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**PHOTOGRAPHIC ATLAS OF STRIATIONS  
FROM SELECTED GLACIAL AND  
NON-GLACIAL ENVIRONMENTS**

C.B. Atkins



**ANTARCTIC RESEARCH CENTRE**  
in association with the

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SCHOOL OF EARTH SCIENCES

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*Te Kura Tātai Aro Whenua*

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VICTORIA UNIVERSITY OF WELLINGTON  
*Te Whare Wananga o te Upoko o te Ika a Maui*

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# CONTENTS

INTRODUCTION.....	1
FIELD LOCATIONS .....	1
METHODS .....	3
 PART ONE: <b>Warm-based glacial striae (Lake Pukaki moraine, Mt Cook, New Zealand)</b>	
Introduction.....	4
Characteristics of warm-based glacial striae .....	5
Striae orientation .....	5
Striae images .....	6
 PART TWO: <b>Polythermal glacial striae (Mackay Glacier, Antarctica)</b>	
Introduction.....	10
Characteristics of polythermal glacial striae.....	11
Striae orientation .....	12
Striae images .....	13
 PART THREE: <b>Cold-based linear abrasion features (Allan Hills, Antarctica)</b>	
Introduction.....	17
Characteristics of cold-based abrasion features .....	18
Striae images .....	20
 PART FOUR: <b>Mass movement striae (debris-Avalanche from Mt Ruapehu and rock-fall from Murchison Valley, New Zealand)</b>	
Introduction.....	25
Murimotu Formation (debris-Avalanche) .....	25
Characteristics of debris-avalanche striae.....	26
Striae orientation .....	26
Striae images .....	27
Murchison Valley (rock-fall) .....	30
Characteristics of rock-fall striae .....	31
Striae orientation .....	31
Striae images .....	32
 PART FIVE: <b>Tectonic striae (Ngapotiki and Wellington Faults, New Zealand)</b>	
Introduction.....	34
Ngapotiki Fault (Wairarapa).....	34
Wellington Fault (Upper Hutt).....	36
Characteristics of tectonic striae .....	36
Striae orientation .....	37
Striae images .....	38
CONCLUSIONS: .....	42
Table 1, Summary striae characteristics .....	44
REFERENCES: .....	45



## INTRODUCTION

Linear abrasion features on rock surfaces are produced by interacting rock particles in relative motion. The most common examples are striations (striae) produced beneath warm-based glaciers. Consequently, striae are one of the most widely recognised means of identifying the passage of past glaciers. However, many non-glacial processes can produce striae. These have been sporadically documented in the geological literature but have failed to make a lasting impression on the wider Earth Sciences community (Schermerhorn, 1974; Zamoruev, 1974). Non-glacial processes include tectonic deformation, meltwater flow, non-glacial ice, wind action, volcanic blasting, mass-movements of rock debris, among others. Many of these produce coarse-grained diamicton deposits similar in character to glacial tills and there are several instances where non-glacial deposits and related striae have been misinterpreted as glacial in origin (see review in Atkins, 2003). Determining whether specific diamicton facies are glacial or non-glacial in origin remains a central problem in stratigraphic studies (Eyles and Eyles, 1992). Therefore a better understanding of key characteristics such as striae improves our ability to correctly interpret the origin of these deposits in the geological record.

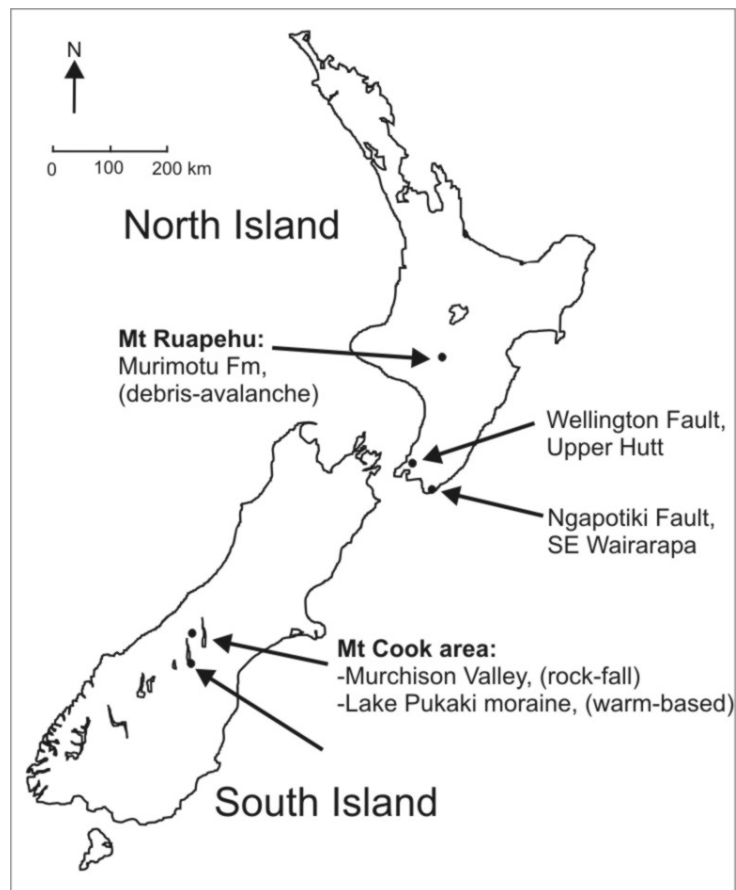
This photographic atlas provides images of striae (and other linear abrasion marks) at a variety of scales from five settings where the origin of the striae is certain. These include three glacial (warm-based, polythermal and cold-based) and two non-glacial settings (mass-movement and tectonic). It is intended as a visual guide to the aspects of striae that are inherently difficult to describe quantitatively. It includes examples and description of both the common and unusual characteristics associated with each environment.

Striae occur in many environments not included here, and therefore this photographic atlas serves as an initial contribution to a visual database of striae on rock surfaces. Atkins (2003) provides a comprehensive review of glacial and non-glacial striae. In addition, it gives further information on each field location mentioned in this report and presents striae data including the orientation with regard to long-axes of clasts, striae dimensions, clast shape and the density of striae on clasts.

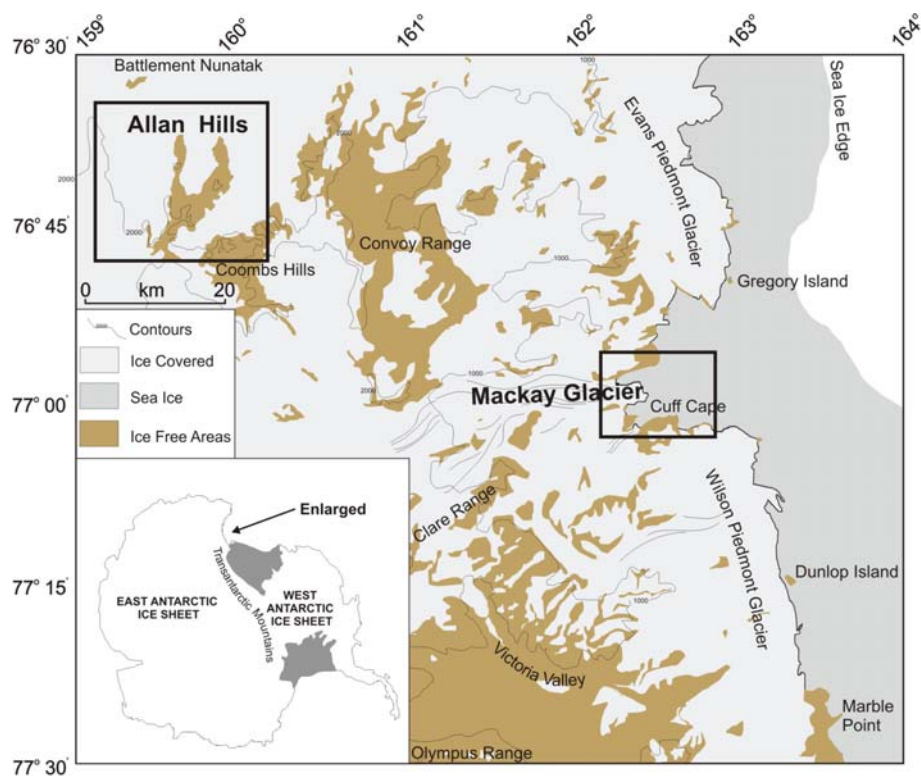
## FIELD LOCALITIES

Striated clasts were collected from five locations in New Zealand (Figure 1). These included warm-based glacial striae from the recent Lake Pukaki moraine and rock-fall striae from modern scree in the Murchison Valley in the Mt Cook region of the South Island. In the North Island, striae from a Holocene debris-avalanche (Murimotu Formation) were collected from Mt Ruapehu and striae from tectonic processes collected from the Wellington and Ngapotiki Faults in the lower North Island.

In Antarctica, polythermal glacially striated clasts were collected from icebergs on the Mackay Glacier tongue and ground moraine from nearby Cuff Cape in Granite Harbour. Finally, striae and other linear abrasion marks produced by a cold-based glacier were documented from the Allan Hills Nunatak in South Victoria Land (Figure 2).



**Figure 1** Location map of New Zealand field sites, (warm-based glacial, debris-avalanche, rock-fall and tectonic).



**Figure 2** Location map of Antarctic field sites, (polythermal glacial and cold-based glacial).

## METHODS

Images of striated clasts presented in this atlas were generated with a Canon G2 4.0 million pixel digital camera mounted vertically on a camera and lighting stand. The stand has an adjustable vertical camera mount and bi-directional lighting (Figure 3). Several removable close-up lenses were utilised depending on the size of the clast.

Lighting direction and angles vary for each image and were designed to provide the clearest image of the striae. The lights used were four 75-watt fog lamps (two on each side on the base plate). These were usually set at 45° and the clast was illuminated from one side only. A free-standing light box with two LED lights set in flexible arms was used for very low-angle lighting on some clasts.

Field photographs of bedrock abrasion features were taken with a conventional 35mm camera using colour positive film.

Images were manipulated in Corel Photo-paint, version 10 to enhance image intensity and contrast.



**Figure 3** Camera and lighting stand used to generate digital images of clasts. The camera is mounted vertically and the clast is illuminated from one side.

# **PART ONE:**

## **WARM-BASED GLACIAL STRIAE - LAKE PUKAKI MORaine, MT COOK REGION, NEW ZEALAND**

### **Introduction**

This section documents striae on clasts abraded by a warm-based glacier. The clasts were collected from a Late Pleistocene till (Lake Pukaki moraine) in the Mt Cook region on the eastern side of the Southern Alps of New Zealand.

The Pukaki moraine was formed by the westward flowing palaeo-Tasman glacier during the last glacial maximum (Otiran Glaciation), (Porter, 1975). This glacier was a warm-based valley glacier that flowed approximately 80 km from the present Tasman, Mueller, Murchison and Hooker Valleys, terminating at about 600 metres above sea-level several km south of the present southern margin of Lake Pukaki (Porter, 1975). Glacial deposits including subglacial till, glaciolacustrine sediments and glaciofluvial gravel are exposed in vertical bluffs on the southern margin of the lake and are here collectively called the Lake Pukaki moraine. Striated clasts were collected from a compact diamicton unit exposed in the moraine complex on the southern margin of the lake (170°10'00" E, 44°10'30"S) (Figure 4). The clast lithologies consist of sandstone and argillite sourced from Jurassic and Triassic age greywacke of the Torlesse Group (Gair, 1967).



**Figure 4** Close-up of the Lake Pukaki moraine. Abundant striated clasts are present in this unit. Tape measure is 2 metres long.

## **Characteristics of warm-based glacial striae**

Small-scale striae occur on 33 % of clasts from the Lake Pukaki moraine. They occur preferentially on argillite clasts (94 % of all argillite compared with 19.5 % of all sandstone). They form on clasts ranging from angular to rounded and preferentially (but not exclusively) on faceted clasts.

A common characteristic of the warm-based glacial clasts from the Pukaki moraine is the high density of striae on clast surfaces. This includes individual striae and a pervasive “background” of microstriae. Microstriae are defined as < 0.25 mm width and < 2 mm length. These striae are clearly visible on fine-grained clasts but difficult to measure individually (WB-1a). Often, larger striae are superimposed on this background, either parallel or sub-parallel to the long-axis (WB-1a, WB-1b, WB-2a, WB-2b). The larger striae sometimes have smaller striae within the abrasion mark and are here termed compound striae (WB-1c). The typical combination of microstriae with larger individual striae occurs on flat glacial facets and on gently curved clast surfaces (WB-3).

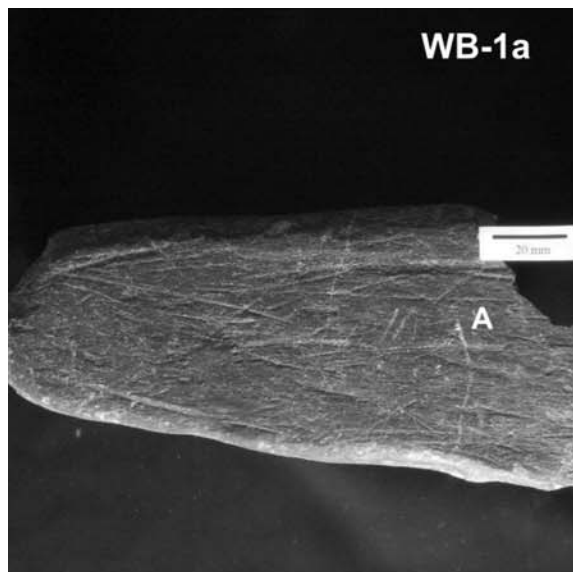
Image WB-5 shows how lithology can influence the generation and preservation of striae. Fine striae including microstriae are clearly visible on the darker argillite portion of the clast but difficult to recognize on the lighter sandstone portion. Image WB-6 is another example showing a sandstone clast that has large striae several mm wide, but no distinguishable microstriae.

Striae length displays great variation and appears to be related to clast size with longer striae forming on longer clasts. Width is less variable, but still related to clast size (widest striae occur on largest clasts). Overall, individual striae on warm-based glacial clasts tend to be clearly defined, long and narrow with only rare compound striae.

## **Striae orientation**

There is a strong association between striae orientation and the shape of the clast. On elongate clasts, striae are typically parallel or sub-parallel to the long-axis of the clast (WB1a, WB-2a) with only a small number of striae occurring at a high angle to the long-axis (WB-1b, WB-2a). There are exceptions to this generalisation. For example, Image WB-4 shows an elongate pebble with variably oriented straight striae on a well-developed facet, but oblique to the long-axis and cross-cutting suggesting that they were formed at different times and different clast orientation. Also the background microstriae are variably oriented.

On clasts that are more equidimensional, the striae have less preferred orientation (WB-7a and WB-7b and WB-8). These equidimensional clasts also display more curved striae. This is attributed to clast alignment during basal glacial transport. Equidimensional clasts more likely to rotate producing curved striae than elongate clasts which establish a stable position (long-axis parallel to flow).



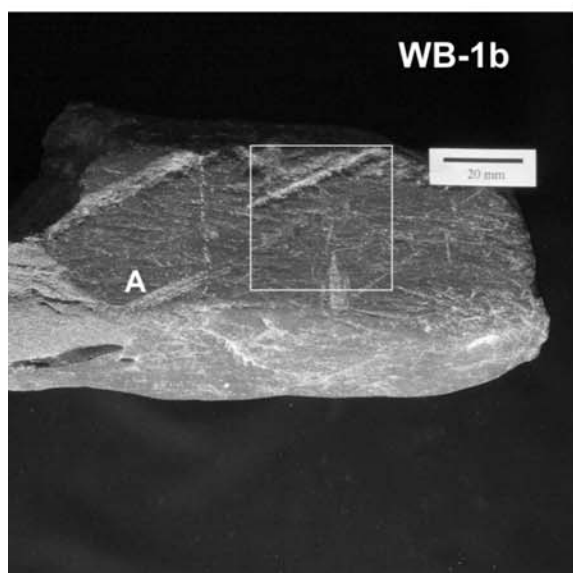
### *Parallel fine glacial striae*

Image WB-1a shows a glacially faceted and striated argillite clast with a bullet shaped stoss end and a sharp, broken lee end.

Abundant fine striae occur on the facet, oriented predominantly parallel to the long axis of the clast. The surface has several larger striae up to 3 mm wide superimposed on a "background" of microstriae that are difficult to identify individually.

Striae orientation typically deviates by less than 15° from the clast long-axis, although rare striae deviate up to 75° degrees (A).

