backcountry

Section 2.6 shows that despite a relatively extensive volume of research based on the spatial variability of snowpack stability, few studies have examined the temporal variability of snowpack stability. Despite this, it is possible to infer expected patterns of temporal variability from spatial variability studies. Examples of this are studies which have shown the spatial variability of snowpack stability to be higher on slopes which are more stable (e.g. Conway and Abrahamson, 1984; Schweizer and Bellaire, 2010). The inference from such a finding is that the spatial variability of snowpack stability for a slope may increase as that slope becomes more stable. Previous studies which specifically addressed the temporal variability of snowpack stability have shown evidence that this is the case (Birkeland and Landry, 2002; Hendrikx and Birkeland, 2008; Hendrikx et al., 2009). Results from the current study support the concept that spatial variability of snowpack stability increases as slope stability increases. Section 4.4.1 provides a comprehensive analysis of snowpack stability for the Craigieburn Valley backcountry. This section demonstrated that the stability of the slope increased between the two days of testing, and the spatial variability of stability results also increased. This concept was supported by results obtained from both the CTs and ECTs undertaken.

In another temporal variability of snowpack stability study, Logan et al. (2007) propose that despite snowpack strengthening at the slope scale, weaker areas of the snowpack tend to remain relatively weak. Due to the considerable spatial variability of snowpack stability observed in the current study, it is difficult to distinguish any so-called weaker areas. Whilst snowpack weaknesses are observed on day one of testing, they cannot be directly compared to any corresponding stability result on day two of testing, due to the gridded method of sampling being offset to a different location of the slope between each day of sampling. In any case, the results of the current study do show that despite an increase of the slope stability overall, areas of considerable weakness did persist. With respect to the CT, two snowpits were rated as having poor stability on 11 July 2012. Most notably, when considering the ECT, one snowpit was rated as having very poor stability. The ECT score of this pit was ECTPV, which is indicative of highly unstable conditions. With the slope stability rated as good, this provides further evidence (along with that explained in Section 5.3.1) of considerable discrepancy between the slope stability rating, and the observed
snowpack stability. In addition, to the author’s knowledge this also represents the first time that such a highly unstable result has been demonstrated on a slope rated as stable in a temporal variability of snowpack stability study.

As has already been established, the overall stability of the Craigieburn Valley backcountry slope increased between the two days of testing. This is further supported by the ECT results obtained. As noted by Simenhois and Birkeland (2009), the simplest interpretation of ECT results is that an ECTPV or ECTP result is indicative of instability, whereas an ECTN or ECTX result is indicative of stability. On 7 July 2012, there were a combined eight ECTPV and ECTP results from 15 ECTs (53%). On 11 July 2012, the number of unstable ECT results dropped to five out of 15 ECTs (33%). In addition, the average number of taps required for an unstable ECT result increased from 7 July 2012 to 11 July 2012, although this temporal change in tap scores was not statistically significant. Hendrikx et al. (2009) statistically demonstrated a relative clustering of ECTP results over time at the slope scale. This was also demonstrated in the present study, according to the Moran’s I analysis undertaken (Table 4.13). This finding adds further weight to the idea that results from one snowpit cannot reliably represent the snowpack stability of an entire slope, and supports the need to dig more than one snowpit in order to make a more accurate assessment of the stability of a slope.

### 5.4.2 Comparisons with New Zealand case studies

Only one previous study contains data of a temporal variability of snowpack stability analysis carried out in New Zealand (Hendrikx and Birkeland, 2008), which clearly limits the ability to make a great deal of comparisons to previous New Zealand case studies. Hendrikx and Birkeland (2008) demonstrated an increase in the mean CT score, from 13.8 to 19, as well as in increase in the standard deviation of the CT score, from 2.5 to 3.7. The present study also showed a significant increase in the mean and standard deviation of CT scores (Section 4.4.1). As such, both studies have indicated an increase in spatial variability of stability results associated with an increase in the overall slope stability. Hendrikx and Birkeland (2008) demonstrated spatial uniformity with respect to the ECT on both days of testing, with only one of the 24 ECTs carried out resulting in an unstable ECT result. As a
result, minimal temporal variability of ECT results was shown. This contrasts to results presented in the current study. As such, this study may be distinguished as the first to demonstrate considerable temporal variability with respect to the ECT in New Zealand.

5.4.3 Rain event case study

Whilst inherently linked to the weather and snowpack (Section 5.2), the rain event case study is examined within the current section due to the important implications it was observed to have on the temporal variability of snowpack stability at Craigieburn Valley. The rain event occurred from 13 July 2012 to 15 July 2012, with a total rainfall of 106 mm occurring over this period. Section 4.5 demonstrates the key effects the rain event had on the Craigieburn Valley snowpack. Most notably, persistent weak layers throughout Craigieburn Valley were removed from the snowpack. In addition, the snowpack depth at the location of the backcountry study site was significantly reduced. The rain event had two direct influences on snowpack stability. Firstly, widespread destabilisation of the Craigieburn Valley snowpack occurred during the early stages of the rainfall event. This was evidenced by the observation of numerous loose snow avalanches, associated with the addition of weight and an increase in temperature that the snowpack would have experienced due to rain. Secondly, upon the conclusion of the rainfall the snowpack refroze, as demonstrated by the hardness of layers observed in snowpits for both the ski area and backcountry (Figures 4.33 and 4.34). This resulted in a stabilising of the snowpack (Table 4.21). Despite the rain event destroying the former persistent weak layers present in the snowpack, a snow profile carried out at the Craigieburn Valley backcountry study site showed evidence of a new persistent weak layer developing within the snowpack (Figure 4.33). This isn’t surprising, given the development of the former persistent weak layers were associated with a rain crust that formed as a result of a separate rain event earlier in the season (23 June 2012, 70 mm total rainfall). Indeed, the snow profile illustrated the three key factors which contribute to persistent weak layer development (Section 2.5.1); a relatively thin snowpack, a relatively high temperature gradient, and the presence of crusts.

Interestingly, a rainfall event occurred one week prior to Hendrikx and Birkeland (2008) carrying out their New Zealand based temporal variability of snowpack stability field
work. The authors attribute their non-spatially variable ECTP results to the homogenising influence of the rainfall events. Their study demonstrated that the rainfall effectively provided a “clean slate” regarding snowpack stability, and thus for their study the only stability concern was subsequent storm snow events occurring atop the rain-soaked snowpack. The present study also demonstrates the homogenising influence of rainfall. However, this study may be distinguished, as the extended fieldwork campaign enabled the observation that storm snow events aren’t the only stability concern that should be considered subsequent to a rainfall event. Specifically, persistent weaknesses were shown to develop within the snowpack. The present study has demonstrated that the development of persistent weaknesses is at least supported, if not enhanced, as a result of rainfall events. Of course, weather conditions subsequent to rainfall events are integral to the development of persistent weak layers – persistent weak layers will not always form following a rainfall event. Analysis of the data of Hendrikx and Birkeland (2008) uncovers reasons which may explain the discrepancy between their post-rain event study and those presented in this study. The snowpack which Hendrikx and Birkeland (2008) tested was deeper, at around 1.5 m. Notably, the temperature gradient measured was relatively low. As such, it appears the development of persistent weak layers was not supported.