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



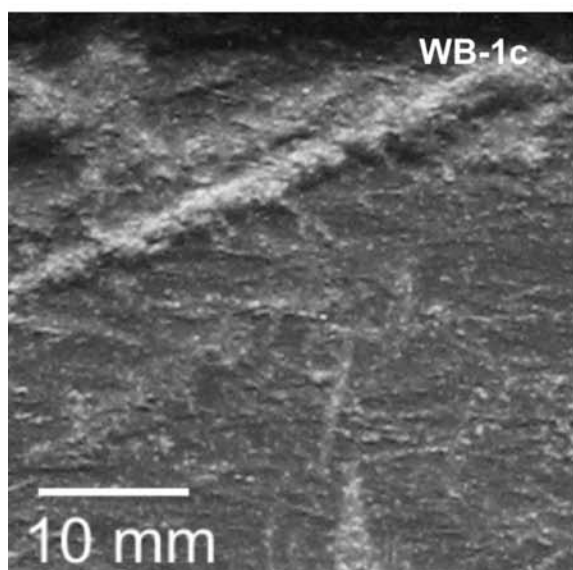
### *Large and small striae*

Image WB-1b shows the obverse facet of the clast in Image WB-1a.

On this surface, many long-axis parallel striae are clear, as well as larger striae oriented oblique to the long-axis. One of these large striae has smaller parallel striae on the surface (compound striation) (A).

Inset square is enlarged in Image WB-1c.

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



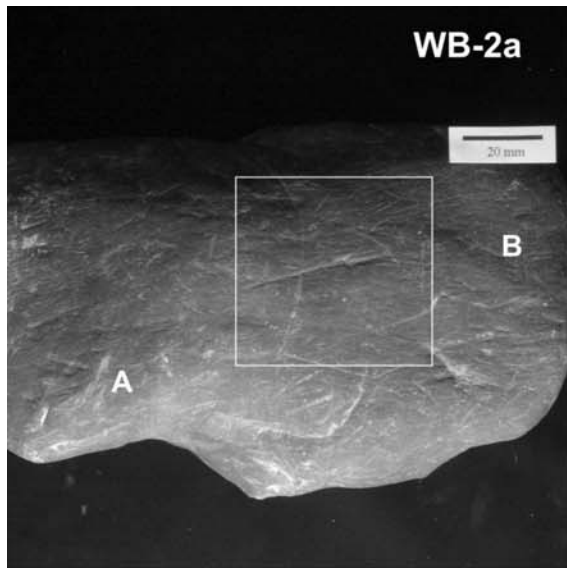
### *Closeup of large and small striae*

Image WB-1c shows closeup detail of the clast surface.

The large striation shown is 38 mm long and 6 mm wide with jagged sides and bottom. Some of these larger striae have several fine parallel striae on their surfaces.

Also visible is the "background" of microstriae (lower part of image).

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



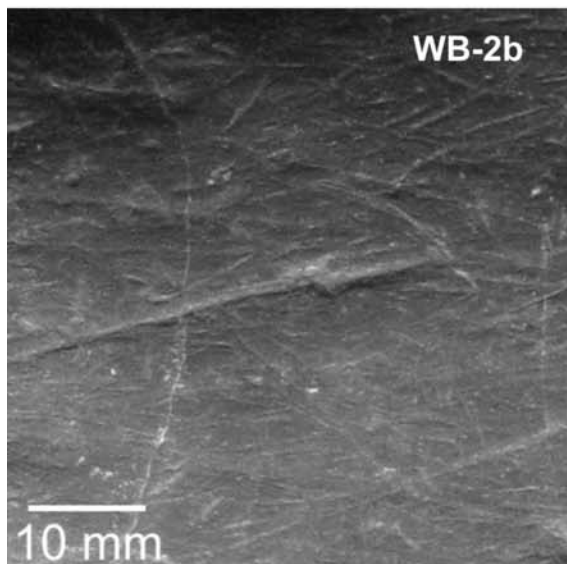
### *Parallel fine striae*

Image WB-2a is another example of parallel glacial striae on a glacially shaped argillite clast. Most striae are sub-parallel to the long-axis of the clast.

The orientation of some larger striae deviate from the clast long-axis by up to 65°(A).

A "background" of microstriae occurs over the entire surface of the clast (B).

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



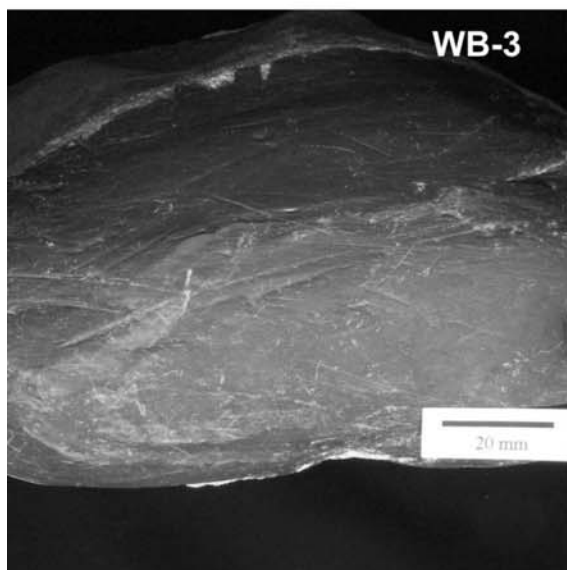
### *Closeup of parallel fine striae*

Image WB-2b shows a closeup of the clast surface.

The large striation in the centre is 30 mm long and up to 1.5 mm wide and deviates by about 15° from the long-axis of the clast.

The "background" microstriae are clearly visible at this scale.

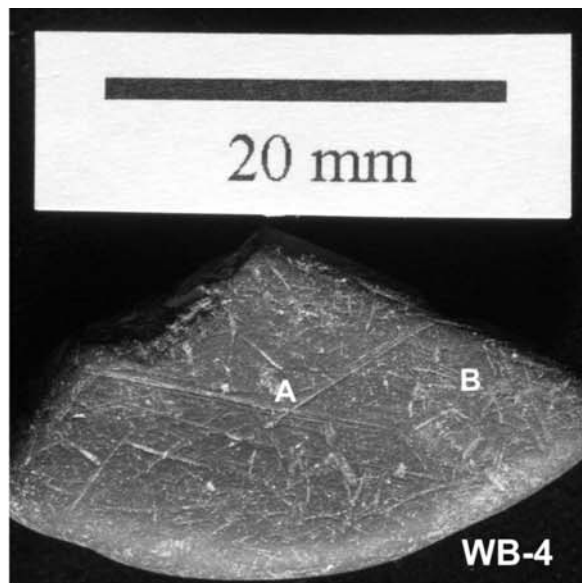
Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



### *Parallel fine striae on a curved surface*

Image WB-3 shows fine striae oriented predominantly parallel to the clast long-axis but on a curved surface rather than a flat facet. This implies that the striating tools were held firmly against the clast as they were dragged over it.

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



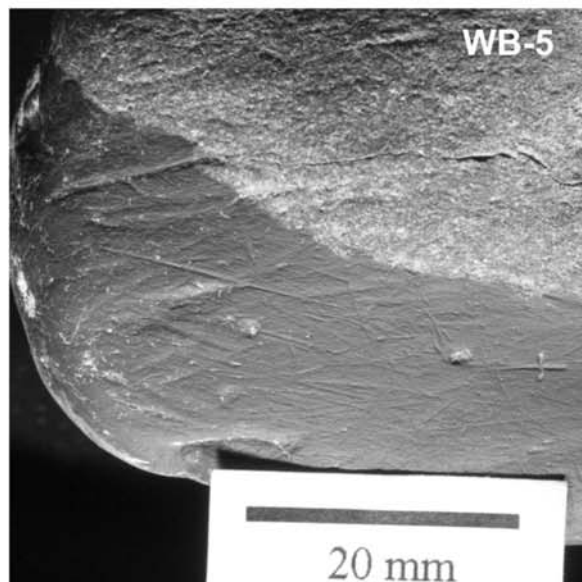
### ***Variably oriented striae***

Image WB-4 shows an argillite clast with a clearly faceted and striated surface that has variably oriented striae.

Two thin straight striae up to 15 mm long are oriented oblique to the long-axis of the clast and intersect (A).

A "background" of microstriae that have no preferred orientation is visible (B)

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



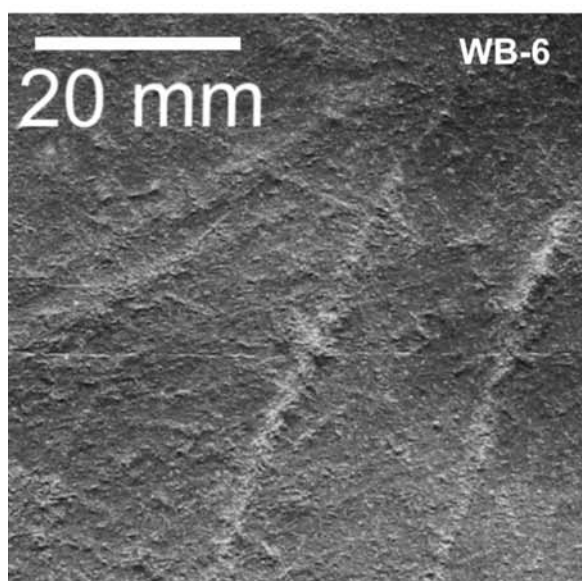
### ***Lithologic influence on striae***

The clast in Image WB-5 contains a contact between sandstone (light colour) and argillite (darker) on the same facet.

Fine glacial striae are obvious on the argillite portion, but less obvious on the sandstone.

This illustrates how lithology can affect striae preservation.

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



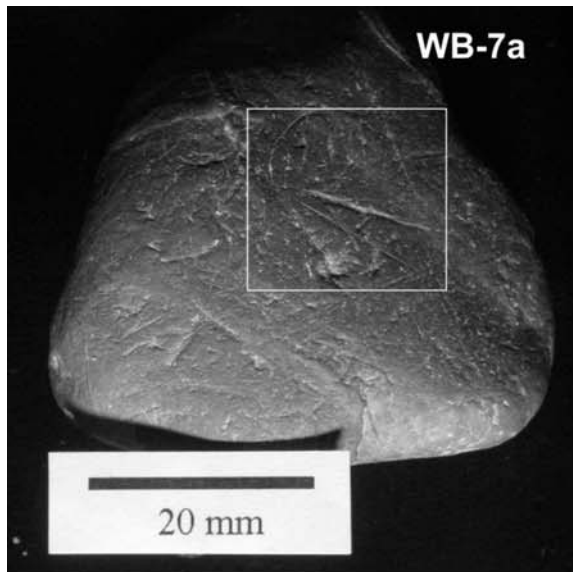
### ***Lithologic influence on striae***

Image WB-6 shows part of a sandstone clast from the Lake Pukaki moraine.

Only larger striae (>2mm wide) are visible.

Microstriae are not distinguishable on the rough surface due to the coarser grainsize.

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



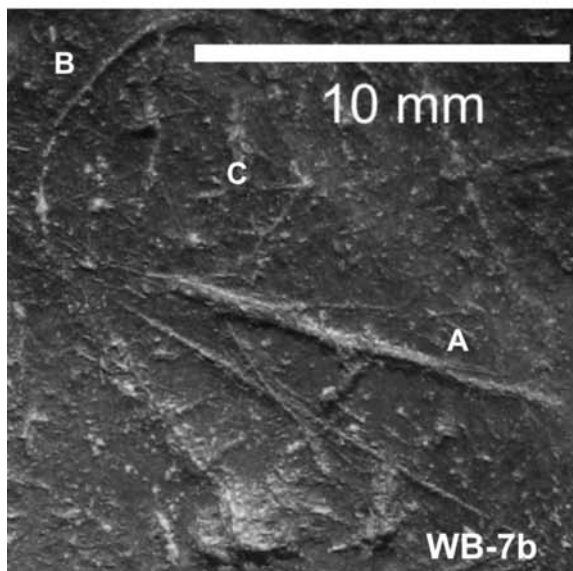
### ***Randomly oriented striae***

Image WB-7a shows a rounded and equidimensional (nearly equal long and intermediate axes) argillite clast.

Striae occur on both sides of the clast and have no preferred orientation, and some are curved. These individual large striae occur against a "background" of microstriae.

The inset square is enlarged in Image WB-7b.

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



### ***Closeup of randomly oriented striae***

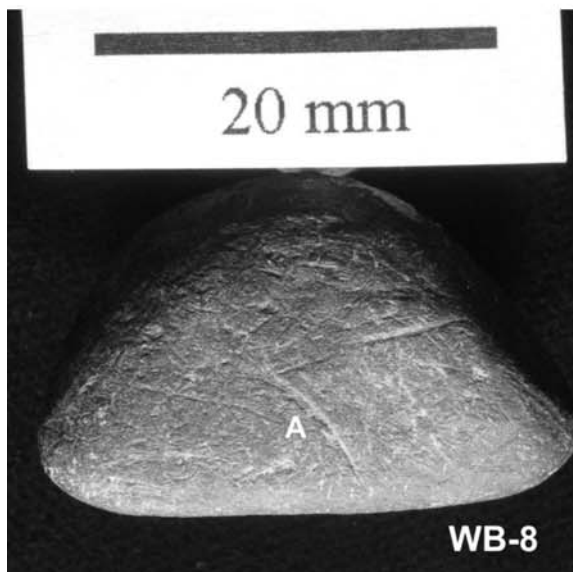
Image WB-7b shows a closeup of the clast surface. Striae include:

A large straight striation, 12 mm long and up to 0.6 mm wide (A).

A curved striation indicating clast rotation during the striation process (B).

A "background" of randomly oriented microstriae (C).

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S



### ***Randomly oriented striae***

Image WB-8 shows an argillite clast with a more defined long-axis than the clast in images WB-7a,b. However, this clast also has random striae orientations.

Individual larger striae are set against a "background" of microstriae.

One of the larger striae is slightly curved, suggesting clast rotation during the striating process (A).

Location: Lake Pukaki moraine, Mt. Cook region, New Zealand, 170°10'00"E 44°10'30"S

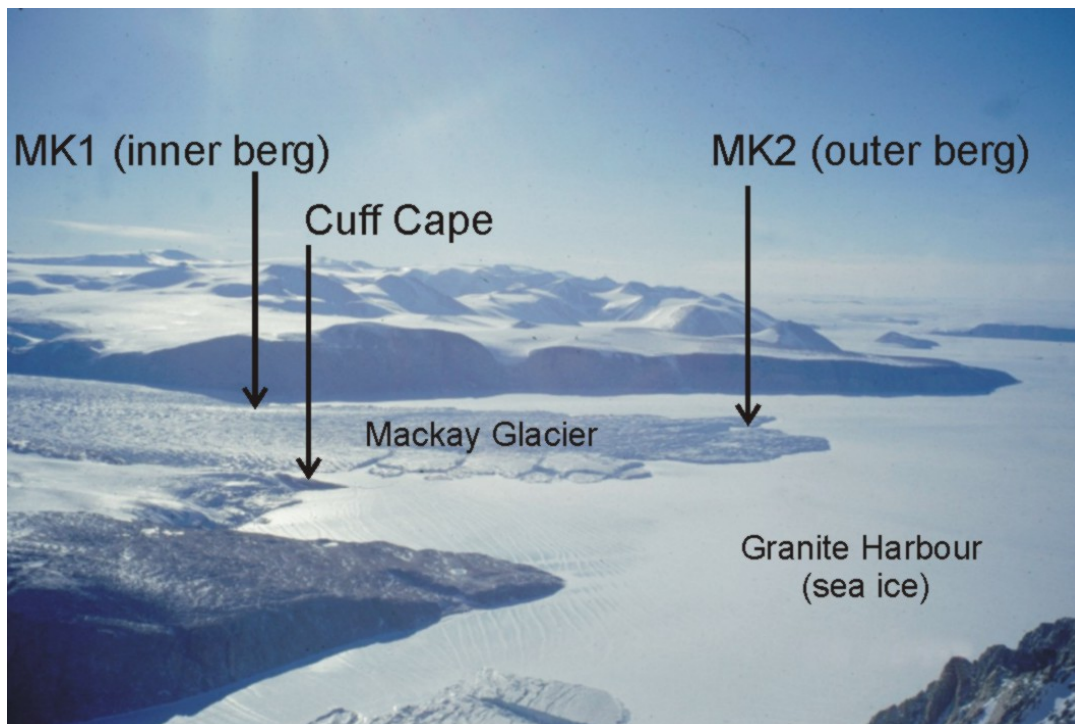
## PART TWO:

### POLYTHERMAL GLACIAL STRIAE - MACKAY GLACIER, GRANITE HARBOUR, ANTARCTICA

#### Introduction

Polythermal glaciers are those that have both warm and cold-based bed conditions. The Mackay Glacier is a polythermal outlet glacier draining from the East Antarctic Ice Sheet into Granite Harbour on the western side of McMurdo Sound, Antarctica (162°30'00"E, 76°57'30"S) (Figure 2). The glacier is approximately 65 km long, 5 km wide and about 500 m thick over much of its length (Macpherson, 1987). It terminates as a floating marine ice tongue approximately 3 km wide and 5 km long (Figure 5). Macpherson (1987) calculated that the Mackay Glacier is wet-based due to pressure melting wherever the glacier exceeds 425 m thickness. Furthermore, the glacier moves at about 212 m a<sup>-1</sup> (up glacier from the grounding-line) with a total discharge of 0.238 km<sup>3</sup> yr<sup>-1</sup>.