A key observation is that rainfall events do appear to result in the homogenising of a snowpack, and also serve to stabilise a snowpack after initially destabilising it. However, the homogenising and stabilisation of the snowpack is only temporary. The present study has demonstrated that along with storm snow instabilities, instability associated with persistent weak layers are also possible subsequent to a rain event. As such, perhaps particular attention must be given to early Austral winter rain events in June and July, as the potential for persistent weak layer development may be exacerbated during these months. Specifically, in association with the formation of a crust within the snowpack (due to rain), the remaining two key components of persistent weak layer development would likely exist in June and July. Firstly, during the early winter, snowpack depths may be relatively thin. Certainly, this can be expected for the Craigieburn Valley, where average snowpack depths generally peak in September (McGregor, 1990). Secondly, June and July are typically the coldest months in the Craigieburn Range. Therefore, relatively high temperature gradients may become established within the snowpack during these months.
With these factors combined, it follows that the likelihood of persistent weak layer development would be relatively high in the early winter, compared to subsequent months in the year.

5.4.4 Implications of observed temporal variability of snowpack stability

This study has demonstrated a change in the spatial variability of slope scale stability over time. A number of key findings were made. The spatial variability of snowpack stability within a slope was shown to increase alongside an increase in overall stability of that slope. Despite an increase in overall stability, considerable instability persisted within the slope. In addition, temporal variability of snowpack stability resulting from external forcing was demonstrated. The findings of this study have a number of implications. Spatial variability of snowpack stability provides challenges when attempting to accurately assess the stability of a slope. As such, signs of instability are sought during stability testing (Schweizer & Wiesinger, 2001). The reasoning for this is that an unstable stability result shows the observer that instability is present within the slope. On the other hand, a stable stability result cannot reliably rule out the presence of instability within a slope. This is an important distinction to make, and contributes to the recommendation of a number of studies, which suggest more than one snowpit should be undertaken when assessing the stability of a single slope (e.g. Birkeland and Chabot, 2006). In addition to this recommendation, results from this study suggest that carrying out two stability tests in each snowpit is valuable. Table 4.12 demonstrated that the pit-scale variability of both CT and fracture character results increased in association with an increase in slope stability. The implication of this is that if variability of stability is observed within a single snowpit, then it may indicate that the slope scale stability is higher than if no variability is observed. These are by no means conclusive results; however this finding supports the potential value of carrying out two stability tests within a single pit.

Because such considerable instability existed on both days of testing, seeking out weakness within the slope would have proven a difficult, if not impossible, task. Specifically, there were no clues that indicated where the areas of instability would be observed. The regional forecast of avalanche danger was low. That fact, combined with no observations of
instability prior to testing, meant the Craigieburn Valley backcountry study site was thought to have good stability. As a result, the areas of considerable instability which were observed on both 7 June 2012 and 11 June 2012 were unexpected. In fact, such discrepancy between the forecasted stability and observed stability has not been previously shown. Despite the presence of considerable instability, the fact that such considerable spatial variability existed on both days of testing in the Craigieburn Valley backcountry probably acted as a stabilising influence on the slope. This is due to the spatial variability, in effect, resisting large scale fracture propagation. This is supported by previous findings which suggest that in order for avalanches to occur, areas of considerable instability need to be large, or numerous, or both (e.g. Conway and Abrahamson, 1984; Föhn, 1988). Therefore, the low avalanche danger rating provided for the Craigieburn Valley was a fair assessment. Given that the avalanche danger was likely to indeed be low, results obtained from the Craigieburn Valley backcountry suggest that the ECT is a more reliable indicator of snowpack stability. Utilising the three-component model of stability, the overall slope stability was rated higher for both days of stability testing when utilising the ECT results, compared to the CT results.

5.5 Avalanche terrain of Craigieburn Valley

McNulty (1984) carried out a detailed in-situ analysis of the avalanche terrain of Craigieburn Valley. To this date, it remains the salient source of literature detailing the avalanche terrain of Craigieburn Valley. The value of McNulty’s publication itself cannot be questioned. However, as established in Section 2.3, the opportunity exists to supplement this material with a more comprehensive analysis of the avalanche terrain of Craigieburn Valley. This is especially necessary for the Craigieburn Valley backcountry, of which McNulty examined at a much broader scale than the ski area terrain. This section will highlight the key findings obtained from an analysis of the Craigieburn Valley avalanche terrain (Section 4.2), which address research objective (1). By spending 35 consecutive days in-situ for the fieldwork campaign, the author of the present study was afforded a unique opportunity to obtain insight into the operation of the Craigieburn Valley Ski Club. As such, practical implications of the comparison of avalanche terrain
between the Craigieburn Valley ski area and the Craigieburn Valley backcountry will be made.

5.5.1 Comparison of Craigieburn Valley ski area and backcountry terrain

Section 4.2 shows that there is a higher proportion of primary avalanche terrain within the Craigieburn Valley ski area compared to the Craigieburn Valley backcountry. More than half of the total terrain for each area comprises primary avalanche terrain. There was a similar distribution of primary avalanche terrain between different elevation bands for each area. The main difference was that 6.1% of primary avalanche terrain for the Craigieburn Valley ski area is located above 1,800 m a.s.l., whereas a corresponding proportion of only 0.2% is observed for the Craigieburn Valley backcountry. This largely supports the findings of McNulty (1984). However, McNulty only provided elevation data for the avalanche starting zones, and found that the minimum elevation for such zones to be 1,400 m a.s.l. The present study is able to distinguish that, theoretically, avalanche initiation could occur on terrain below 1,400 m a.s.l. Specifically, 16% of Craigieburn Valley primary avalanche initiation terrain is located below 1,400 m a.s.l., and the corresponding proportion for the Craigieburn Valley backcountry is also 16%. This is in accordance with McGregor (1989), who noted examples of slope angles in excess of 30° on avalanche paths below the avalanche starting zone identified. Minimal primary avalanche terrain within the Craigieburn Valley is of a northerly or north-westerly aspect. This supports the observation made by McGregor (1989), who examined 137 active avalanche paths along the Craigieburn range, and found none had a northerly or north-westerly aspect. As demonstrated in Section 4.2, slope aspect of primary avalanche terrain showed considerable discrepancy between the Craigieburn Valley ski area and the Craigieburn Valley backcountry. Just 25% of primary avalanche initiation terrain within the Craigieburn Valley ski area has a slope aspect with a southerly component, compared to 94% of the Craigieburn Valley backcountry.
5.5.2 Implications for the Craigieburn Valley Ski Club

Craigieburn Valley snow safety practitioners are guided by a comprehensive snow safety plan. Within this plan, it is acknowledged that there is an expanding use of terrain both inside and outside the ski area boundary. Due to such an increase in exposure to avalanche terrain, there is an associated increase in potential avalanche hazard. Hazard mitigation is a primary focus for snow safety practitioners, and requires active management; through the closure of slopes during periods of enhanced avalanche risk, to active avalanche control work including bombing. Craigieburn Valley management has indicated a desire to expand their current ski area boundary (Jarmin, pers. comm. 2012). Doing so would require additional active management of slope stability to that which is already undertaken. One of the key findings of the present study was that despite the expectation of a slope having good stability, considerable instability was observed. This further supports the need for active observation and management of snowpack stability. This study has demonstrated that the primary avalanche terrain of the backcountry has an appreciably different distribution of slope aspect compared to the ski area. As such, expanding the ski area boundary could pose challenges to snow safety practitioners, as they would have to deal with a greater proportion of terrain with a southerly slope angle component. This is important, because southerly component aspects tend to remain shaded, especially during June and July. Thus, the snowpack in these locations will tend to have relatively lower temperatures, meaning weaknesses will generally persist for a longer period of time (McClung and Schaerer, 2006). It appears that snow safety practitioners at Craigieburn Valley already have a challenging workload in order to mitigate avalanche hazard within the current ski area boundary. Given the size of the current ski area, the number of snow safety staff currently employed is significantly fewer than for similar sized ski areas in the United States (Konigsberg, pers. comm. 2012). Therefore, if Craigieburn Valley ski area management were to extend the ski area boundary, it would be pertinent to re-assess their current staffing needs, to ensure that effective hazard mitigation would continue to be met (Figure 5.3).
The Craigieburn Valley backcountry can be accessed relatively easily from the ski area. This makes the backcountry terrain particularly enticing for recreationalists. Currently, the ski area boundary is well defined on maps, but is not quite so well defined in-situ. As such, the potential exists for recreationalists to enter into backcountry terrain unaware. This may be attributed to the naivety of such recreationalists as much as anything else. Nevertheless, it presents a potentially worrying scenario, where ill-equipped recreationalists end up skiing in the backcountry. This has been observed at Craigieburn Valley in the past, and predominantly occurs on “powder-days”, where recreationalists ski progressively further into the backcountry in search of un-tracked snow (Preston, pers. comm. 2012). The nature of the Craigieburn Valley backcountry terrain is such that avalanches triggered in the backcountry can possibly run into areas within the ski area boundary, endangering users of that terrain. Certainly, under the right conditions, avalanches triggered in the backcountry may also threaten the ski area access road. Currently, snow safety practitioners mitigate
this hazard by closing access to the backcountry when unstable conditions are present. However, this study has shown that areas of considerable instability can exist in the Craigieburn Valley backcountry when the expected stability of a slope is good. With this in mind, it may be of value for Craigieburn Valley ski area management to define the in-situ ski area boundary with greater clarity, to ensure recreationalists are under no illusions as to when they are entering uncontrolled backcountry terrain.

5.6 Research caveats

A primary caveat of this research is that it represents a snapshot of snowpack stability. A specific range of weather conditions occurred prior to and during stability sampling, which resulted in the observed snowpack structure, and associated spatial and temporal variability of snowpack stability. Snowpack stability testing was carried out on two slopes on three different days of testing, and as such, can only be considered as representative of the location and times at which they were tested. Currently, an online information exchange of observations by New Zealand snow safety practitioners (named “InfoEx”) is facilitated by the New Zealand Avalanche Centre. Perusal of this over the course of the fieldwork campaign demonstrated variation in weather variables along the Craigieburn Range, which conforms to anecdotal evidence. For example, after the passage of a cold front associated with a southerly airflow (24 June 2012, Section 4.3), Porter Heights Ski Area (at the southern end of the Craigieburn Range) received 10 cm of new snow, whereas Craigieburn Valley (at the northern end of the Craigieburn Range) received 5 cm of new snow. As such, it supports the notion that there is difficulty in reliably extrapolating stability data beyond the areas which were tested - not to mention the observed unreliability of a single snowpit at representing the overall stability of a single slope.

As demonstrated in Section 3.3.1.1, the sampling strategy employed for stability testing of the Craigieburn Valley backcountry was intrusive. Care was taken to minimise snowpack disturbance between snowpits. However, it is possible that sampling on the first day affected the results obtained on the second day. Birkeland and Landry (2002) propose that snowpack creep may have implications for temporal variability of snowpack stability. Given that testing during the present study was carried out on an inclined slope, snowpack
creep was likely to have contributed to changes in snowpack structure in some way. However, as noted by Hendriks et al. (2009), there are currently no unobtrusive strategies with which to carry out such a temporal variability analysis.

Stability testing for the present study was carried out on slopes rated as having good stability. This was necessary given the slope angle of slopes tested – stability testing during unstable conditions would have been too dangerous. As such, this may have created a potential bias towards stable results being observed. Nevertheless, highly unstable results were still demonstrated in the current study. Furthermore, the results of stability testing during periods of good stability are arguably more pertinent, and have greater practical implications, than those obtained during poor stability. This is because recreationalists tend to stay out of the backcountry during periods of poor stability.

The resolution of the digital elevation model (DEM) used in this study was 15 m by 15 m. Whilst this proved sufficient for the present study, it may be of benefit to use a higher resolution DEM in future if greater detail and spatial accuracy is required.

5.7 Summary

The present study has demonstrated both spatial variability and temporal variability of snowpack stability at the slope scale in New Zealand. The contribution of weather to snowpack stability has been highlighted. This is epitomised by the effects rainfall events are observed to have on the seasonal snowpack of Craigieburn Valley. The present study has successfully demonstrated that stability testing from a single snowpit cannot reliably represent the snowpack stability of an entire slope. Very unstable stability results were observed on a slope which was rated as having good stability. To the author’s knowledge, this is the first time such discrepancy has been demonstrated, and is most likely due to the southerly aspect of the Craigieburn Valley backcountry slope tested. Certainly, the results suggest that early winter is a time when considerable spatial variability of snowpack stability may be observed at both the slope- and inter-slope scale. This may be attributed in part to the relatively low air temperatures and snowpack depths of early Austral winter, as well as the exacerbated discrepancy of direct solar radiation between slopes of differing
aspects, due to the large zenith angles of the sun during winter. Thus, the results of this study may facilitate future awareness of snowpack stability concerns, and the mitigation of associated potential avalanche hazard. The present study is further distinguished as the first to demonstrate both spatial and temporal variability of ECTP results in New Zealand. As a result, this study has contributed to the knowledge of the spatial and temporal variability of snowpack stability in New Zealand. A cartographically-derived DEM was utilised in order to enable a detailed analysis of the avalanche terrain of Craigieburn Valley. Such analysis was able to quantify the significant disparity in the slope angle of primary avalanche terrain between the Craigieburn Valley ski area and the Craigieburn Valley backcountry. The disparity observed, combined with stability testing results of the present study, emphasise the need for recreationalists to be adequately educated and equipped before heading into the backcountry.
Chapter 6

Conclusions

Fieldwork for this research was carried out at Craigieburn Valley, New Zealand, a popular recreational area where people are at risk of potential avalanche activity. The primary objectives of this research (research objective 2) were to investigate the spatial variability of snowpack stability at the slope scale, and how that spatial variability changes over time. To achieve this, a combination of snowpack observations and stability tests were performed, and an overlapping grid sampling strategy was applied. The other objective of this thesis was to supplement previous research pertaining to the avalanche terrain of Craigieburn Valley. This was achieved through the use of a cartographically-derived digital elevation model (DEM) of New Zealand, and a geographic information system. In order to facilitate the successful mitigation of avalanche hazard, the potential avalanche hazard must first be understood. Through a combination of snowpack stability observations and avalanche terrain analysis presented in this research, an enhanced understanding of the avalanche hazard faced by Craigieburn Valley has been achieved. Furthermore, this study has made a valuable contribution to the knowledge of spatial and temporal variability of snowpack stability in the New Zealand setting.

6.1 Key findings

The key findings of this research were:

- Considerable spatial variability of snowpack stability on an undisturbed uniform slope was observed. As such, stability testing from a single snowpit could not
reliably represent the snowpack stability of an entire slope. The implication of this result is that more than one snowpit should be dug on a single slope, in order to enhance the likelihood of achieving an accurate assessment of the snowpack stability of a slope.