Layers of debris-rich ice containing faceted and striated clasts were collected from two icebergs (MK 1 and MK 2) along the ice tongue margins. These bergs are considered to represent marginal portions of basal ice of the Mackay Glacier that detached and floated upside down to the surface as the glacier passed the grounding-line (Figure 6). The layers are generally englacial and are likely to have been elevated from the bed to an englacial position by glaciotectonic faulting or folding. Striated clasts were collected from these layers and from a low, partially ice covered granite bedrock ridge (Cuff Cape) at the southern margin of the glacier (Figure 5).



**Figure 5** View of northern Granite Harbour (looking north from Mt. England) showing the floating ice-tongue of the Mackay Glacier with sample sites MK 1 (inner berg), MK 2 (outer berg) and Cuff Cape on the immediate southern margin of the Glacier.



**Figure 6** Sample site on an overturned glacier berg (MK 1) near the present grounding-line of the Mackay Glacier. Note the bag and hammer (circle) for scale.

### Characteristics of polythermal glacial striae

Less than 10% of clasts from the overturned berg samples (MK 1 and MK 2) display striae. They preferentially occur on fine-grained sedimentary clasts, but also on some dolerite clasts and rarely on granite clasts. Striae preferentially occur on clearly faceted surfaces of sub-angular to rounded clasts.

The surfaces tend to be pervasively striated with a “background” of microstriae ( $< 2$  mm long and  $< 0.25$  mm wide). Microstriae occur on both flat facets and on slightly curved surfaces. Superimposed on this “background” are larger, distinct striae up to 4 mm wide and several 10’s of mm long (P-1a, P-1b, P-2a, P-2b, P-6). Some of the wider striae are compound striae made up of several smaller striae. This occurs on both smaller clasts (P-1a, P-1b) and larger clasts where compound striae up to 20 mm wide occur (P-9a). Image P-9a and P-9b show an example of a compound striation that is curved and almost perpendicular to the long-axis suggestive of clast rotation during the striation process.

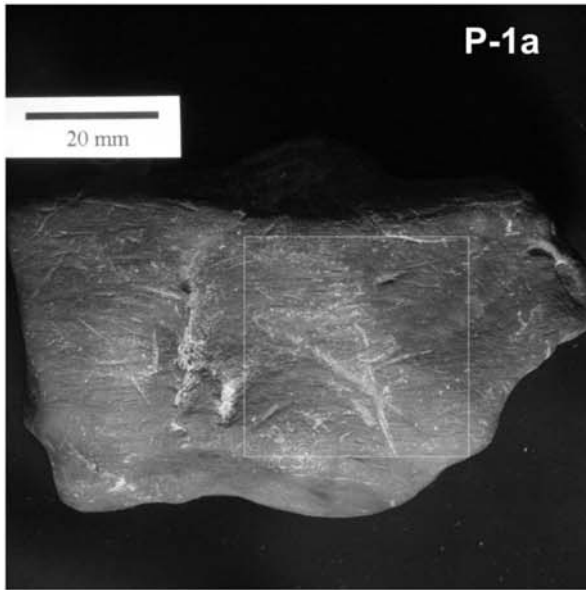
The generation of striae is influenced by the lithology of the clast. Image P-4 shows a clast with a well-developed facet containing a contact between fine-grained dolerite (darker portion) and coarse-grained granite (lighter portion). Striae are clearly visible on the dolerite but not on the granite. Striae that are visible on coarse-grained lithologies are usually wide ( $> 2$  mm) and on larger clasts. Image P-5 shows a glacial facet on a granite clast, but the striae are poorly inscribed and only the largest striae are individually distinguishable.

Overall, individual striae are generally long and narrow with clear with regular channel shapes and appear similar to warm-based glacial striae although the relationship between striae size and clast size is not as obvious as on warm-based glacial clasts.

## **Striae orientation**

Striae orientation is closely related to the long-axis of the clast. Most striae are predominantly oriented parallel to the long-axis of elongate clasts although some deviate up to 90° from the long-axis (P-1a, P-3, P-6, P-9a, P-9b) and occasionally these striae cross-cut. These characteristics suggest that most striae are inscribed while the clast is aligned with the ice flow but occasional rotation occurs.

There are exceptions to this generalisation and a few moderately elongate clasts show multiple orientations that are not preferentially aligned with the clast long-axis (P-7). Furthermore, Image P-8 shows an almost equidimensional clast that has mostly parallel striae indicating the clast has not rotated during the striation process (P-8).



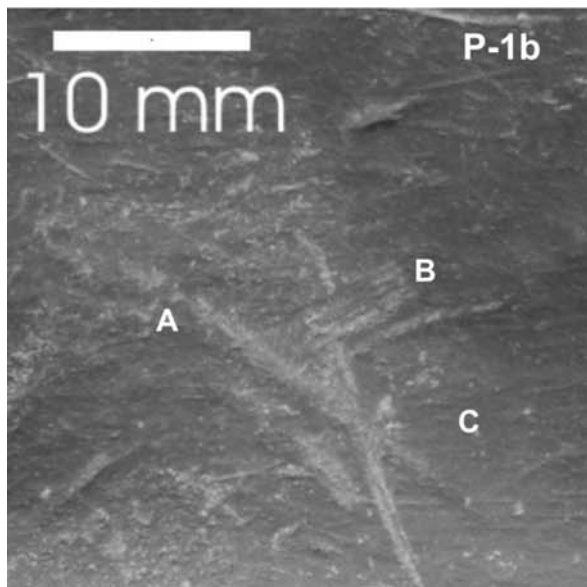
### ***Large and small striae***

Image P-1a shows a faceted mudstone clast from Cuff Cape. The striae are oriented predominantly parallel to the long-axis of the clast, but a few deviate up to 70° degrees from the long-axis.

The clast shows a background of "microstriae" accompanied by several larger individual striae.

The inset square is enlarged in Image P-1b.

Location: Cuff Cape, Antarctica  
162°30'00"E 76°59'00"S



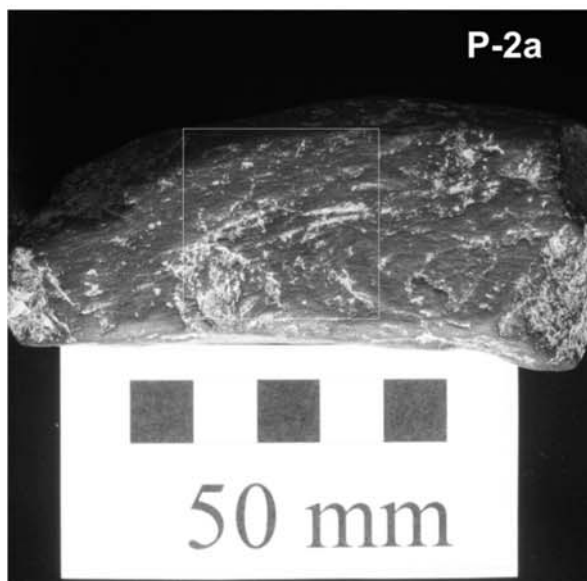
### ***Closeup of large and small striae***

This image shows a close up view of the clast in Image P-1a.

Several individual striae are oriented oblique to the long-axis of the clast (A).

One is a compound striation consisting of several smaller parallel striae (B).

(A) and (B) are set against a "background" of microstriae that are generally parallel to the clast long-axis of the clast (C).



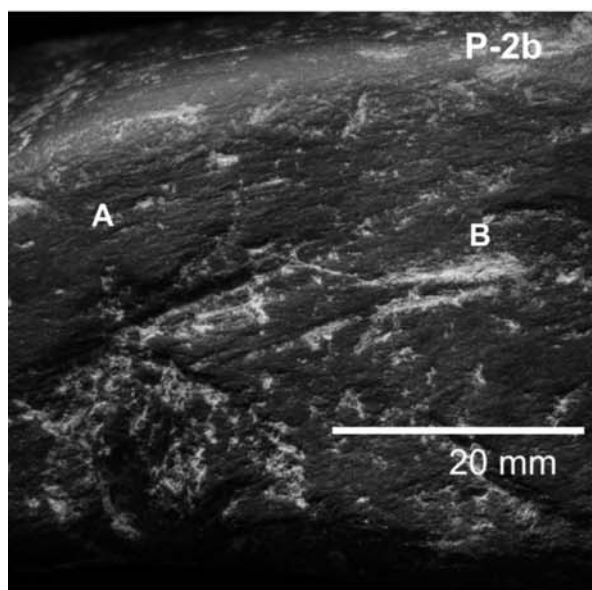
### ***Long-axis parallel striae***

Image P-2a shows a striated mudstone clast from the Mackay Glacier. It has four facets that show striae. The striae are predominantly parallel to the long-axis.

A background of microstriae covers the surface of the clast. A few larger striae are also visible on the surface.

The inset square is enlarged in the Image P-2b.

Location: Mackay Glacier, Antarctica  
162°30'00"E 76°57'00"S



### ***Mudstone clast closeup***

Image P-2b shows a close up of the mudstone clast in Image P-2a.

A "background" of microstriae covering almost the entire surface is visible at this scale (A).

Larger striae up to 4 mm wide are superimposed on this surface (B).

Location: Mackay Glacier, Antarctica  
162°30'00"E 76°57'00"S

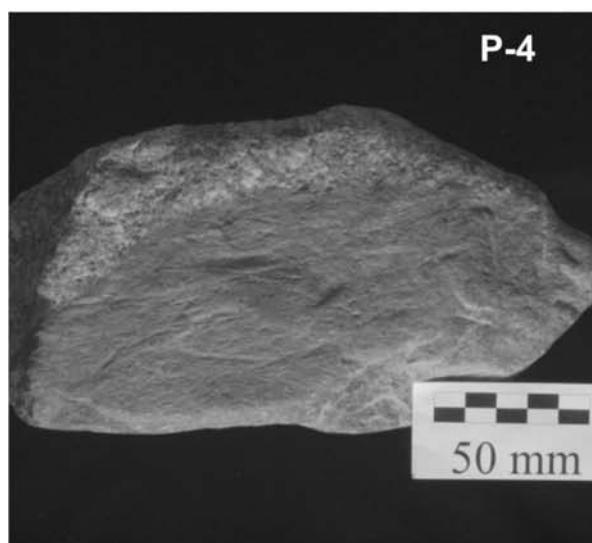


### ***Sparse large striae***

The clast in Image P-3 from the Mackay Glacier shows large individual striae ( up to 27 mm long and 3 mm wide) oriented parallel to the long-axis

Unlike most other clasts, this one does not display the characteristic "background" of microstriae.

Location: Mackay Glacier, Antarctica  
162°30'00"E 76°57'00"S

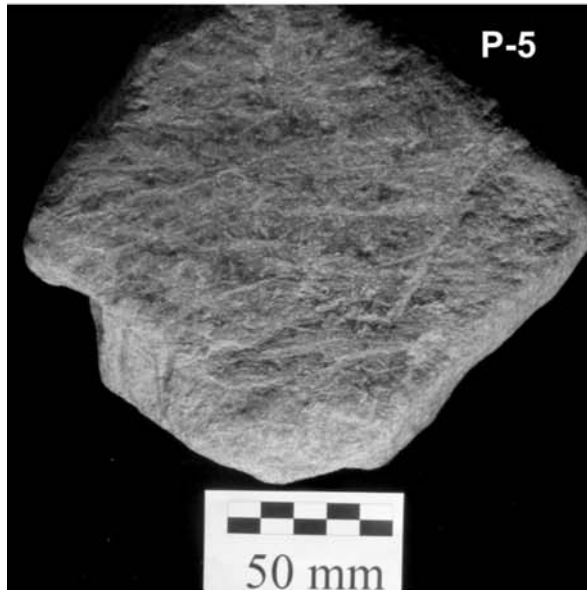


### ***Cuff Cape dolerite/granite contact***

Image P-4 shows a glacially faceted clast that contains a contact between dolerite (darker grey area in lower part) and granite (lighter, speckled area).

Striae parallel to the long-axis of the clast are clearly visible on the dolerite portion but not on the granite, even though the surface has been abraded. This illustrates the important influence lithology has on striae generation.

Location: Cuff Cape, Antarctica  
162°30'00"E 76°59'00"S

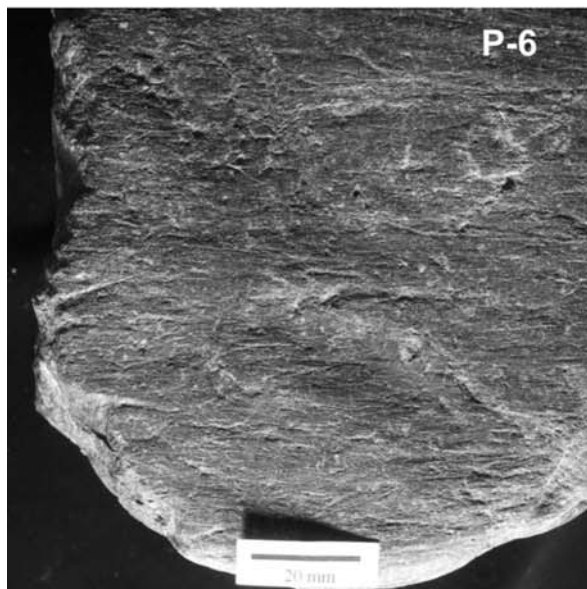


### ***Indistinct striae on glacial facet***

Image P-5 shows a medium grained granite clast from the Mackay Glacier. The clast shows a clear glacial facet, with abundant but poorly inscribed parallel striae.

Background microstriae are not present and only the larger individual striae are visible, again indicating that lithology influences striae generation

Location: Mackay Glacier, Antarctica  
162°30'00"E 76°57'00"S

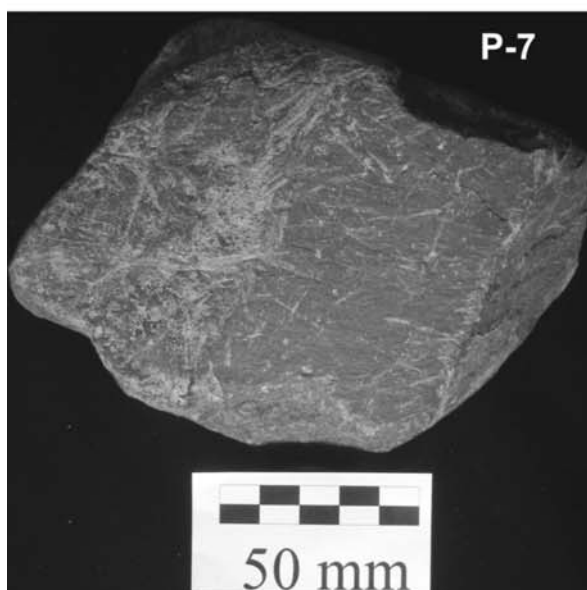


### ***Long-axis parallel striae***

Image P-6 shows a well developed facet on an elongate dolerite clast. The surface is intensely striated with striae oriented almost exclusively parallel to the long-axis of the clast.

These striae are set against a background of microstriae.

Location: Cuff Cape, Antarctica  
162°30'00"E 76°59'00"S

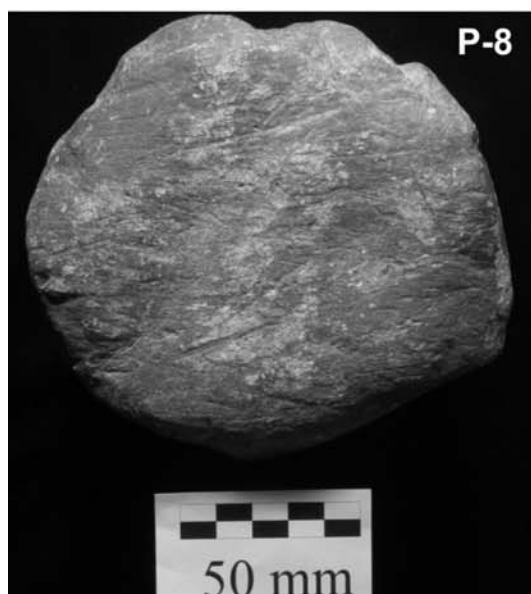


### ***Short striae with no preferred orientation***

Image P-7 shows a clear glacial facet on a dolerite clast, with striae that are mostly short and not oriented parallel to the long-axis.

This indicates that clast shape does not necessarily influence the orientation of the striae.