- Very unstable stability test results were obtained within a slope, despite an expectation that the slope had good stability. This is the first time such a discrepancy between the expected snowpack stability and the observed snowpack stability has been demonstrated. This result confirms that local stability can vary considerably from the regional forecast. The implication of this result is that the obligation of backcountry recreationalists to be equipped with the necessary snow safety skills and equipment when headed into the backcountry is reinforced. Furthermore, the onus must be placed on recreationalists to be able to make their own informed stability assessments, rather than rely solely upon regional avalanche forecasts.

- Given a lack of adverse weather conditions, both snowpack stability, and the spatial variability of snowpack stability, increased with time. Despite an increase in overall stability of a slope, snowpack stability tests demonstrating significant weakness persisted. According to Moran’s I analyses, a relative clustering of compression test (CT) and extended column test (ECT) results over time was shown. These results further support the need to dig more than one snowpit on a given slope in order to make a more accurate assessment of stability.

- With respect to fracture propagation potential at the slope scale (ECTP results), both spatial variability and changes in the spatial variability over time were observed. This has not been previously demonstrated in New Zealand. The results of the present study also showed that the ECT is a more reliable indicator of snowpack stability compared to the CT.

- Rainfall events have a significant influence on the evolution of snowpack stability during early Austral winter. The formation of rain crusts as a result of rain events
appears to support the development of persistent weak layers. This is exacerbated given the relatively thin snowpack depths and relatively low air temperatures typically observed in the early winter at Craigieburn Valley. Through an interpretation of future climate and snowfall projections, it is expected that the development of persistent weak layers will likely prevail into the foreseeable future at Craigieburn Valley. Widespread avalanche activity occurred during the initial stages of rainfall. However snowpack stability increased markedly subsequent to the conclusion of rainfall, once the snowpack had ‘refrozen’. Furthermore, limited stability testing subsequent to the rain event showed virtually no spatial variability in snowpack stability results. These results demonstrate the homogenising influence rainfall events may have on a snowpack, which serve to provide a temporary “clean slate” of snowpack stability.

- Greater than 50% of all Craigieburn Valley terrain may be considered primary avalanche terrain; that is, over half of all Craigieburn Valley terrain has a slope angle of between 30° and 45°. There is considerable discrepancy between the avalanche terrain of the Craigieburn Valley ski area and the Craigieburn Valley backcountry regarding slope aspect. 94% (93 ha.) of Craigieburn Valley backcountry primary avalanche terrain has a slope aspect with a southerly component, compared to 25% (38 ha.) of the Craigieburn Valley ski area. The implication of this finding is that snowpack weaknesses are likely to persist for a longer period of time in the Craigieburn Valley backcountry compared to the Craigieburn Valley ski area. As a result, this poses potential challenges for avalanche hazard mitigation within the Craigieburn Valley. In order to facilitate the continued avalanche hazard in Craigieburn Valley, it may be of value for the Craigieburn Valley Ski Club to: (1) Define the ski area boundary more clearly in-situ; and (2) if the Craigieburn Valley Ski Club were to expand the current ski area boundary further into the Craigieburn Valley backcountry, it would be pertinent to re-assess their current staffing needs.
6.2. Future research

Given the key findings of this research, several suggestions may be made regarding avenues of future research that could further improve the current state of knowledge surrounding snowpack stability and the associated avalanche hazard. The present study represents a snapshot of snowpack stability (Section 5.6). A great deal more research on a range of different weak layers and a range of different snowpack structures is necessary to provide greater conviction to the results presented in this study. This is especially pertinent regarding the analysis of temporal patterns of snowpack stability, given that this is a field of which a relative paucity of studies has been undertaken. Carrying out similar studies based in New Zealand would enable further valuable contributions to the understanding and mitigation of avalanche hazard in this country to be made. The present study identified considerable discrepancy between the expected snowpack stability of a slope, and the stability ratings obtained from testing in-situ. As such, further research could be carried out in New Zealand to investigate the accuracy and reliability of avalanche forecasts on, for example, a range of different aspects and weak layers of primary concern.

Stability testing and observations performed for the present study were carried out at a limited spatial scale. The advent of InfoEx has facilitated the sharing of weather, snowpack and avalanche observations between all ski areas in New Zealand. As such, InfoEx serves as a rich source of snowpack stability information, which as yet appears to be untapped from a research perspective. A comprehensive study of weather, snowpack and avalanche observations encompassing numerous regions of New Zealand over a single timeframe could be undertaken, allowing a relatively large spatial scale of information to be gathered. The success of such a study would hinge on the reliability of observations made by numerous different observers. However, interesting insights, at a spatial scale much larger than that of the present study, could be achieved.

A more detailed investigation of avalanche terrain than that provided in the present study could be carried out given a higher resolution DEM. Furthermore, the use of DEMs for avalanche terrain analysis could prove valuable with respect to avalanche hazard mitigation. Backcountry touring is proving increasingly popular with recreationalists. DEMs could be utilised to examine backcountry areas, in order to identify areas that are of
primary concern regarding avalanche formation. This could be especially valuable as a
vehicle from which to promote safe travel and route identification in backcountry terrain,
particularly as avalanche paths of the backcountry tend not to be mapped, and the
knowledge regarding snowpack stability and avalanche occurrences in the backcountry is
generally less than that of ski areas.
References


140


Appendices
Appendix A

Snow profile interpretation

This appendix will deconstruct a snow profile in order to aid the interpretation of snow profiles presented in this study. Note that the snow profile examined in this appendix is an artificial snow profile; in no way does it accurately represent the snowpack observed within Craigieburn Valley during this study.
Figure A.1  An example of a full snow profile, presented in the same manner in which all snow profiles are presented in this thesis. This profile will subsequently be deconstructed (Figures A.2, A.3 and A.4).
There are 8 layers of snow in this snowpack. Each layer is distinguished by a blue ‘block’. The hardness of each layer is represented by the width of the block - harder layers are wider. The hardness of each layer is qualified according to the bar highlighted light green. For example, Layer 5 has a ‘F’ (fist) hardness, and Layer 6 has a ‘K’ (knife) hardness. Each layer is 10 cm thick. The layer thickness is indicated by the column highlighted yellow, showing depths in cm. The scale starts at 0 cm at the bottom, meaning Layer 8 is sitting immediately atop the ground surface. The highest value (in this case 80 cm) represents the total snow depth of the snowpack, meaning Layer 1 is the uppermost layer of the snowpack. Highlighted orange is the temperature scale, in degrees Celsius. The ‘red line joined by dots’ (in this case running diagonally from bottom right to top left) shows the snowpack temperatures, with the ‘dots’ indicating the depths where snow temperatures were measured. The second red line, which runs horizontally (in this case between Layers 6 and 7) is used to indicate the weak layer or interface of primary concern with respect to snowpack stability.

**Figure A.2** Deconstruction of layer identification, layer hardness, layer thickness, snowpack temperature, and weak layer/interface of primary concern.
Figure A.3 Deconstruction of snow crystal type, snow crystal size and snow density. Each row (and its associated variables) represents the variables measured for each layer identified within the snowpack. Layer 7 shows an example of two different types of snow crystals being identified within the same layer. As such, two snow crystal sizes are provided for that layer, representing the crystal size of each type of snow crystal identified. Layer 8 shows an example of liquid water being observed, as indicated by the ‘M’ beside the associated snow crystal size.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Snow Crystal Type</th>
<th>Size (mm)</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>☯</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>☯</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>☯</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>☯</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>☯</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>☯</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>☯ (☐)</td>
<td>1.0, 1.5</td>
<td>600</td>
</tr>
<tr>
<td>8</td>
<td>☯</td>
<td>1.0</td>
<td>800</td>
</tr>
</tbody>
</table>
Figure A.4  Snow crystal types observed in the present study. As such, this is not a comprehensive list of all snow crystal types.
Appendix B

Stability test results

This appendix comprises all compression test (CT) and extended column test (ECT) results obtained from stability testing performed at Craigieburn Valley. Note that results are presented following standard recording procedure, outlined by the New Zealand Mountain Safety Council Guidelines (2011), i.e.: “stability test data code” “tap score” “fracture character” on “weak layer/interface snow crystal size (mm)” “weak layer/interface snow crystal type” @ “depth from snow surface (cm)”.
Table B.1  Compression test (CT) results obtained from the Craigieburn Valley backcountry study slope on 7 July 2012. Two CTs were performed in each snowpit. A description as to whether or not the fractures occurred on the weak layer of primary concern (identified from the associated full snow profile; Figure 4.12) is provided.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>CT #1 score</th>
<th>CT #2 score</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>CTVSC on 1 mm □ @ 37↓</td>
<td>CTH21SC on 1 mm □ @ 39↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>A2</td>
<td>CTVSC on 1 mm □ @ 42↓</td>
<td>CTVSC on 1 mm □ @ 41↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>A3</td>
<td>CTVSP on 1 mm □ @ 34↓</td>
<td>CTVSP on 1 mm □ @ 34↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>B1</td>
<td>CTM12BRK on 1 mm □ @ 26↓</td>
<td>CTM14RP on 1 mm □ @ 27↓</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>B2</td>
<td>CTM13SC on 1 mm □ @ 23↓</td>
<td>CTM14SC on 1 mm □ @ 23↓</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>B3</td>
<td>CTV21SC on 1 mm □ @ 23↓</td>
<td>CTV24SC on 1 mm □ @ 23↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>C1</td>
<td>CTM16SC on 1 mm □ @ 25↓</td>
<td>CTM11SC on 1 mm □ @ 25↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>C2</td>
<td>CTM12SC on 1 mm □ @ 37↓</td>
<td>CTM14SC on 1 mm □ @ 38↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>C3</td>
<td>CTV25SC on 1 mm □ @ 38↓</td>
<td>CTV21SC on 1 mm □ @ 38↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>D1</td>
<td>CTM18BRK on 1 mm □ @ 22↓</td>
<td>CTM16RP on 1 mm □ @ 22↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>D2</td>
<td>CTV21SC on 1 mm □ @ 33↓</td>
<td>CTV22SC on 1 mm □ @ 34↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>D3</td>
<td>CTV17SC on 1 mm □ @ 27↓</td>
<td>CTE7SC on 1 mm □ @ 20↓</td>
<td>CT #1 did occur on weak layer of primary concern, CT #2 did not</td>
</tr>
<tr>
<td>E1</td>
<td>CTM14SC on 1 mm □ @ 27↓</td>
<td>CTM13SC on 1 mm □ @ 27↓</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>E2</td>
<td>CTM11SC on 1 mm □ @ 27↓</td>
<td>CTM13SC on 1 mm □ @ 28↓</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>E3</td>
<td>CTV17SC on 1 mm □ @ 27↓</td>
<td>CTV19SC on 1 mm □ @ 28↓</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
</tbody>
</table>
Table B.2  Extended column test (ECT) results obtained from the Craigieburn Valley backcountry study slope on 7 July 2012. One ECT was performed in each snowpit. A description as to whether or not the fractures occurred on the weak layer of primary concern (identified from the associated full snow profile; Figure 4.12) is provided.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>ECT score</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>ECTP26SC on 1 mm □ @ 37↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>A2</td>
<td>ECTP26SC on 1 mm □ @ 43↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>A3</td>
<td>ECTP8SC on 1 mm □ @ 35↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>B1</td>
<td>ECTN22BRK on 1 mm □ @ 27↓</td>
<td>Result did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>B2</td>
<td>ECTP13SC on 1 mm □ @ 23↓</td>
<td>Result did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>B3</td>
<td>ECTN25BRK on 1 mm □ @ 23↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>C1</td>
<td>ECTP22SC on 1 mm □ @ 34↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>C2</td>
<td>ECTPVSP on 1 mm □ @ 35↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>C3</td>
<td>ECTP14SC on 1 mm □ @ 35↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>D1</td>
<td>ECTN18BRK on 1 mm □ @ 22↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>D2</td>
<td>ECTP21SC on 1 mm □ @ 35↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>D3</td>
<td>ECTN14BRK on 1 mm □ @ 28↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>E1</td>
<td>ECTN12BRK on 1 mm □ @ 26↓</td>
<td>Result did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>E2</td>
<td>ECTN13BRK on 1 mm □ @ 27↓</td>
<td>Result did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>E3</td>
<td>ECTN28BRK on 1 mm □ @ 28↓</td>
<td>Result did not occur on weak layer of primary concern</td>
</tr>
</tbody>
</table>
Table B.3 Compression test (CT) results obtained from the Craigieburn Valley backcountry study slope on 11 July 2012. Two CTs were performed in each snowpit. A description as to whether or not the fractures occurred on the weak layer of primary concern (identified from the associated full snow profile; Figure 4.13) is provided.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>CT #1 score</th>
<th>CT #2 score</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1.5</td>
<td>CTH28SC on 1.5 mm □ @ 35 ‡</td>
<td>CTH24SC on 1.5 mm □ @ 35 ‡</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>AA2.5</td>
<td>CTH26SC on 1.5 mm □ @ 35 ‡</td>
<td>CTH24SC on 1.5 mm □ @ 35 ‡</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>AA3.5</td>
<td>CTH28BRK on 1.5 mm □ @ 29 ‡</td>
<td>CTH23SC on 1 mm □ @ 24 ‡</td>
<td>CT #1 did occur on weak layer of primary concern, CT #2 did not</td>
</tr>
<tr>
<td>BB1.5</td>
<td>CTM15SC on 1 mm □ @ 40 ‡</td>
<td>CTH23SC on 1 mm □ @ 39 ‡</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>BB2.5</td>
<td>CTM19SC on 1 mm □ @ 37 ‡</td>
<td>CTM19SC on 1 mm □ @ 38 ‡</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>BB3.5</td>
<td>CTH25SC on 1.5 mm □ @ 49 ‡</td>
<td>CTH28SC on 1.5 mm □ @ 23 ‡</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>CC1.5</td>
<td>CTH21SC on 1.5 mm □ @ 26 ‡</td>
<td>CTM17SC on 1.5 mm □ @ 27 ‡</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>CC2.5</td>
<td>CTH23SC on 1.5 mm □ @ 32 ‡</td>
<td>CTH21SC on 1.5 mm □ @ 35 ‡</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>CC3.5</td>
<td>CTH22SC on 1.5 mm □ @ 28 ‡</td>
<td>CTH21SC on 1.5 mm □ @ 29 ‡</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>DD1.5</td>
<td>CTM15SC on 1 mm □ @ 34 ‡</td>
<td>CTM14SC on 1 mm □ @ 33 ‡</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>DD2.5</td>