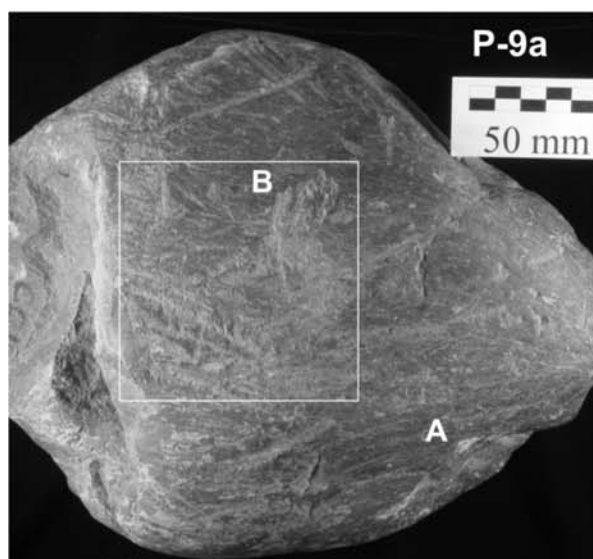
Location: Cuff Cape, Antarctica  
162°30'00"E 76°59'00"S



### ***Parallel striae on equidimensional clast***

The clast in image P-8 does not have a distinct long-axis. Nevertheless, the striae are oriented predominantly parallel to the long-axis, suggesting that clast form does not necessarily influence striae orientation.

Location: Cuff Cape, Antarctica  
162°30'00"E 76°59'00"S



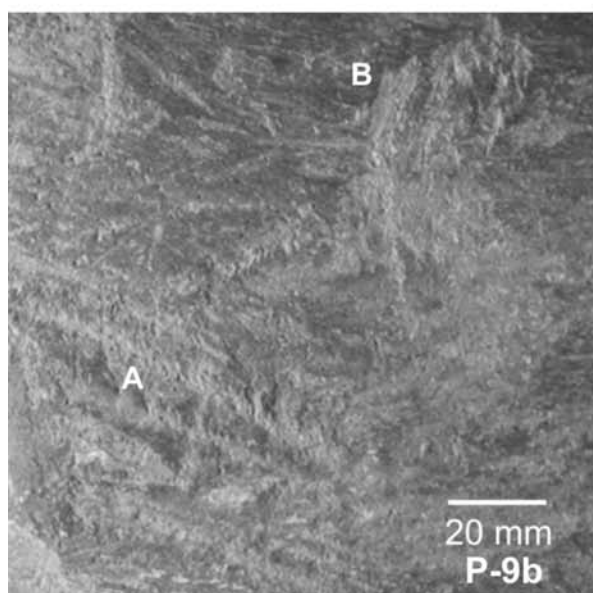
### ***Large compound striae***

Image P-9a shows a large dolerite cobble showing a bullet nose (right) and a plucked lee end (left). It displays a densely striated surface, with striae predominantly parallel to long-axis, although some diverge from the bullet nose (A).

Large compound striae (up to 20 mm wide and 60 mm long) occur with finer parallel striae on the surface (B).

A "background" of microstriae is also visible. Inset square is enlarged in image P-9b.

Location: Cuff Cape, Antarctica  
162°30'00"E 76°59'00"S



### ***Closeup of large compound striae***

Image P-9b shows a close up of the clast surface. The large compound striae have irregular channel shapes and uneven channel surfaces with several striae making up the overall abrasion mark (A).

The upper righthand part of the image shows a broad compound striation that is curved and almost perpendicular to the long-axis, suggesting clast rotation during the abrasion process (B).

Location: Cuff Cape, Antarctica  
162°30'00"E 76°59'00"S

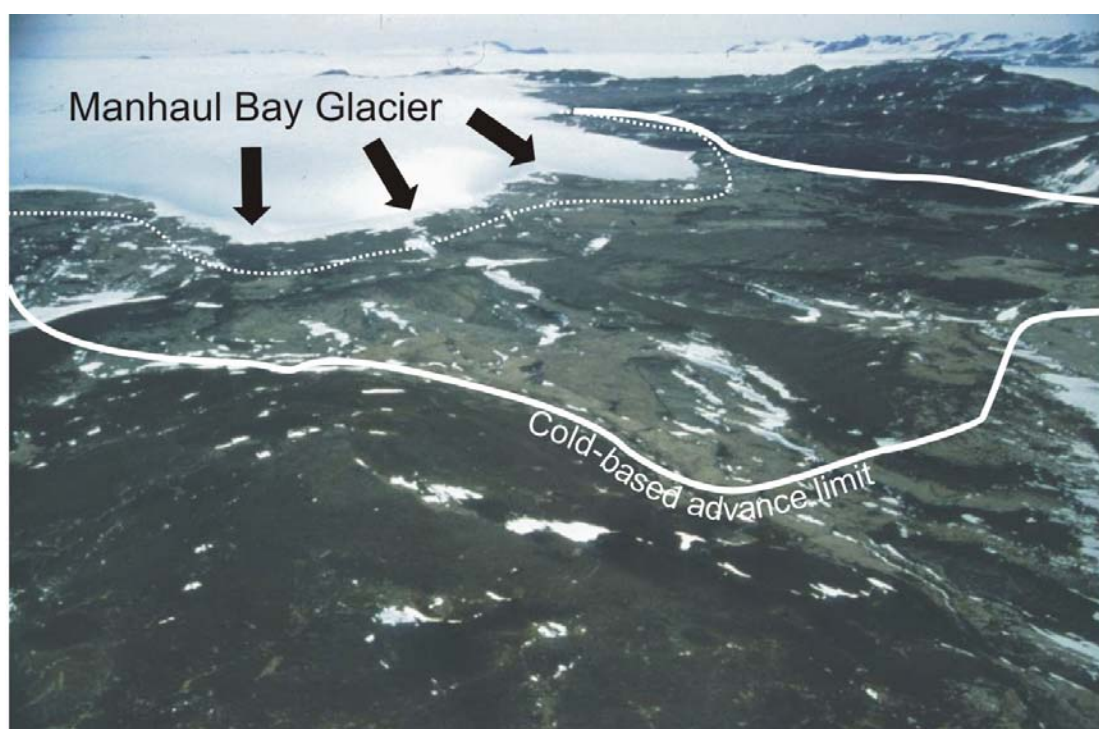
## PART THREE:

### COLD-BASED LINEAR ABRASION FEATURES - ALLAN HILLS, ANTARCTICA

#### Introduction

This section documents newly discovered abrasion features created beneath a cold-based glacier in Antarctica. This discovery is significant as it is commonly assumed that sliding and erosion cannot occur beneath cold-based ice. Further details are reported in Atkins and Barrett (2000) and Atkins et al. (2002).

The Allan Hills ( $159^{\circ}40'E$ ,  $76^{\circ}42'S$ ) form a wishbone-shaped nunatak situated high (1600-2100 m above sea level) in the Transantarctic Mountains in south Victoria Land at the edge of the present East Antarctic Ice Sheet (EAIS) (Figure 2). The bedrock geology is described in Grapes et al. (1974). The Manhaul Bay Glacier (unofficial name) occupies the centre of the wishbone and broad U-shaped valley in the eastern part of Allan Hills is partially occupied by a tongue of the Odell Glacier. Both glaciers are calculated to be entirely cold-based (Atkins 20032). Retreat of these glaciers, presumably from Last Glacial Maximum advance, has exposed a variety of abrasional features on rock platforms and ridges (Figure 7). These abrasion features are considered to have formed under cold-based conditions are most common close to the present ice margin but occur over a wide area of central Allan Hills.



**Figure 7** Aerial photograph of central Allan Hills looking north east, showing the Manhaul Bay Glacier and the maximum advance limit (solid line) and area around the ice margin where abrasion features are most common (dotted line). Black arrows indicate the past advance direction.

## Characteristics of cold-based glacial erosion features

The abrasion features occur mainly on Beacon Supergroup sandstone surfaces and Ferrar Dolerite clasts close to the margins of the Manhaul Bay and Odell Glaciers, but are also found on dolerite clasts embedded in patches of Cenozoic Sirius diamictite. The marks are variable in shape, size and grouping and range from broad scrapes to narrow grooves and gouges, unlike the consistent, uniform sets of parallel striae and grooves common on bedrock abraded by warm-based sliding ice. The linear abrasion features at Allan Hills can be broadly divided into four types.

### *Type 1: Broad Scrapes (Bedrock)*

Broad unweathered scrapes range up to 500 mm width, 40 mm depth, 1200 mm length, but defined as (width >75 mm, depth > 15 mm, length >340 mm). They typically consist of many smaller striae or grooves centimetres or millimetres in width. Some examples show progressive increase in depth and width with an abrupt terminus (CB-1a, CB-1b). Often the abrasion mark has crushed sandstone remnants of the abrading tool smeared onto the surface, particularly at the deepest terminal wall (CB-1b). Occasionally, small centimetre-scale “levées” occur along the sides of the abrasion mark (CB-2).

### *Type 2: Individual striae and grooves (Bedrock)*

Type 2 abrasions are variably shaped, unweathered individual linear abrasions (scrapes, striae, and grooves). They are defined as: length unlimited, width < 75 mm, depth <15 mm). Where several marks occur in one location, they are generally sub-parallel (CB-3). Some show a progressive increase in depth and width (nail-head) whereas others have more symmetrical, tapered ends. Occasionally, individual marks occur “in line” to form a trail of marks up to 2 m in length (CB-4, CB-5). Some marks have crushed sandstone remnants of the abrading tool smeared onto the surface and are sometimes bordered by small centimetre-scale “levées.”

### *Type 3: Scraped boulders and cobbles*

Variably shaped, unweathered scrapes up to several centimetres wide (and related striae) occur on the stoss side of some weathered dolerite boulders and cobbles embedded in Sirius diamictite. Abrasion has removed the characteristic dark brown desert varnish from the surfaces of the clasts leaving distinct marks (CB-6, CB-7).

The density of striae is very low, with typically only one or two striae occurring on one clast. The striae are not related to specific clast shapes or roundness and occur on both flat and curved surfaces (CB-6, CB-8). The striae only occur on the northern side of clasts as this is the side of the clast facing the Manhaul Bay Glacier and is therefore interpreted as the stoss side. Some abrasions preferentially occur on raised portions of the clast such as ridges between faces and appear to influence the orientation and curvature of the abrasion (CB-10).

The size of the abrasions varies markedly from individual striae on a single surface (CB-8) to larger compound scrapes made up of many smaller striae (CB-9a, CB-9b). This abrasion mark was produced by one abrading particle but the abrasions appear “intermittent” with several individual abrasions “in-line” as the striator has made contact with the raised parts of the surface.

*Type 4: Ridge-and-Groove lineations (Bedrock)*

Localised bedrock surfaces display abraded patches with many parallel fine lineations (millimetre scale width and depth), described here as ridge-and-groove lineations. These abraded patches occur within thin carbonaceous layers beneath brecciated sandstone debris (CB-11) and indicate north to south glacier movement. The surfaces are typically dark and have a platy appearance and sheen similar to slickensides (CB-12). Some examples have part of the overlying layer still attached to the abraded surface (CB-13).

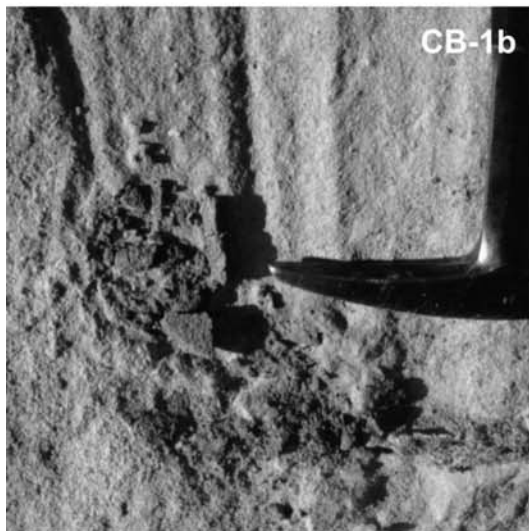


### ***Type 1: Broad scrapes***

Image CB-1a shows a broad unweathered scrape. This range up to 500 mm width, 40 mm depth, 1200 mm length and typically consist of many smaller striae or grooves centimetres or millimetres in width.

This example shows progressive increase in depth and width, with an abrupt terminus.

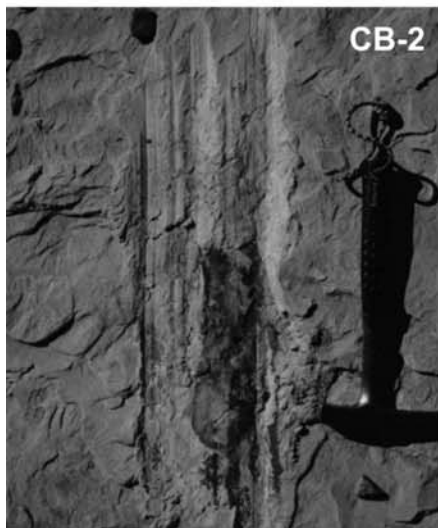
Location: Allan Hills, Antarctica,  
159°42'20"E 76°41'51"S



### ***Broad scrape-closeup***

Image CB-1b shows a closeup of the end of the broad scrape in Image CB-1a. The crushed remnants of the abrading tool are visible at the terminal wall, indicating the abrading fragment disintegrated.

Location: Allan Hills, Antarctica,  
159°42'20"E 76°41'51"S



### ***Type 1: Broad scrape***

Image CB-2 shows an example of a type 1 abrasion that has a symmetrical shape. (i.e. does not become progressively deeper and wider. Here, the abrading tool has contacted the bedrock surface, and then lifted off again.

Occasionally, small cm-scale "levees" occur along the sides of the abrasion mark.

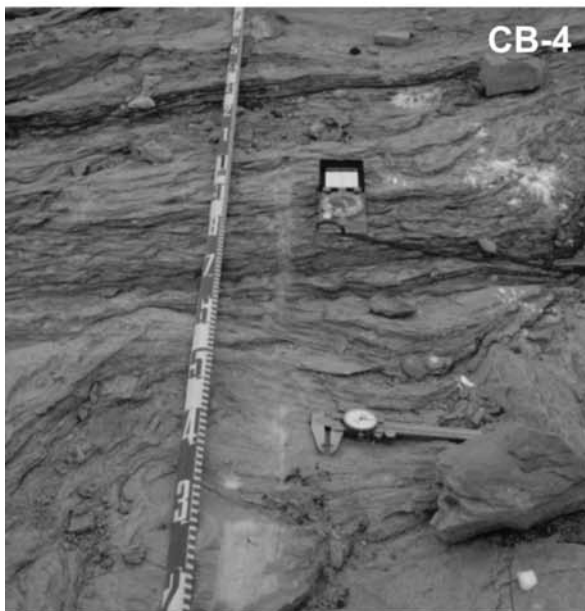
Location: Allan Hills, Antarctica,  
159°43'50"E 76°41'43"S



### ***Type 2: Individual striae and grooves***

Variably shaped, unweathered, individual linear abrasions (scrapes, striae, and grooves) make up a wide variety of discrete abrasion marks (typically cm in width and depth and decimetres long). Often, they are sub-parallel (Image CB-3). Some show a progressive increase in depth and width whereas others have more symmetrical, tapered ends. Some marks have crushed sandstone remnants of the abrading tool smeared onto the surface.

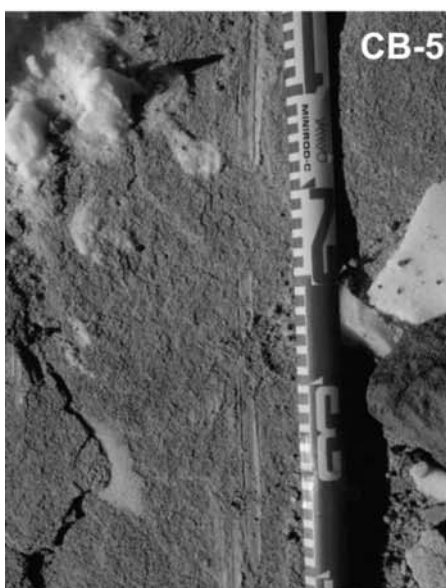
Location: Allan Hills, Antarctica,  
159°40'00"E 76°41'54"S



### ***Individual striae and grooves***

Image CB-4 shows an example of a type 2 abrasion where several abrasions occur "in line" over 2 m, indicating the abrading tool made contact several times as it progressed across the surface.

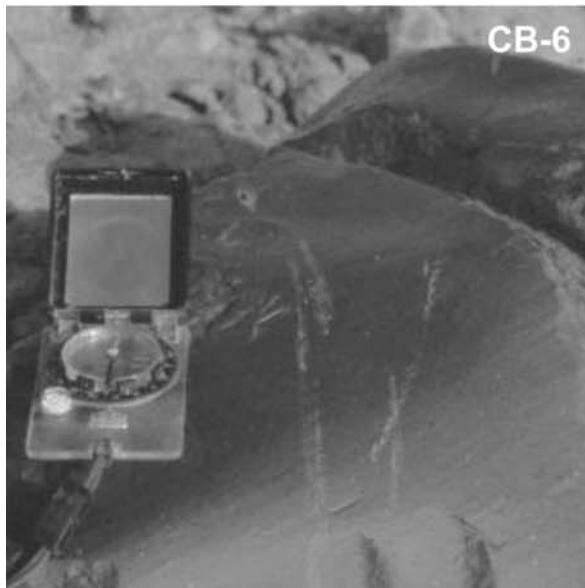
Location: Allan Hills, Antarctica,  
159°38'30"E 76°41'25"S



### ***Individual striae and grooves***

Image CB-5 shows a closeup of a typical type 2 abrasion. Width and depth are variable along the intermittent but distinct abrasion.

Location: Allan Hills, Antarctica,  
159°45'30"E 76°42'58"S



### ***Type 3: Scraped boulders and cobbles***

Type 3 abrasion marks are variably shaped, unweathered scrapes up to several cm wide (and related striae) that occur on the stoss side of some weathered dolerite clasts.

The characteristic dark brown desert varnish has been cut through leaving a clear abrasion marks (CB-6).

Some boulders have been overturned, exposing the non-wind polished surface underneath.

Location: Allan Hills, Antarctica,  
159°38'00"E 76°41'15"S



### ***Scraped boulders and cobbles***

Image CB-7 shows scraped clasts on a Beacon bedrock surface. These clasts have fresh abrasion marks on the stoss sides and often concentrated along prominent ridges on the clasts.

Location: Allan Hills, Antarctica,  
159°38'00"E 76°41'15"S

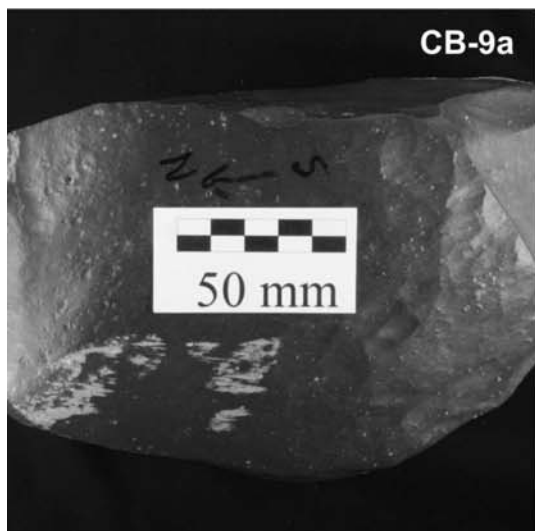


### ***Scraped boulders and cobbles***

Image CB-8 shows a type 3 abrasion on a desert varnished dolerite clast. The abrasion occurs on a wind sculpted facet and has cut through the brown weathered surface leaving a distinct abrasion mark.

Ice flow was from left to right (north to south).

Location: Allan Hills, Antarctica,  
159°40'40"E 76°42'25"S

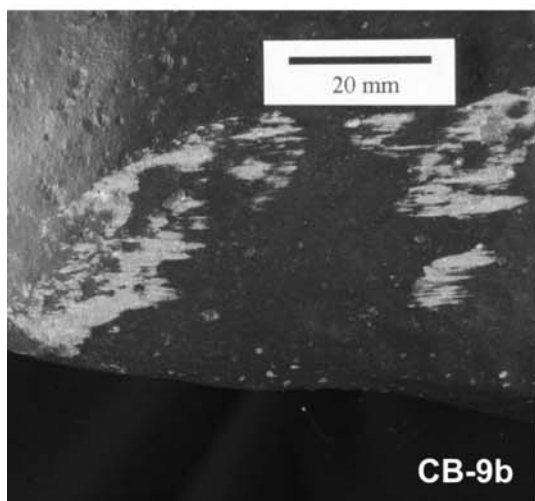


### *Type 3: Scraped boulders and cobbles*

Image CB-9a shows another type 3 abrasion on a desert varnished dolerite cobble. The abrasion begins on the stoss side and ends on the highest point of the broad top surface where the abrading tool has lifted off.

Abrasion has cut through the brown weathered surface leaving a distinct mark. Ice flow was from left to right (north to south).

Location: Allan Hills, Antarctica,  
159°37'00"E 76°42'12"S

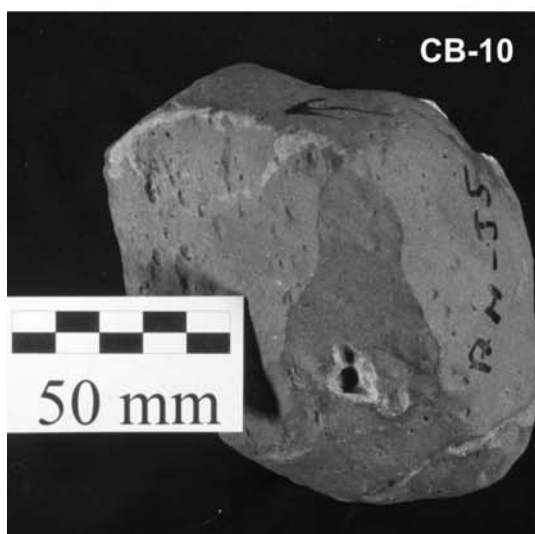


### *Scraped boulders and cobbles close up*

Image CB-9b shows closeup of the type 3 abrasion in Image CB-9a.

It consists of many linear abrasions created by the overriding tool. The tool is likely to have been another dolerite clast as all other local lithologies are softer than the dolerite.

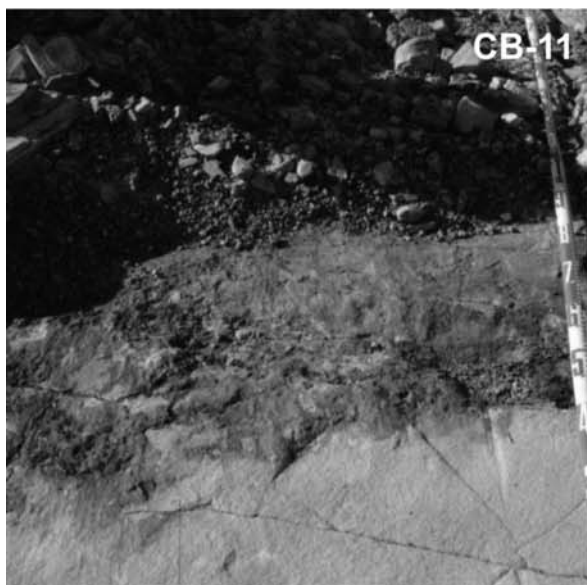
Location: Allan Hills, Antarctica,  
159°37'00"E 76°42'12"S



### *Scraped boulders and cobbles*

Image CB-10 shows an example of type 3 abrasion where the stoss side of a prominent ridge on the clast has been abraded. The ridge in this case is oriented approximately north-south. The abrading rock has contacted the stoss side of this clast and has been dragged up the stoss side and lifted off at the highest point. Ice flow was from left to right (north to south).

Location: Allan Hills, Antarctica,  
159°42'10"E 76°42'38"S



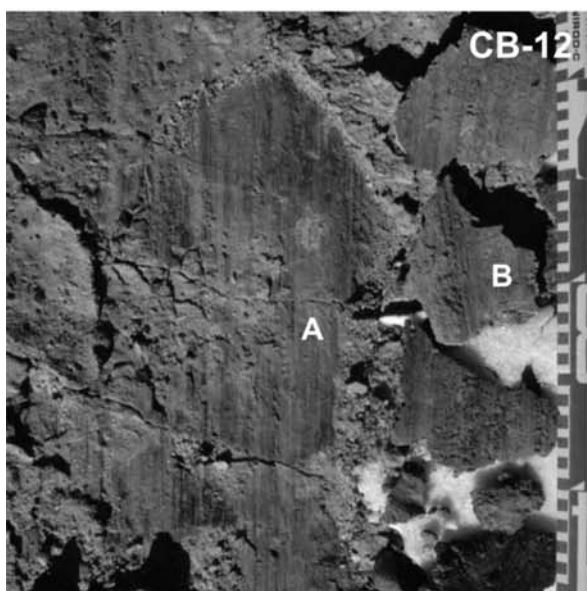
#### ***Type 4: Ridge-and-groove lineations***

Image CB-11 displays a carbonaceous surface beneath brecciated sandstone debris.

The surface has abraded patches consisting of many parallel lineations (ridge-and-groove lineations).

These are produced by slip on the carbonaceous layers due to glaciotectionic ice loading.

Location: Allan Hills, Antarctica,  
159°42'20"E 76°41'53"S



#### ***Ridge-and-groove lineations***

Image CB-12 shows a closeup of a slickensided surface showing mm scale ridges and grooves that are produced on the slip plane (A).

On the right is the overlying layer that has been removed from the abraded surface (B).

The surfaces sheen similar to slickensides.

Location: Allan Hills, Antarctica,  
159°42'20"E 76°41'53"S



#### ***Ridge-and-groove lineations***

Image CB-13 shows another closeup of a ridge-and-groove surface that has been partially weathered. In the upper centre of the image is part of the overlying layer still attached onto the abraded surface.

Location: Allan Hills, Antarctica,  
159°42'20"E 76°41'53"S

## **PART FOUR:**

### **MASS MOVEMENT STRIAE - MURIMOTU FORMATION , MT RUAPEHU AND MURCHISON VALLEY, NEW ZEALAND**

#### **Introduction**

This section documents striae produced by gravity-driven movements of rock debris by examining two mass-movement deposits of very different character. The first example is a debris-avalanche deposit of Holocene age on the lower slopes of Mt. Ruapehu in the North Island of New Zealand, and the second is a modern rock-fall from the Murchison Valley in the South Island of New Zealand (Figure 1).

#### **MURIMOTU FORMATION, (DEBRIS-AVALANCHE), MT RUAPEHU, NEW ZEALAND**

Mt Ruapehu (2797 m) is an active andesitic stratovolcano in the southern part of the Taupo Volcanic Zone, New Zealand, with a distinctive area of mounded topography on the lower northwestern slopes. This is part of the Murimotu Formation, which has been identified as a Holocene debris-avalanche deposit formed by a large sector collapse of the volcano flank (Palmer and Neall, 1989). A roadside exposure of one debris-avalanche mound (175°30'30"E 39°10'10"S) shows the deposit consists of a very poorly sorted diamicton containing andesite and andesite/dacite clasts, some of which are striated (Figure 8).



**Figure 8** Exposure of poorly sorted debris-avalanche mound of the Murimotu Formation, Mt Ruapehu on State Highway 48.

## **Characteristics of debris-avalanche striae**

Striae occur on 10 % of the clasts from the Murimotu Formation. They occur on both the andesite and andesite/dacite, but only on very angular clasts. The striae predominantly occur on weathered fracture (often flat) surfaces (e.g. DA-1), but occasionally on curved surfaces (DA-5).

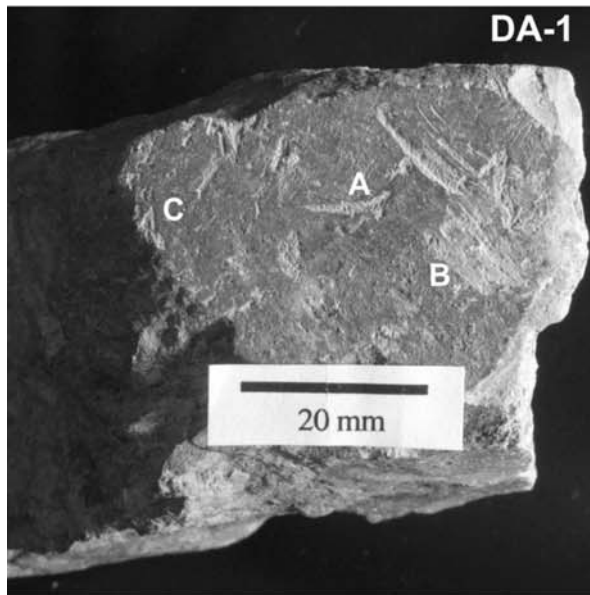
Striae density is variable but generally lower than on glacially striated clasts. Rare examples show a high density of striae but most clasts show a low concentration of individual striae on a given face and a patchy distribution of background microstriae (DA-1, DA-6a, DA-6b). Broad compound striae (up to 10 mm wide) made up of several smaller striae are common (DA-1, DA-2b, DA-5). Curved striae occur on some clasts (DA-1) suggesting some clast rotation during the striating process.

Striae length and width vary greatly and individual striations often show variation in width along the length. Overall, striae are less regular in shape and striae length is generally shorter than striae on warm-based and polythermal glacial clasts. Striae width is greater for debris-avalanche clasts reflecting the abundance of compound striae.

## **Striae orientation**

Clasts typically show multiple striae orientations on single surfaces (DA-1, DA-5, DA-6a), regardless of how elongate the clast is. This includes both individual striae and background microstriae. However, some clasts show weak preferred orientation of individual striae, occasionally oblique to the long-axis (DA-2a, DA-2b) although one clast displays a set of parallel striae on an individual face (DA-3). Striae are not preferentially aligned with the long-axis of the clasts and sometimes occur on minor clast faces (clast ends) (DA-1). This characteristic is only seen on debris-avalanche and tectonically striated clasts.

Another unusual characteristic is fine sub-mm width striae that appear to radiate from the centre of the clast (DA-4a and DA-4b). The surface has several larger striae superimposed on the finer striae. The process producing these splayed striae is not clear.



### *Individual randomly oriented striae*

Image DA-1 shows a flat, weathered surface on the end of an andesite clast. The striae have multiple orientations and consist of:

Slightly curved striae up to 12 mm long and 2.5 mm wide (A).

Compound striae (up to 12 mm long, 6 mm wide) consisting of many smaller striae (B).

"Background" microstriae (barely visible) (<0.2 mm wide and <2 mm long) (C).

Striae on the ends of clasts only occurs in debris-avalanche and tectonic environments. Location: Murimotu Fm, Mt Ruapehu, New Zealand, 175°30'30"E 39°10'10"S



### *Sets of sub-parallel striae*

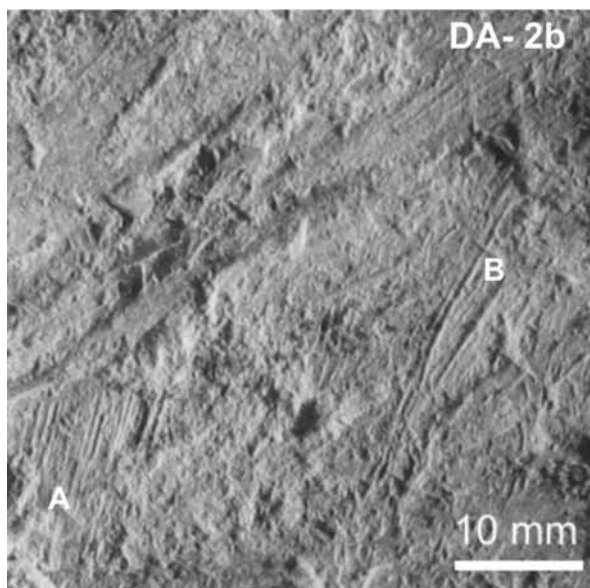
In contrast to Image DA-1, the clast in Image DA-2a shows a large, uneven face of an andesite/dacite clast with frequent overlapping striae. The striae comprise:

Broad compound striae oblique to the long axis (A).

Individual striae with multiple orientations are also present (B).

Inset square enlarged in Image DA-2b.

Location: Murimotu Fm, Mt Ruapehu, New Zealand, 175°30'30"E 39°10'10"S



### *Closeup of sub-parallel striae*

A closeup of the inset area in Image DA-2a shows:

Fine parallel striae (< 0.5 mm wide) forming compound striation 10 mm wide (A).

Several individual striae up to 20 mm long and up to 1 mm wide (B).

Location: Murimotu Fm, Mt Ruapehu, New Zealand, 175°30'30"E 39°10'10"S

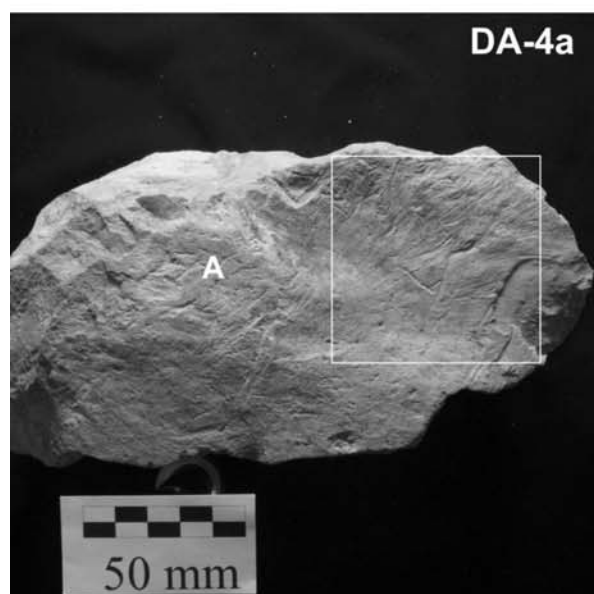


### ***Parallel striae on an equidimensional clast***

Image DA-3 shows a weathered flat surface of an equidimensional andesite clast.