<td>CTH22SC on 1 mm □ @ 35 ‡</td>
<td>CTM14SC on 1.5 mm □ @ 45 ‡</td>
<td>CT #1 did not occur on weak layer of primary concern, CT #2 did</td>
</tr>
<tr>
<td>DD3.5</td>
<td>CTM13SC on 1 mm □ @ 30 ‡</td>
<td>CTE1SP on 1.5 mm □ @ 48 ‡</td>
<td>CT #1 did not occur on weak layer of primary concern, CT #2 did</td>
</tr>
<tr>
<td>EE1.5</td>
<td>CTM16BRK on 1 mm □ @ 15 ‡</td>
<td>CTM18BRK on 1.5 mm □ @ 24 ‡</td>
<td>CT #1 did not occur on weak layer of primary concern, CT #2 did</td>
</tr>
<tr>
<td>EE2.5</td>
<td>CTE6SC on 1 mm □ @ 23 ‡</td>
<td>CTE7SC on 1 mm □ @ 26 ‡</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>EE3.5</td>
<td>CTH21SC on 1.5 mm □ @ 27 ‡</td>
<td>CTH22BRK on 1.5 mm □ @ 35 ‡</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
</tbody>
</table>
Table B.4  Extended column test (ECT) results obtained from the Craigieburn Valley backcountry study slope on 11 July 2012. One ECT was performed in each snowpit. A description as to whether or not the fractures occurred on the weak layer of primary concern (identified from the associated full snow profile; Figure 4.13) is provided.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>ECT score</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1.5</td>
<td>ECTN25RP on 1.5 mm □ @ 35°</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>AA2.5</td>
<td>ECTN25RP on 1.5 mm □ @ 35°</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>AA3.5</td>
<td>ECTN28BRK on 1.5 mm □ @ 29°</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>BB1.5</td>
<td>ECTP11SC on 1 mm □ @ 39°</td>
<td>Result <em>did not</em> occur on weak layer of primary concern</td>
</tr>
<tr>
<td>BB2.5</td>
<td>ECTN25SC on 1 mm □ @ 37°</td>
<td>Result <em>did not</em> occur on weak layer of primary concern</td>
</tr>
<tr>
<td>BB3.5</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>CC1.5</td>
<td>ECTP30SP on 1.5 mm □ @ 30°</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>CC2.5</td>
<td>ECTP28RP on 1.5 mm □ @ 36°</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>CC3.5</td>
<td>ECTN22SC on 1.5 mm □ @ 30°</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>DD1.5</td>
<td>ECTP20SC on 1mm □ @ 34°</td>
<td>Result <em>did not</em> occur on weak layer of primary concern</td>
</tr>
<tr>
<td>DD2.5</td>
<td>ECTN23SC on 1 mm □ @ 30°</td>
<td>Result <em>did not</em> occur on weak layer of primary concern</td>
</tr>
<tr>
<td>DD3.5</td>
<td>ECTPVSC on 1.5 mm □ @ 46°</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>EE1.5</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>EE2.5</td>
<td>ECTN15BRK on 1 mm □ @ 25°</td>
<td>Result <em>did not</em> occur on weak layer of primary concern</td>
</tr>
<tr>
<td>EE3.5</td>
<td>ECTN25BRK on 1 mm □ @ 19°</td>
<td>Result <em>did not</em> occur on weak layer of primary concern</td>
</tr>
</tbody>
</table>
Table B.5  Compression test (CT) results obtained from the Craigieburn Valley ski area study slope on 9 July 2012. Two CTs were performed in each snowpit. A description as to whether or not the fractures occurred on the weak layer of primary concern (identified from the associated full snow profile; Figure 4.14) is provided.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>CT #1 score</th>
<th>CT #2 score</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>CTE8SC on 0.5 mm □ @ 13↓</td>
<td>CTH21SC on 0.5 mm □ @ 13↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>C3</td>
<td>CTM12SC on 0.5 mm □ @ 18↓</td>
<td>CTH21BRK on 0.5 mm □ @ 20↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>A1</td>
<td>CTH28SC on 0.5 mm □ @ 34↓</td>
<td>CTH28BRK on 0.5 mm □ @ 17↓</td>
<td>CT #1 did not occur on weak layer of primary concern, CT #2 did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>A3</td>
<td>CTM12SC on 0.5 mm □ @ 17↓</td>
<td>CTM11SC on 0.5 mm □ @ 16↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>B2</td>
<td>CTM19SC on 0.5 mm □ @ 16↓</td>
<td>CTM11SC on 0.5 mm □ @ 17↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>F1</td>
<td>CTN</td>
<td>CTN</td>
<td>No fractures occurred during stability testing</td>
</tr>
<tr>
<td>F3</td>
<td>CTN</td>
<td>CTN</td>
<td>No fractures occurred during stability testing</td>
</tr>
<tr>
<td>D1</td>
<td>CTH26SC on 0.5 mm □ @ 34↓</td>
<td>CTH26SC on 0.5 mm □ @ 34↓</td>
<td>Both fractures did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>D3</td>
<td>CTH21RP on 0.5 mm □ @ 7↓</td>
<td>CTH22RP on 0.5 mm □ @ 20↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>E2</td>
<td>CTM13SC on 0.5 mm □ @ 18↓</td>
<td>CTM11SC on 0.5 mm □ @ 17↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>I1</td>
<td>CTH25SC on 0.5 mm □ @ 40↓</td>
<td>CTH29SC on 0.5 mm □ @ 40↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>I3</td>
<td>CTH26SC on 0.5 mm □ @ 34↓</td>
<td>CTH24SC on 0.5 mm □ @ 34↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>G1</td>
<td>CTH12SC on 0.5 mm □ @ 18↓</td>
<td>CTE10SC on 0.5 mm □ @ 16↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>G3</td>
<td>CTE7SC on 0.5 mm □ @ 16↓</td>
<td>CTH23SC on 0.5 mm □ @ 40↓</td>
<td>CT #1 did occur on weak layer of primary concern, CT #2 did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>H2</td>
<td>CTH21SC on 0.5 mm □ @ 28↓</td>
<td>CTH24SC on 0.5 mm □ @ 28↓</td>
<td>Both fractures did occur on weak layer of primary concern</td>
</tr>
</tbody>
</table>
Table B.6  Extended column test (ECT) results obtained from the Craigieburn Valley ski area study slope on 9 July 2012. One ECT was performed in each snowpit. A description as to whether or not the fractures occurred on the weak layer of primary concern (identified from the associated full snow profile; Figure 4.14) is provided.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>ECT score</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>ECTN13BRK on 0.5 mm □ @ 13↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>C3</td>
<td>ECTN23BRK on 0.5 mm □ @ 18↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>A1</td>
<td>ECTN15BRK on 0.5 mm □ @ 17↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>A3</td>
<td>ECTN23BRK on 0.5 mm □ @ 23↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>B2</td>
<td>ECTN17SC on 0.5 mm □ @ 17↓</td>
<td>Result did occur on weak layer of primary concern</td>
</tr>
<tr>
<td>F1</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>F3</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>D1</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>D3</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>E2</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>I1</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>I3</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>G1</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
<tr>
<td>G3</td>
<td>ECTP28SC on 0.5 mm □ @ 40↓</td>
<td>Result did not occur on weak layer of primary concern</td>
</tr>
<tr>
<td>H2</td>
<td>ECTX</td>
<td>No fracture occurred</td>
</tr>
</tbody>
</table>
Table B.7  Compression test (CT) and extended column test (ECT) results obtained from the Craigieburn Valley backcountry study slope and the Craigieburn Valley ski area study slope, on 21 July 2012 and 22 July 2012, respectively.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>CT #1 score</th>
<th>CT #2 score</th>
<th>ECT score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>CTN</td>
<td>CTN</td>
<td>ECTX</td>
</tr>
<tr>
<td>B</td>
<td>CTN</td>
<td>CTN</td>
<td>ECTX</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>CT #1 score</th>
<th>CT #2 score</th>
<th>ECT score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>CTN</td>
<td>CTN</td>
<td>ECTX</td>
</tr>
<tr>
<td>B</td>
<td>CTN</td>
<td>CTN</td>
<td>ECTX</td>
</tr>
<tr>
<td>C</td>
<td>CTM15BRK on 1 mm ● @ 4↓</td>
<td>CTM11BRK on 1 mm ● @ 4↓</td>
<td>ECTN21BRK on 1 mm ● @ 4↓</td>
</tr>
<tr>
<td>D</td>
<td>CTN</td>
<td>CTH21BRK on 1 mm ● @ 4↓</td>
<td>ECTX</td>
</tr>
<tr>
<td>E</td>
<td>CTN</td>
<td>CTN</td>
<td>ECTX</td>
</tr>
<tr>
<td>F</td>
<td>CTN</td>
<td>CTN</td>
<td>ECTX</td>
</tr>
<tr>
<td>G</td>
<td>CTN</td>
<td>CTN</td>
<td>ECTX</td>
</tr>
</tbody>
</table>
Appendix C