The striae are up to 25 mm long and have variable widths along a single striation (maximum width is 2 mm). These striae are parallel to each other, but occur on an face with no distinct long axis.

Location: Murimotu Fm, Mt Ruapehu  
175°30'30"E 39°10'10"S



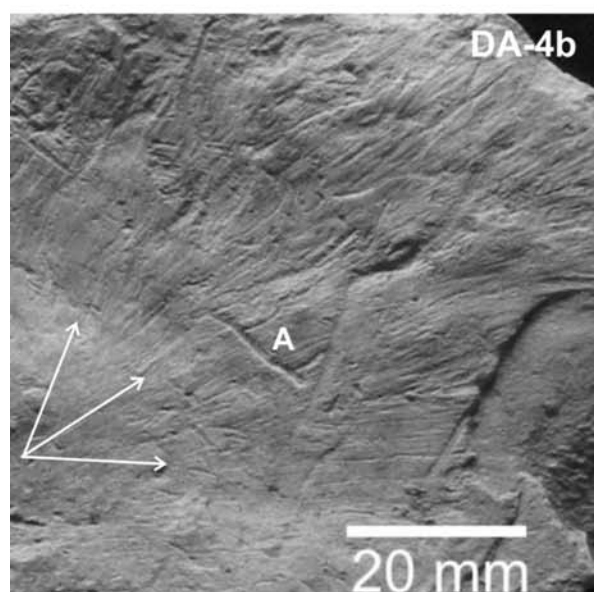
### ***Individual and splayed striae***

Image DA-4a shows a large undulating surface of an andesite/dacite clast that displays:

Many individual striae with no preferred orientation and also compound striae (A).

Fine striae that splay out toward the clast margins. This area is enlarged in Image DA-4b.

Location: Murimotu Fm, Mt Ruapehu, New Zealand, 175°30'30"E 39°10'10"S

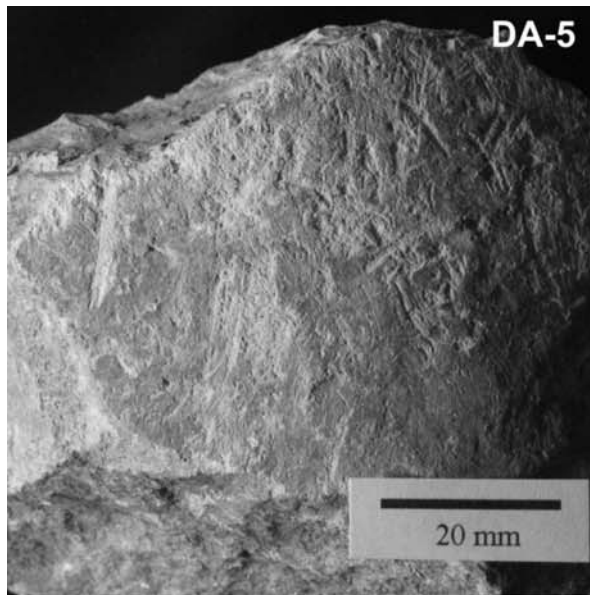


### ***Closeup of splayed striae***

This image shows the detail of the fine radiating striae (< 0.05 mm wide and up to 10 mm long). Arrows indicate the spread of striae orientations. The reason for this splayed pattern is not clear.

A larger striation cuts across the splayed striae (A).

Location: Murimotu Fm, Mt Ruapehu, New Zealand, 175°30'30"E 39°10'10"S



### ***Striae on curved surfaces***

Image DA-5 shows a weathered andesite clast with individual striae on a curved surface. These show wide variation in shape with no preferred orientation.

This illustrates that striae do not form exclusively on flat surfaces.

Location: Murimotu Fm, Mt Ruapehu  
175°30'30"E 39°10'10"S

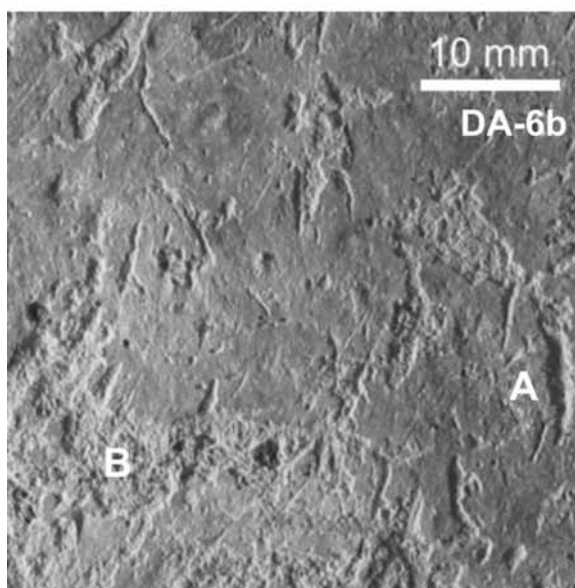


### ***Small striae and variable orientation***

Image DA-6a shows an andesite/dacite clast with a flat weathered surface. This surface contains abundant small striae with a wide variation in striae orientation and only a weak preferred orientation, oblique to the clast long axis.

Inset square is enlarged in Image DA-6b.

Location: Murimotu Fm, Mt Ruapehu  
175°30'30"E 39°10'10"S



### ***Closeup of variably oriented striae***

Image DA-6b shows a closeup of the clast in Image DA-6a.

Individual striae are generally less than 5 mm long and 0.5 mm wide although one is 2.5 mm wide (A).

Occasionally, many striae overlap forming completely abraded patches (B).

Location: Murimotu Fm, Mt Ruapehu  
175°30'30"E 39°10'10"S

## MURCHISON VALLEY, (ROCK-FALL DEPOSIT), NEW ZEALAND

The Murchison Valley is situated in the Mt Cook region of the central South Island of New Zealand (Figure 1). The valley contains the Murchison Glacier and a braided gravel outwash system that extends downstream from the glacier terminus to the confluence with the Tasman Valley. The Murchison valley is surrounded by steep mountain topography consisting of Mesozoic greywacke sandstone and argillite (Gair, 1967).

Extensive modern scree slopes are present on the eastern side of the Murchison Valley. The slopes are active and in some places reach the valley floor. The scree slopes comprise largely rock-fall debris and are composed of sandstone and argillite clasts. The deposits are very poorly sorted with clast sizes ranging from boulders to pebbles. The clasts are typically broken and angular, with many of the argillite clasts split along bedding planes. Striated clasts were collected from the base of the active surface scree slope (170°19'45"E, 43°36'30"S) (Figure 9).



**Figure 9** Rock-fall deposit on the eastern side of the Murchison Valley. Active scree slopes extend into the modern proglacial lake. Note the large range in clast size and angular shape.

## **Characteristics of rock-fall striae**

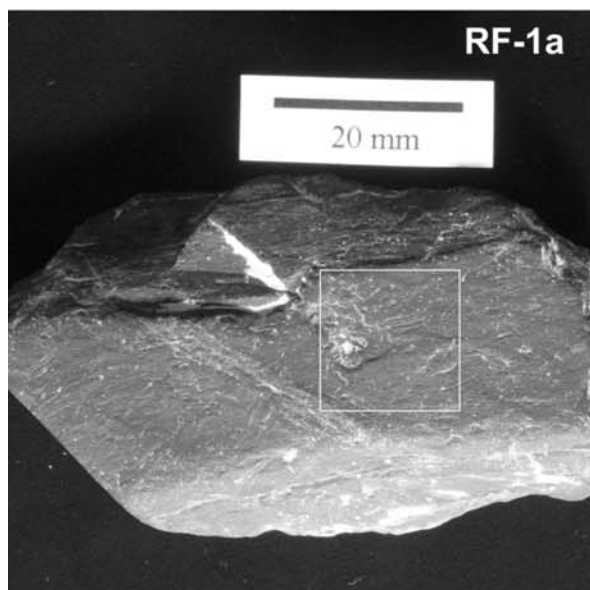
Striae occur on 26 % of clasts in the Murchison rock-fall deposit. Striae occur exclusively on argillite clasts in the very angular to sub-rounded classes. They generally occur on the flat fracture surfaces, which are common because the argillite fractures along pre-existing bedding planes.

The density of both individual and background microstriae varies greatly. Image RF-1a and RF-1b shows a high density of microstriae as well as small individual striae over most of the clast surface. Contrasting with this, Image RF-3a and RF-3b show only a patchy distribution of background microstriae and rare individual striae. Compound striae made up of several smaller striae occur on some clasts (RF-2, RF-4) and curved striae occur on some clasts

Striae length is generally shorter than on warm-based and polythermal glacial clasts and slightly narrower, except for the occasional compound striation. This in part probably reflects the small size of the rock-fall clasts. Striae size does not appear to be related to clast size.

## **Striae orientation**

Striae show a wide variation in orientation characteristics. Striae do not appear to be related to clast shape and many clasts show multiple orientations with no preferred alignment with the long-axis of the clast (RF-2). Others show weakly grouped sets of striae sub-parallel to the long-axis (RF-1a, RF-1b, RF-4) and one example displays individual parallel striae that are oriented at a high angle to long-axis of the clast (RF-3a, RF-3b).



***Small-scale striae, sub-parallel to the long-axis***

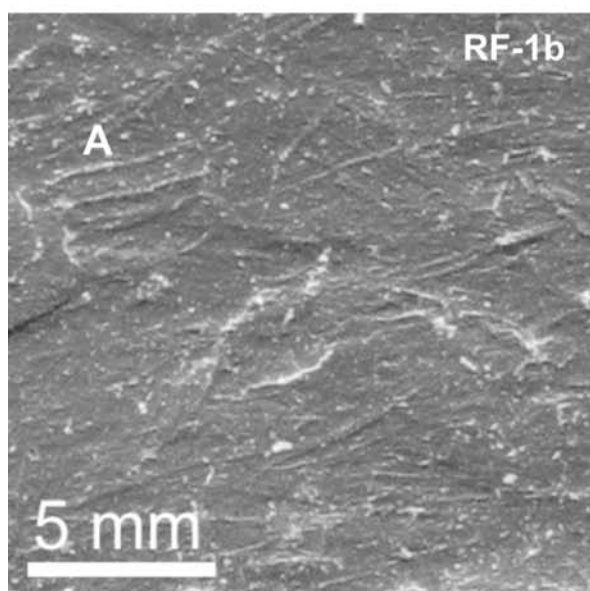
Image RF-1a shows rock-fall striae on an elongate argillite clast.

A high density of small individual striae occur predominantly aligned parallel to the long-axis of the clast.

A "background" of microstriae occur over most of the clast surface.

Inset square is enlarged in Image RF-1b.

Location: Murchison Valley, Mt Cook region, New Zealand,  
170°19'45"E 43°36'30"S



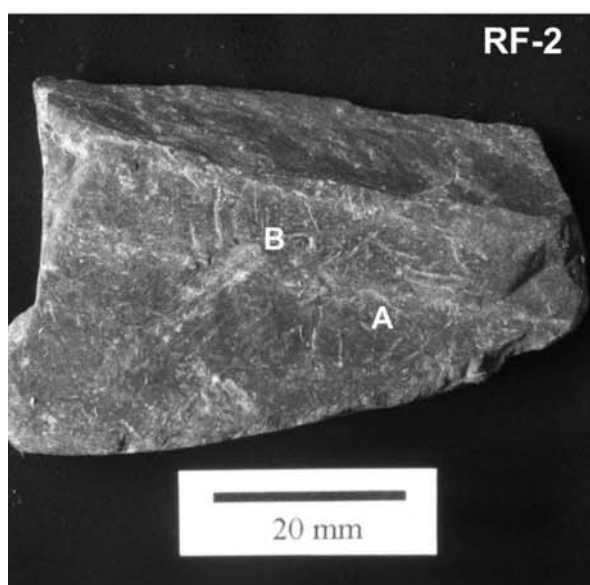
***Small-scale striae, sub-parallel to the long-axis***

Image RF-1b shows a closeup of the clast surface.

The high density of microstriae is visible with larger individual striae (up to 5 mm long) also present (A).

Most striae are sub parallel to the long-axis of the clast.

Location: Murchison Valley, Mt Cook region, New Zealand,  
170°19'45"E 43°36'30"S



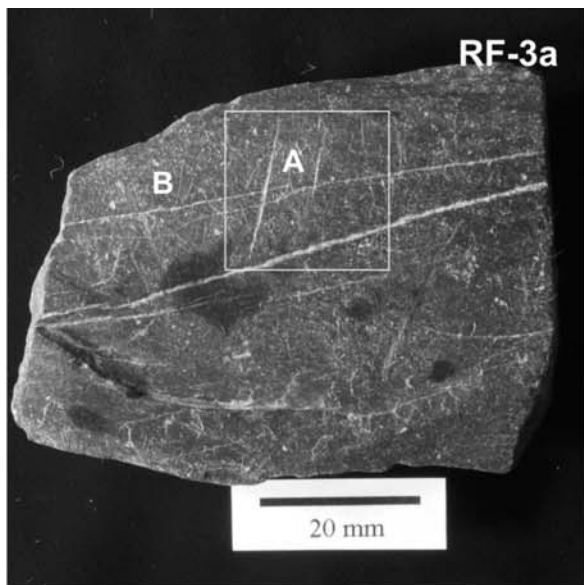
***Individual striae and compound striae***

The clast in image RF-2 is an angular argillite clast with a typical flat fracture face and sharp edges. Striae consist of:

Many small striae with no preferred orientation (A).

A large compound striation that is 12 mm long and 4 mm wide. This has smaller parallel striae on the surface (not visible at this scale) (B).

Location: Murchison Valley, Mt Cook region, New Zealand,  
170°19'45"E 43°36'30"S



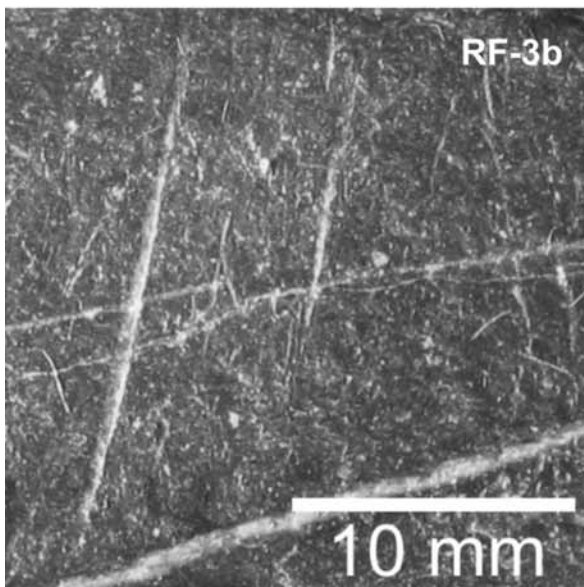
### *Parallel striae oblique to long-axis*

Image RF-3a shows several well-defined parallel striae that are not oriented parallel to the clast long-axis (A).

Parts of the clast show a patchy "background" of microstriae (B).

Inset square is enlarged in Image RF-3b.

Location: Murchison Valley, Mt Cook region, New Zealand,  
170°19'45"E 43°36'30"S

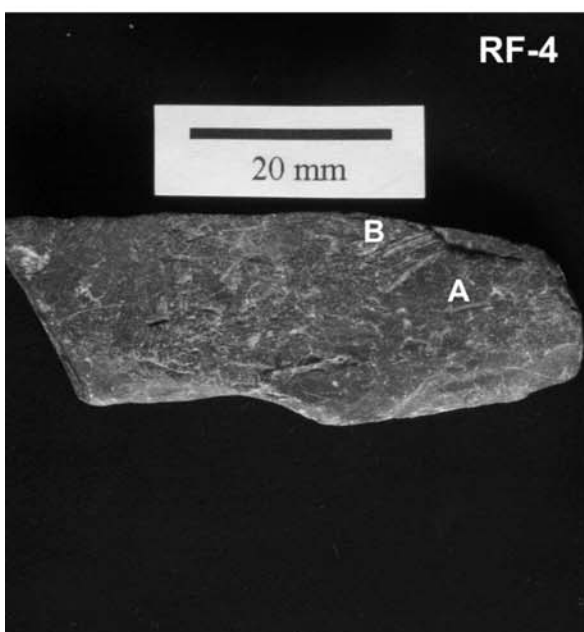


### *Parallel striae oblique to long-axis*

Image RF-3b shows a closeup view of the clast surface. Two well-defined parallel striae are visible, the largest is 18 mm long and 0.5 mm wide.