Individual snowpit stability ratings

This appendix includes the stability ratings obtained from individual snowpits during this study. These stability ratings were based on a rating scheme developed for this study, which utilised the stability indication obtained from the three-component model of stability. Section 3.4.1.1 describes how the stability indications regarding snowpack strength, energy and structure were obtained. Table 3.6 provides the stability indication thresholds applied to each component.
Table C.1  Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 7 July 2012, with respect to the compression test (CT) score. The mean overall stability represents the overall stability rating of the slope, based on the ratings obtained from all 15 individual snowpits.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength (tap score)</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Fair (16.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 - Fair</td>
</tr>
<tr>
<td>A2</td>
<td>Poor (13)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>A3</td>
<td>Very poor (0)</td>
<td>Poor</td>
<td>Poor</td>
<td>2 - Very poor</td>
</tr>
<tr>
<td>B1</td>
<td>Poor (13)</td>
<td>Good</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>B2</td>
<td>Fair (13.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 - Fair</td>
</tr>
<tr>
<td>B3</td>
<td>Good (22.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>C1</td>
<td>Fair (13.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 - Fair</td>
</tr>
<tr>
<td>C2</td>
<td>Poor (13)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>C3</td>
<td>Good (23)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>D1</td>
<td>Fair (17)</td>
<td>Good</td>
<td>Poor</td>
<td>6 - Fair</td>
</tr>
<tr>
<td>D2</td>
<td>Good (21.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>D3</td>
<td>Poor (12)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>E1</td>
<td>Fair (13.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 - Fair</td>
</tr>
<tr>
<td>E2</td>
<td>Poor (12)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>E3</td>
<td>Fair (18)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 - Fair</td>
</tr>
</tbody>
</table>

Mean overall stability: 4.0 - Fair
Table C.2  Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 7 July 2012, with respect to the extended column test (ECT) score. The mean overall stability represents the overall stability rating of the slope, based on the ratings obtained from all 15 individual snowpits.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength (tap score)</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Good (26)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>A2</td>
<td>Good (26)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>A3</td>
<td>Poor (8)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 – Poor</td>
</tr>
<tr>
<td>B1</td>
<td>Good (22)</td>
<td>Good</td>
<td>Poor</td>
<td>7 – Good</td>
</tr>
<tr>
<td>B2</td>
<td>Poor (13)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 – Poor</td>
</tr>
<tr>
<td>B3</td>
<td>Good (25)</td>
<td>Good</td>
<td>Poor</td>
<td>7 – Good</td>
</tr>
<tr>
<td>C1</td>
<td>Good (22)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>C2</td>
<td>Very poor (0)</td>
<td>Poor</td>
<td>Poor</td>
<td>2 – Very poor</td>
</tr>
<tr>
<td>C3</td>
<td>Fair (14)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 – Fair</td>
</tr>
<tr>
<td>D1</td>
<td>Fair (18)</td>
<td>Good</td>
<td>Poor</td>
<td>6 – Fair</td>
</tr>
<tr>
<td>D2</td>
<td>Good (21)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>D3</td>
<td>Fair (14)</td>
<td>Good</td>
<td>Poor</td>
<td>6 – Fair</td>
</tr>
<tr>
<td>E1</td>
<td>Poor (12)</td>
<td>Good</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>E2</td>
<td>Poor (13)</td>
<td>Good</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>E3</td>
<td>Good (28)</td>
<td>Good</td>
<td>Poor</td>
<td>7 - Good</td>
</tr>
</tbody>
</table>

Mean overall stability:  5.0 - Fair
Table C.3 Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 11 July 2012, with respect to the compression test (CT) score. The mean overall stability represents the overall stability rating of the slope, based on the ratings obtained from all 15 individual snowpits.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength (tap score)</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1.5</td>
<td>Good (26)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>AA2.5</td>
<td>Good (25)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>AA3.5</td>
<td>Good (25.5)</td>
<td>Fair</td>
<td>Poor</td>
<td>6 – Fair</td>
</tr>
<tr>
<td>BB1.5</td>
<td>Fair (19)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 - Fair</td>
</tr>
<tr>
<td>BB2.5</td>
<td>Fair (19)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 - Fair</td>
</tr>
<tr>
<td>BB3.5</td>
<td>Good (26.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>CC1.5</td>
<td>Fair (19)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 – Fair</td>
</tr>
<tr>
<td>CC2.5</td>
<td>Good (22)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>CC3.5</td>
<td>Good (21.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>DD1.5</td>
<td>Fair (14.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 – Fair</td>
</tr>
<tr>
<td>DD2.5</td>
<td>Fair (18)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 – Fair</td>
</tr>
<tr>
<td>DD3.5</td>
<td>Poor (7)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>EE1.5</td>
<td>Fair (17)</td>
<td>Good</td>
<td>Poor</td>
<td>4 – Fair</td>
</tr>
<tr>
<td>EE2.5</td>
<td>Poor (6.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>EE3.5</td>
<td>Good (21.5)</td>
<td>Fair</td>
<td>Poor</td>
<td>6 - Fair</td>
</tr>
</tbody>
</table>

Mean overall stability: 4.47 - Fair
Table C.4  Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 11 July 2012, with respect to the extended column test (ECT) score. The mean overall stability represents the overall stability rating of the slope, based on the ratings obtained from all 15 individual snowpits.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength (tap score)</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1.5</td>
<td>Good (25)</td>
<td>Good</td>
<td>Poor</td>
<td>7 - Good</td>
</tr>
<tr>
<td>AA2.5</td>
<td>Good (25)</td>
<td>Good</td>
<td>Poor</td>
<td>7 - Good</td>
</tr>
<tr>
<td>AA3.5</td>
<td>Good (28)</td>
<td>Good</td>
<td>Poor</td>
<td>7 - Good</td>
</tr>
<tr>
<td>BB1.5</td>
<td>Poor (11)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>BB2.5</td>
<td>Good (25)</td>
<td>Fair</td>
<td>Poor</td>
<td>6 - Fair</td>
</tr>
<tr>
<td>BB3.5</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 - Good</td>
</tr>
<tr>
<td>CC1.5</td>
<td>Good (30)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>CC2.5</td>
<td>Good (28)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>CC3.5</td>
<td>Good (22)</td>
<td>Fair</td>
<td>Poor</td>
<td>6 – Fair</td>
</tr>
<tr>
<td>DD1.5</td>
<td>Good (20)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>DD2.5</td>
<td>Good (23)</td>
<td>Fair</td>
<td>Poor</td>
<td>6 – Fair</td>
</tr>
<tr>
<td>DD3.5</td>
<td>Very poor (0)</td>
<td>Poor</td>
<td>Poor</td>
<td>2 – Very poor</td>
</tr>
<tr>
<td>EE1.5</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 - Good</td>
</tr>
<tr>
<td>EE2.5</td>
<td>Fair (15)</td>
<td>Good</td>
<td>Poor</td>
<td>6 – Fair</td>
</tr>
<tr>
<td>EE3.5</td>
<td>Good (25)</td>
<td>Good</td>
<td>Poor</td>
<td>7 - Good</td>
</tr>
</tbody>
</table>

Mean overall stability: 6.0 - Fair
Table C.5 Individual snowpit stability ratings obtained from the Craigieburn Valley ski area on 9 July 2012, with respect to the compression test (CT) score. The mean overall stability represents the overall stability rating of the slope, based on the ratings obtained from all 15 individual snowpits.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength (tap score)</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Fair (14.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 – Fair</td>
</tr>
<tr>
<td>C3</td>
<td>Fair (16.5)</td>
<td>Fair</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>A1</td>
<td>Good (28)</td>
<td>Fair</td>
<td>Poor</td>
<td>6 - Fair</td>
</tr>
<tr>
<td>A3</td>
<td>Poor (11.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>B2</td>
<td>Fair (15)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 – Fair</td>
</tr>
<tr>
<td>F1</td>
<td>Very good (CTN)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 - Good</td>
</tr>
<tr>
<td>F3</td>
<td>Very good (CTN)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 - Good</td>
</tr>
<tr>
<td>D1</td>
<td>Good (26)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>D3</td>
<td>Good (21.5)</td>
<td>Good</td>
<td>Poor</td>
<td>7 - Good</td>
</tr>
<tr>
<td>E2</td>
<td>Poor (12)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>I1</td>
<td>Good (27)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 – Poor</td>
</tr>
<tr>
<td>I3</td>
<td>Good (25)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>G1</td>
<td>Poor (11)</td>
<td>Poor</td>
<td>Poor</td>
<td>3 - Poor</td>
</tr>
<tr>
<td>G3</td>
<td>Fair (15)</td>
<td>Poor</td>
<td>Poor</td>
<td>4 - Fair</td>
</tr>
<tr>
<td>H2</td>
<td>Good (22.5)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
</tbody>
</table>

Mean overall stability: 5.0 - Fair
Table C.6  Individual snowpit stability ratings obtained from the Craigieburn Valley ski area on 9 July 2012, with respect to the extended column test (ECT) score. The mean overall stability represents the overall stability rating of the slope, based on the ratings obtained from all 15 individual snowpits.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength (tap score)</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Poor (13)</td>
<td>Good</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>C3</td>
<td>Good (23)</td>
<td>Good</td>
<td>Poor</td>
<td>7 - Good</td>
</tr>
<tr>
<td>A1</td>
<td>Fair (15)</td>
<td>Good</td>
<td>Poor</td>
<td>6 - Fair</td>
</tr>
<tr>
<td>A3</td>
<td>Good (23)</td>
<td>Good</td>
<td>Poor</td>
<td>7 - Good</td>
</tr>
<tr>
<td>B2</td>
<td>Fair (17)</td>
<td>Fair</td>
<td>Poor</td>
<td>5 - Fair</td>
</tr>
<tr>
<td>F1</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 – Good</td>
</tr>
<tr>
<td>F3</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 – Good</td>
</tr>
<tr>
<td>D1</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 – Good</td>
</tr>
<tr>
<td>D3</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 – Good</td>
</tr>
<tr>
<td>E2</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 – Good</td>
</tr>
<tr>
<td>I1</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 – Good</td>
</tr>
<tr>
<td>I3</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 – Good</td>
</tr>
<tr>
<td>G1</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 – Good</td>
</tr>
<tr>
<td>G3</td>
<td>Good (28)</td>
<td>Poor</td>
<td>Poor</td>
<td>5 – Fair</td>
</tr>
<tr>
<td>H2</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Poor</td>
<td>9 – Good</td>
</tr>
</tbody>
</table>

Mean overall stability: 7.73 - Good
Table C.7 Individual snowpit stability ratings obtained from the Craigieburn Valley backcountry on 21 July 2012, with respect to the compression test (CT) and extended column test (ECT) score, respectively. The mean overall stability represents the overall stability rating of the slope, based on the ratings obtained from the two individual snowpits.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall stability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compression Test</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Very good (CTN)</td>
<td>Very good</td>
<td>Fair</td>
<td>10 – Very good</td>
</tr>
<tr>
<td>B</td>
<td>Very good (CTN)</td>
<td>Very good</td>
<td>Fair</td>
<td>10 – Very good</td>
</tr>
<tr>
<td><strong>Mean overall stability:</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>10 – Very good</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall stability</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extended Column Test</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Fair</td>
<td>10 – Very good</td>
</tr>
<tr>
<td>B</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Fair</td>
<td>10 – Very good</td>
</tr>
<tr>
<td><strong>Mean overall stability:</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>10 – Very good</strong></td>
</tr>
</tbody>
</table>
Table C.8 Individual snowpit stability ratings obtained from the Craigieburn Valley ski area on 22 July 2012, with respect to the compression test (CT) score. The mean overall stability represents the overall stability rating of the slope, based on the ratings obtained from all 7 individual snowpits.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Very good (CTN)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
<tr>
<td>B</td>
<td>Very good (CTN)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
<tr>
<td>C</td>
<td>Poor (13)</td>
<td>Good</td>
<td>Very good</td>
<td>8 – Good</td>
</tr>
<tr>
<td>D</td>
<td>Good (21)</td>
<td>Good</td>
<td>Very good</td>
<td>10 – Very good</td>
</tr>
<tr>
<td>E</td>
<td>Very good (CTN)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
<tr>
<td>F</td>
<td>Very good (CTN)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
<tr>
<td>G</td>
<td>Very good (CTN)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
</tbody>
</table>

Mean overall stability: 11.14 – Very good

Table C.9 Individual snowpit stability ratings obtained from the Craigieburn Valley ski area on 22 July 2012, with respect to the extended column test (ECT) score. The mean overall stability represents the overall stability rating of the slope, based on the ratings obtained from all 7 individual snowpits.

<table>
<thead>
<tr>
<th>Snowpit</th>
<th>Strength</th>
<th>Energy</th>
<th>Structure</th>
<th>Overall stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
<tr>
<td>B</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
<tr>
<td>C</td>
<td>Good (21)</td>
<td>Good</td>
<td>Very good</td>
<td>10 – Very good</td>
</tr>
<tr>
<td>D</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
<tr>
<td>E</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
<tr>
<td>F</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
<tr>
<td>G</td>
<td>Very good (ECTX)</td>
<td>Very good</td>
<td>Very good</td>
<td>12 – Very good</td>
</tr>
</tbody>
</table>

Mean overall stability: 11.71 – Very good