A "background" of microstriae with no preferred orientation is visible around the larger striae.

Location: Murchison Valley, Mt Cook region, New Zealand,  
170°19'45"E 43°36'30"S



### *Rare small striae*

The clast in Image RF-4 shows only a few small striae oriented oblique to the clast long-axis. These include:

Short (< 5 mm) individual striae (A).

A wider compound striation that has several smaller parallel striae (B).

Location: Murchison Valley, Mt Cook region, New Zealand, 1  
70°19'45"E 43°36'30"S

## **PART FIVE:**

### **TECTONIC STRIAE - NGAPOTIKI AND WELLINGTON FAULTS, NEW ZEALAND**

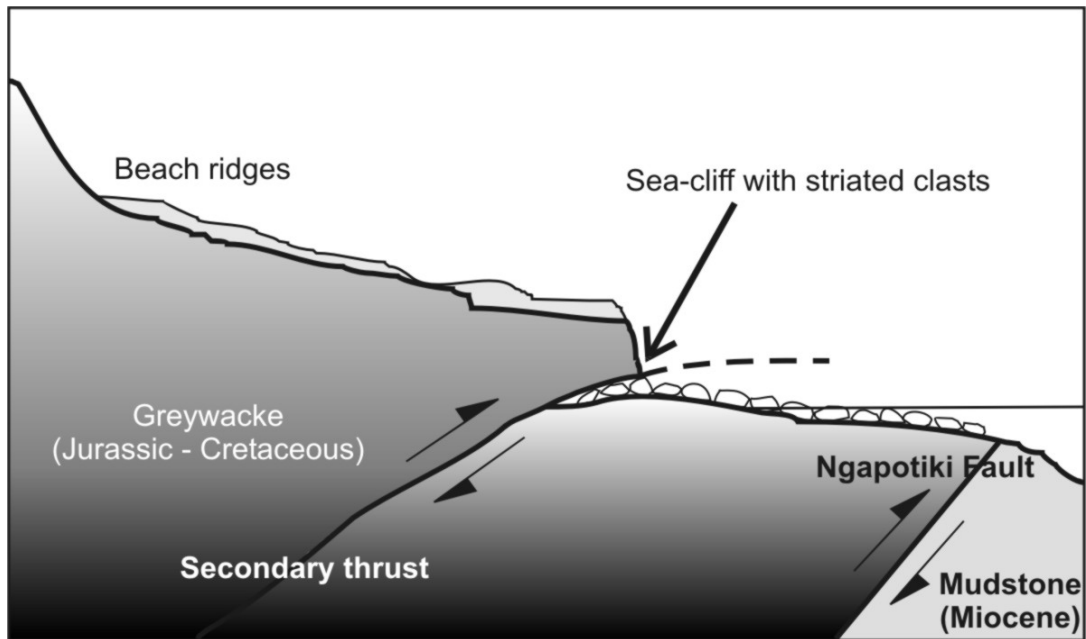
#### **Introduction**

This section documents striae on conglomerate clasts that have been incorporated into shear planes of two major active faults in the southern North Island, New Zealand (Figure 1). The first example is the Ngapotiki Fault, where Mesozoic greywacke bedrock is thrust over modern beach gravels and at the second example is the Wellington Fault where Mesozoic greywacke deforms Holocene fluvial conglomerate.

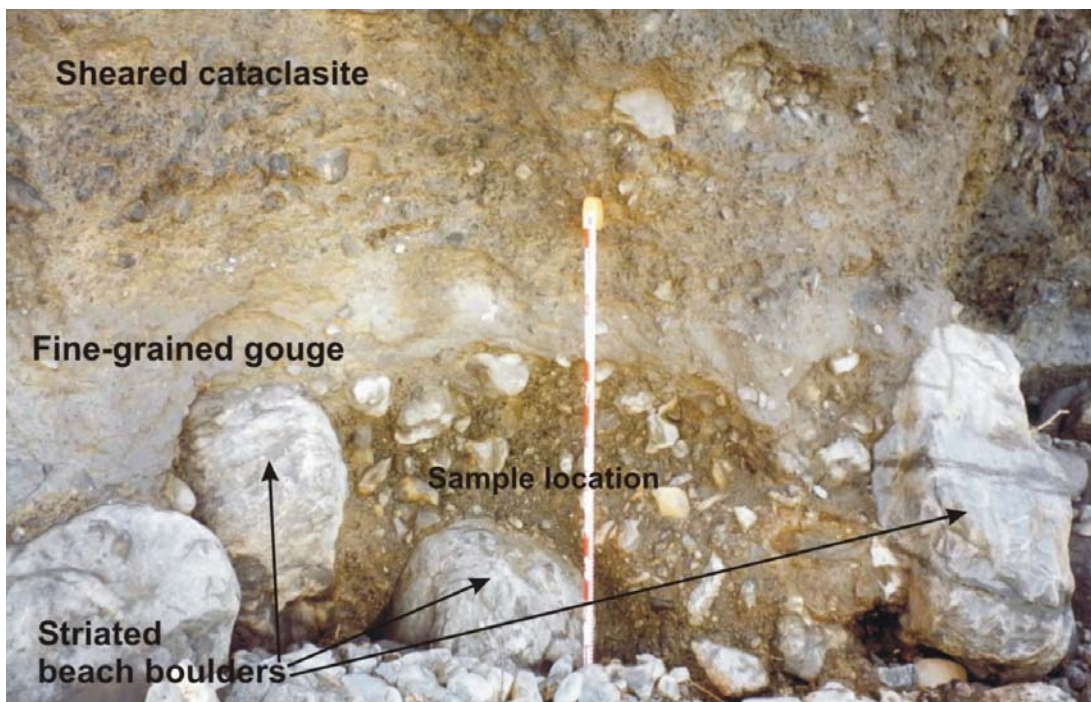
#### **NGAPOTIKI FAULT, WAIRARAPA, NEW ZEALAND**

The Ngapotiki Fault is located in the southeast Wairarapa region of the North Island. The fault is active and juxtaposes Late Jurassic-Early Cretaceous greywackes of the Aorangi Range with Late Miocene marine strata. The fault contact strikes approximately north-south and dips west at about 45° (Grapes et al., 1997). The inferred position of the Ngapotiki Fault contact between greywacke and Miocene mudstone lies seaward of the modern beach. However, a secondary low-angle pug-lined thrust plane has formed within a wide zone of sheared greywacke that forms the hanging wall of the Ngapotiki Fault and is exposed in the present sea-cliff (175°22'10"E, 41°35'05"S). This has created a situation where crushed greywacke is thrust over the modern beach (Grapes et al., 1997) (Figure 10).

Several rounded beach boulders and associated beach gravel are partly enclosed and overlain by the greywacke cataclasite. Striated clasts were collected from the sheared conglomerate layer at the base of the outcrop at the modern beach level (Figure 11).



**Figure 10** Schematic cross-section showing the Ngapotiki Fault and secondary fault, thrusting crushed greywacke over the modern beach (modified from Grapes et al., 1997).

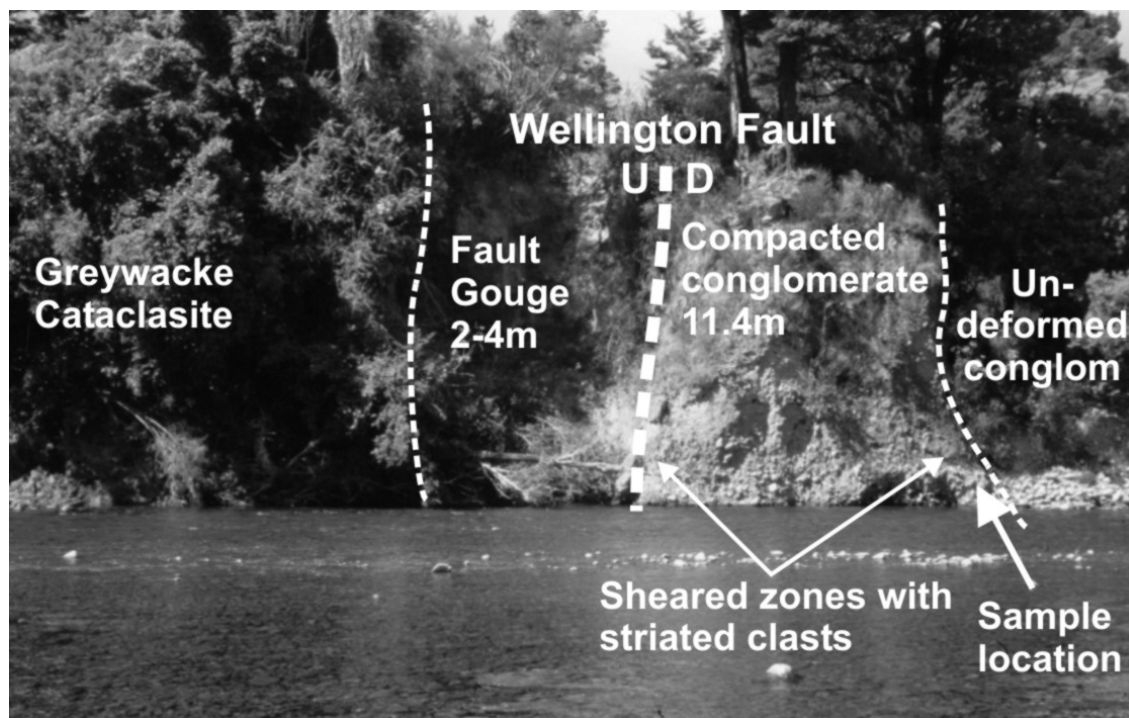


**Figure 11** Closeup of *in situ* striated beach boulders and conglomerate. A shear plane with fine-grained fault gouge is visible above the boulders. Striated clasts were collected from the deformed conglomerate layer around the larger beach boulders.

## WELLINGTON FAULT, HARCOURT PARK, NEW ZEALAND

The Wellington Fault is a predominantly dextral reverse fault with a near vertical dipping fault plane. At Harcourt Park in Upper Hutt, the fault offsets a series of Quaternary alluvial terraces (Berryman, 1990).

The fault is exposed in the Hutt River (175°05'00"E, 41°07'00"S) and contacts crushed greywacke with fluvial conglomerate. Fault movement has created a compacted unit within the conglomerate that is approximately 11 metres wide. Near vertical shear planes on both the up and downstream sides of the unit contain fault gouge with fractured and striated clasts. On the downstream side, the compacted conglomerate contacts undeformed, horizontally bedded fluvial conglomerate. (Figure 12).



**Figure 12** Exposure of the Wellington Fault in the bank of the Hutt River at Harcourt Park. Shear planes containing striated clasts occur on each side of the compacted conglomerate unit.

### Characteristics of tectonic striae

Striae occur on 22% of the clasts from the Ngapotiki Fault sample and 43% of clasts from the Wellington Fault. In both examples the striae occur preferentially on argillite clasts.

For the Ngapotiki Fault, striae occur on clasts in all roundness classes except the most angular and the most rounded. The striae occur on both the fractured clasts as well as on whole clasts. For the Wellington Fault, striae occur in all roundness classes except the most angular and are most prevalent on more rounded clasts.

Striae density varies greatly. Some clasts show a high density of both background microstriae and larger individual striae (T-2) while others have a generally low density

and patchy distribution (T-6, T-7, T-8a, T-8b). Some show pervasively abraded surfaces that truncate the clast surface. In these cases, individual striae are difficult to identify but they overlap forming a series of ridges and grooves that produce a corrugated surface (T-1, T-4).

A feature that is peculiar to tectonically striated clasts is a concentration of striae on the margins of some clasts, where the curvature increases toward the end. An example is shown in Image T-4, where abrasion has truncated part of a surface on a rounded clast formed a flat corrugated surface. Further examples of striae concentrated at the margins of surfaces are shown in Image T-5 and T-6.

Striae occasionally occur on the ends of clasts. Image T-3 shows parallel striae that form a set 8 mm wide. These are parallel to the long-axis of the face, but not the clast. Striae on clast ends are observed only on tectonic and debris-avalanche clasts.

Curved striae are common except on corrugated surfaces and compound striae are often present, especially on larger clasts such as the clast in Image T-8a. The close-up view in Image T-8b shows that the widest striae are compound striae. Tectonically striated clasts show wide variation in length and width but overall appear to be related to clast size with longer and wider striae occurring on the larger clasts.

### **Striae orientation**

Tectonic striae have a wide range in orientation characteristics and are not consistently related to clast long-axes. Image T-1 shows ridge and groove striae parallel to the long-axis of an elongate clast. However, some elongate clasts have multiple striae orientations that deviate up to 90° from the clast long-axis (Image T-7, T-10). Others display parallel striae that occur over a curved surface oblique to the long-axis (T-9).

Image T-8a shows a large sandstone clast with moderate preferred orientation oblique to the clast long-axis, as does the smaller clast in Image T-11. However, both examples also have some striae at a high angle to the long-axis.

Finally, Image T-2 shows multiple striae orientations (some curved) on a small near-equidimensional clast, suggesting that the clast rotated while it was striated.

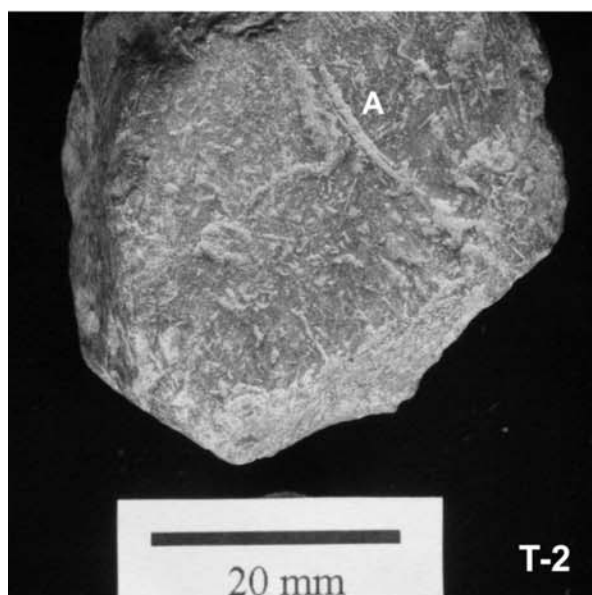


### *Long-axis parallel striae*

Image T-1 shows an angular argillite clast from the Ngapotiki Fault with a flat planed and densely striated surface.

Individual striae are indistinct but together make up a series of ridge and grooves parallel to the long-axis of the clast giving a corrugated appearance.

Location: Ngapotiki Fault, New Zealand  
175°21'10"E 41°35'05"S



### *Multiple striae orientations*

Image T-2 shows a small, almost equidimensional argillite clast. The surface has abundant, mostly short striae with no preferred orientation. The largest striae is 15 mm long, 1 mm wide and slightly curved (A).

The curved striae together with the lack of preferred striae orientation, indicates clast rotation during the striating process.

Location: Wellington Fault, New Zealand  
175°05'00"E 41°07'00"S



### *Striae on clast ends*

Image T-3 shows striae on the end of a sub-angular argillite clast (A).

Striae are up to 30 mm long and parallel forming a set 8 mm wide that is parallel to the long-axis of the face.

Also visible is an individual short, wide striation almost perpendicular to the main set of striae and long-axis of the face (B).

Striae on clast ends are only observed on tectonic and debris-avalanche clasts

Location: Ngapotiki Fault, New Zealand  
175°21'07"E 41°35'03"S



***Planed surface and parallel striae concentrated on clast margin***

This sandstone clast is a well-rounded beach clast incorporated in the Ngapotiki Fault.

The surface displays indistinct ridge and grooves parallel to the long-axis that form an obvious corrugated surface.

The abrasion truncates the clast surface but terminates abruptly where the curvature of the surface increases.

Location: Ngapotiki Fault, New Zealand  
175°21'07"E 41°35'03"S

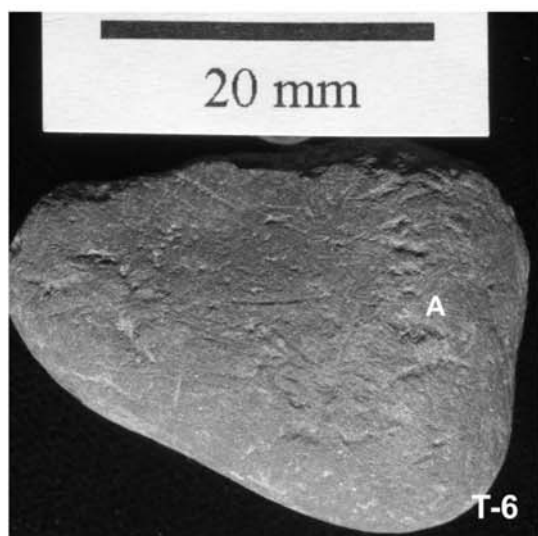


***Parallel striae concentrated on clast margin***

The clast in Image T-5 displays faint striae sub-parallel to the long-axis of the clast, but concentrated at the margin of the surface where the curvature of the clast increases (A).

Also visible is extensional open fractures oriented approximately perpendicular to the striae orientation and long-axis of the clast (B).

Location: Ngapotiki Fault, New Zealand  
175°21'07"E 41°35'03"S



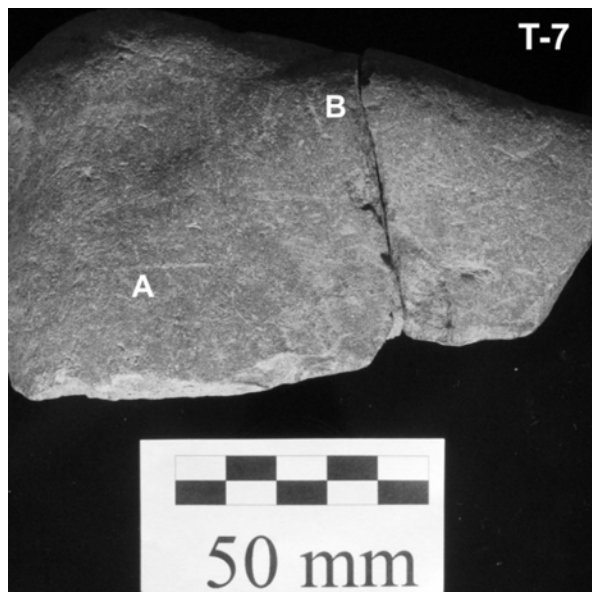
***Striae concentrated on clast margin***

This argillite clast from the Wellington Fault shows a concentration of striae at the extreme end of the flat surface where the curvature of the clast increases (A).

This concentration of striae at the margins, occurs on tectonic clasts of all sizes

A few striae with variable orientations are also present.

Location: Wellington Fault, New Zealand  
175°05'00"E 41°07'00"S

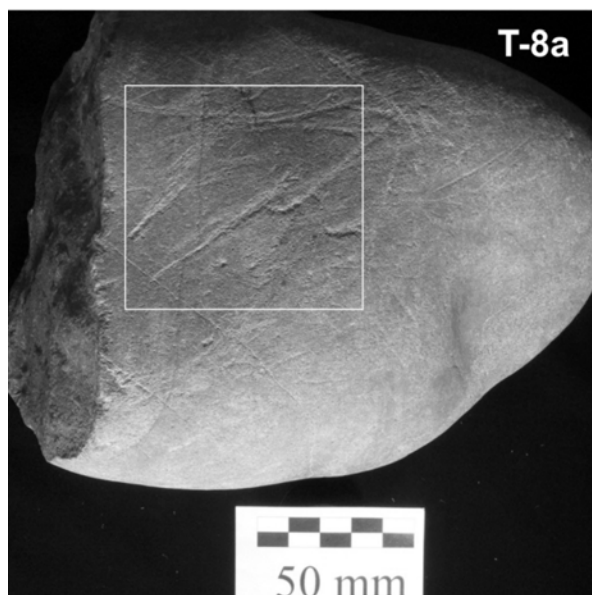


### ***Broken and striated clast***

Image T-7 is a sandstone clast from the Wellington Fault. The surface shows some striae oriented parallel to the long-axis of the clast (A), but others at various orientations up to 90° from the long-axis (B).

The clast has been fractured by tectonic movement and the break is oriented approximately perpendicular to the long-axis of the clast. No striae occur on the fractured surface.

Location: Wellington Fault, New Zealand  
175°05'00"E 41°07'00"S

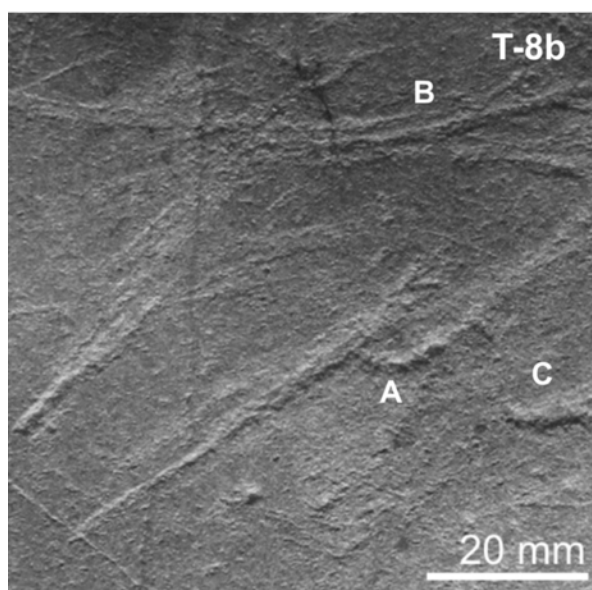


### ***Large striae on cobble***

The sandstone cobble in Image T-8a is a well-rounded fluvial clast from the Wellington Fault. The clast was oriented with the long-axis parallel to the slip plane in the outcrop.

Most striae are oblique to the long-axis. Some are compound striae with smaller parallel striae on the surface. Parts of the surface show a patchy background of microstriae. This clast has also been fractured perpendicular to the long-axis.

Location: Wellington Fault, New Zealand  
175°05'00"E 41°07'00"S



### ***Closeup of large striae***

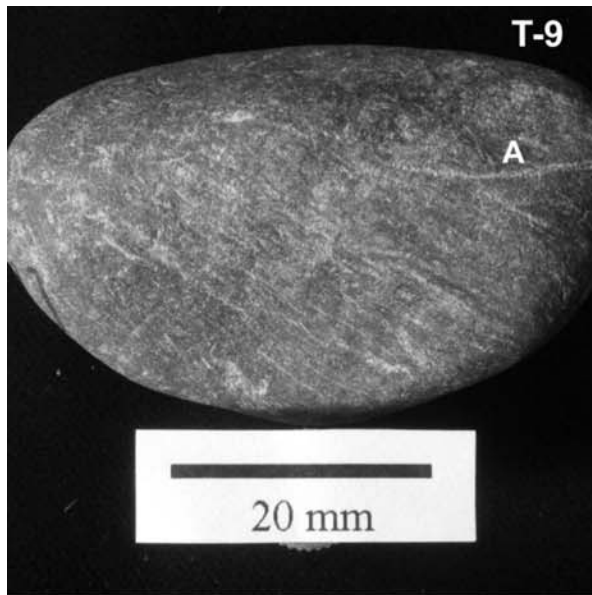
The striae are up to 86 mm long and 5 mm wide (the largest measured in this study).

An individual striation that curves by about 60° at one end suggesting the striating fragment rotated out of the striation track (A).

A curved compound (5 mm wide) with smaller parallel striae on the surface (B).

A short and wide striation (8 mm long and 4 mm wide) (C).

Location: Wellington Fault, New Zealand  
175°05'00"E 41°07'00"S



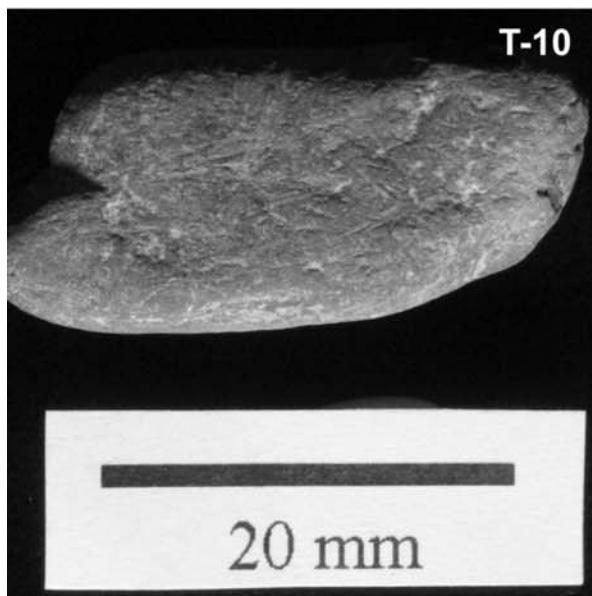
***Parallel striae oblique to the long-axis on a curved surface***

The clast in image T-9 has parallel, fine striae oblique to the long-axis of the clast and are continuous over a curved surface.

Most striae are indistinct but overall make up a densely abraded surface.

One larger, clear striation is 17 mm long and 0.5 mm wide and oriented parallel to the long-axis (A).

Location: Ngapotiki Fault, New Zealand  
175°21'07"E 41°35'03"S



***Multiple striae orientations***

This small argillite clast from the Wellington Fault has small striae with multiple orientations despite the clast having a well-defined long-axis.

Location: Wellington Fault, New Zealand  
175°05'00"E 41°07'00"S



***Sub-parallel striae on curved surface***

This argillite clast from the Ngapotiki Fault clast that has no flat surfaces, but shows a few striae that are sub-parallel to the long-axis of the clast (A).

The striae are straight and extend over the curved surface.

Location: Ngapotiki Fault, New Zealand  
175°21'07"E 41°5'03"S

## CONCLUSIONS

Striae are produced by a variety of processes in a wide range of geological settings. The examples presented in this photographic atlas indicate that there are some observable and measurable differences in striae formed in the various settings. However, there is significant overlap in many characteristics, and striae alone have only limited use in reliably discriminating between environments. The combination of striae analyses in relation to clast shape allows striated clasts to be adequately described and provides enough criteria to make a sound judgement as to whether they are glacial or non-glacial in origin. Table 1 summarises important striae characteristics from all the settings mentioned.

### **Striae percent and clast shape**

The percentage of striated clasts in a deposit is not in itself a good indicator of its origin. The generation of striae is dependent on lithology in all settings, regardless of the process. The relationship between striae, clast faces and roundness is a useful indicator of striae origin, with warm-based and polythermal glacial striae preferentially occurring on faceted surfaces of subrounded to rounded clasts. This contrasts clearly with debris-avalanche striae, which are found preferentially on sharp edged fracture faces of very angular clasts and occasionally on clast ends, and rock-fall striae that occur on flat faces of angular to sub-rounded clasts. Striae preferentially occur on subrounded and rounded clasts in the tectonic samples, although in the examples used here, this depends largely on the character of the pre-existing conglomerate deposit. However, partially planed surfaces with ridge and groove striae and striae on the ends of clasts appear to be characteristic of tectonically striated clasts. Striae from cold-based glaciers are very rare and unrelated to clast shape as the striae are generated on in-situ clasts.

### **Striae density**

Striae density is useful in discriminating between different striae origins. Striae on clasts from warm-based ice (Lake Pukaki moraine) and polythermal ice (Mackay Glacier debris) have a high density of both individual striae and background microstriae and are usually evenly distributed on faceted surfaces. This contrasts with cold-based glacial and non-glacial examples. Cold-based glacial striae are sparse and debris-avalanche and rock-fall clasts show wide variability but generally lower striae density and patchy distribution. Tectonic clasts also show wide variation in striae density. On the tectonic clasts, striae density is related to the clast size, with larger clasts showing lower density. The striae distribution is often greatest on the margins of clast surfaces where the curvature increases toward the end.

### **Striae size**

Striae size is not particularly useful characteristic. On similar sized-clasts, striae length and width do not differ greatly. Warm-based and polythermal glacial striae are generally long and narrow with clear regular channel shape compared to striae in other settings. In addition, striae size on warm-based and polythermal glacial clasts appears to be related to clast size with longer and wider striae occurring on larger clasts. Debris-avalanche striae

are generally shorter and wider with irregular shapes and common compound striae. The striae size is not related to clast size. Rock-fall striae are also generally shorter than warm-based and polythermal glacial striae but tend to be narrower (except for compound striae). Rock-fall striae size is not related to clast size. Tectonic striae vary greatly but show the longest and widest striae of all settings except cold-based glacial. Striae size appears to be related to clast size on tectonic clasts and compound striae are common. Cold-based glacial striae are generally much wider and longer than all other examples and are unrelated to clast size.

### **Striae orientation**

Warm-based and polythermal glacial clasts show a strong tendency for striae to be parallel or sub-parallel to the clast long-axis, consistent with observations from other known glacial deposits. However, there are exceptions, and some clasts show no preferred orientation particularly if the clast is nearly equidimensional. These clasts also show curved striae suggesting that they are more likely to rotate and receive striae of multiple orientations. Overall, orientation characteristics of striae on the warm-based and polythermal clasts are similar. Cold-based glacial striae are not related to clast long-axes. Striae orientation reflects the direction of glacier flow and occur on the stoss side of embedded clasts.

The Murimoto debris-avalanche clasts commonly show no preferred striae orientation, or weak clustering of striae that are usually not related to the clast long-axis. Some clasts show curved striae. Rare examples display parallel striae on a single surface, but not related to the clast long-axis. Similarly, the Murchison Valley rock-fall clasts typically show no preferred orientation or weakly clustered striae, sometimes sub-parallel to the long-axis. These clasts sometimes show curved striae.

Finally, striated clasts from the Ngapotiki and Wellington Faults show striae that range from long-axis parallel on some elongate clasts to no preferred orientation. However, other variably shaped clasts show moderately grouped striae oblique to the clast long-axis. All the tectonically striated clasts show at least one curved striation, indicating some rotation occurred during the striating process.

### **Future work**

To develop striae analysis as a more effective palaeoenvironmental tool, future research could concentrate on producing further systematic descriptions of striae from both glacial and non-glacial environments. This might involve recording further distinctive features of striae by extending this photographic atlas, but also is likely to require a more sophisticated approach, possibly employing computer-based digital image analysis to recognise more subtle differences in striae shape.

Table 1. Summary table of striae characteristics from all environments studied.

Striae characteristics						
Environment	Warm-based glacial	Polythermal glacial	Cold-based glacial	Mass-movement		Tectonic
Example	Lake Pukaki moraine	Mackay Glacier	Manhaul Bay Glacier	Debris-avalanche (Murimotu Fm)	Rock-fall MurchisonVly	Ngapotiki Fault Wellington Fault
<b>Striae % and lithology</b>	33 % striated clasts Striae preferentially on argillite	< 10% striated clasts Striae preferentially on fine-grained sedimentary clasts	Very rare	10 % striated clasts Striae occur on both lithologies (andesite and andesite/ dacite)	26 % striated clasts Striae occur exclusively on argillite clasts	22 % striated clasts Striae slightly more common on argillite clasts
<b>Facets/flat faces/ fractures</b>	Striae usually occur on clear facets and rarely on curved surfaces	Striae occur only on clear facets	Striae occur only on one side (up-glacier side)	Striae typically occur on fracture faces that are often unrelated to clast long-axis	Striae only occur on fresh flat fracture surfaces	Striae occur on whole and fractured clasts. Occur on curved and flat surfaces
<b>Striae and clast roundness</b>	Striae occur on angular to well-rounded clasts. Most common on rounded clasts	Striae occur on angular to rounded clasts	Roundness not applicable (ventifact clasts)	Striae only occur on very-angular clasts	Striae occur on very-angular to sub-rounded clasts	Striae occur on angular to rounded but preferentially on rounded
<b>Striae density</b>	High density of individual and background striae. Striae are widely distributed	High density of individual and background striae. Striae are widely distributed	Very low density of individual striae. No background striae	Variable and patchy density of individual and background striae	Variable and patchy density of individual and background striae	Variable density of individual and background striae. Larger clasts have lower striae density than smaller clasts
<b>Striae and clast size</b>	Generally clear, regular striae that are long and narrow with larger striae on larger clasts	Generally clear, regular striae that are long and narrow but not clearly related to clast size	Long and wide irregular shapes. Striae size unrelated to clast size	Irregular striae shapes. Generally shorter and wider than warm-based striae. Unrelated to clast size	Irregular shapes. Generally shorter and narrower than warm-based striae. Unrelated to clast size	Wide variation in shape and size. Longer and wider striae occur on larger clasts
<b>Striae orientation</b>	Commonly parallel to long-axis on elongate clasts, less parallel on more rounded or equidimensional clasts	Commonly parallel to long-axis on elongate clasts, but some exceptions	Unrelated to clast long-axis, but oriented north-south (ice-flow direction)	Striae usually have no preferred orientation, but occasional weakly clustered and rare parallel striae. Generally unrelated to long-axis	Striae show no preferred orientation or weak clustering, but generally unrelated to the clast long-axis	Striae orientation ranges from no preferred orientation to parallel. Some show long-axis parallel striae, but many are weakly clustered and oblique to the long-axis
<b>Other</b>	Some curved striae	Some clasts show curved striae	Cut through desert varnish	Some clasts show curved striae	All clasts show curved striae	Some curved striae, rare striae on clast ends. Striae sometimes concentrated on margins of clast faces

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