Report on the landslide that blocked SH 1 and the railway line near Rosy Morn Stream south of Kaikoura on 10 September 2010

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GNS Science Report 2010/59
14 January 2010

BIBLIOGRAPHIC REFERENCE

Hancox, G.T. 2010. Report on the landslide that blocked SH 1 and the railway line near Rosy Morn Stream south of Kaikoura on 10 September 2010, *GNS Science Report* 2010/59. 33 p.

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ISSN 1177-2425
ISBN 978-0-478-19807-2

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ABSTRACT

This report describes and evaluates the cause of the landslide which blocked SH 1 and the railway line near Rosy Morn Stream 12 km south of Kaikoura on 10 September 2010. The landslide was a moderately large (about 50,000 m3) debris and rock slide, and occurred on the toe of a large prehistoric landslide on the steep (45-50°) coastal slope. This slope is formed of indurated (hard), interbedded, well jointed greywacke sandstone and mudstone (argillite) bedrock, and is overlain by thin colluvial deposits. The 2010 landslide was a significant event justifying a response and report under the GeoNet Project of GSN Science, mainly because of the disruption it caused to transport by closure of an important road and rail link to Christchurch at a time when supplies were urgently needed there after the Darfield earthquake. Normal road and rail access was blocked for one week while the debris was cleared away.

The results of this study indicate that the landslide cannot be attributed to any one triggering event, but instead it appears to have been caused by a combination of factors. These factors include unfavourable geological conditions, shaking caused by the Darfield earthquake mainshock and the long sequence of aftershocks, greater than average rainfall over the preceding four months, and low to moderate rainfall over three days before the failure, all combined to cause the landslide on 10 September. Because of the timing of the aftershocks, rock falls at the site, and rainfall in the area, which stopped about 12 hours before the main failure, the cumulative effect of the mainshock and aftershocks is seen as a particularly important factor in the initiation of the landslide and in bringing the slope to failure.

The Darfield earthquake mainshock on 4 September 2010 was felt strongly at South Bay, Kaikoura, about 12 km east-northeast of the landslide site and 175 km from the earthquake's epicentre, with moderately strong, long-duration shaking (~MM 6, PGA ~0.015 g) at the slip site. A key feature of the mainshock shaking at South Bay was the marked long-period content of the strong motion record, with a peak ground displacement of 44 mm, which was very large in relation to the peak ground acceleration of about 0.01 g. There was also a marked north-south polarisation to the motion. The recorded ground motions equate to a felt intensity of MM 4-5 in the South Bay area. At the landslide site on the steep coastal cliff south of Kaikoura ground motions are likely to have been amplified by topographic effects, possibly reaching ~MM 6 locally. The dominant north-south direction of the ground displacement is also likely to have had a destabilising effect on the landslide, which moved in a south-southeast direction (~155°). That shaking would have been unfavourable for the slope, and may have been responsible for starting the slope failure process. Over the six days from 4–10 September 2010 when the landslide occurred there were 120 earthquakes of magnitude 4.0 to 4.9, and 11 of magnitude 5.0 or greater, which caused low intensity shaking at the landslide site (<MM 3-4, with peak ground accelerations of ~0.001–0.007 g). Earthquake shaking is believed to have further weakened the rock mass forming the slope, which was probably made more susceptible to failure due to greater than average longer-term rainfall. The 32 mm of rain that fell over three days prior to the landslide was probably not on its own of any great significance, as the slope had survived more intense rainfall ten days before the failure, and considerably more than that several times over the last 35 years or more.

In the context of the overall slope failure process, the earlier prehistoric slope failure, adverse geological structures within the slope and greater than average longer-term rainfall are therefore seen as factors that pre-conditioned the slope and made it susceptible to failure on 10 September. The Darfield earthquake and the aftershock sequence are believed to have acted more in a triggering role. The cumulative effect of the Darfield earthquake mainshock and the prolonged sequence of low intensity aftershocks are therefore believed to have been the most significant factor in triggering the landslide. There is a strong possibility that the slope would not have failed on 10 September 2010 if the Darfield earthquake and aftershocks had not occurred. However given the poor rock condition and earlier failure history of the slope, it probably would have failed at some time in the future. The recent failure oversteepened the coastal slope, making it more susceptible to further collapses, some of which might be large enough to again close the railway line and SH 1.

Despite its modest size, the 2010 landslide south of Kaikoura was of geotechnical significance as it provided reasonably convincing evidence that under some conditions cumulative low intensity shaking can trigger moderately large landslides on some highly susceptible slopes at distances greater than 100 km from the epicentre. This possibility should be taken into account in future earthquake and landslide hazard and risk assessments in New Zealand.

KEYWORDS

Earthquake-induced landslides, landslide susceptibility, rainfall induced landslides, landslide causes, triggers, hazard and risk, Kaikoura, North Canterbury, 2010 Darfield earthquake, New Zealand.

1. INTRODUCTION

At about 10:15 pm on Friday 10 September 2010, State Highway 1 (SH 1) was closed by a large landslide near Rosy Morn Stream, approximately 12 km south of Kaikoura. The landslide also blocked the South Island Main North Railway Line (MNL), disrupting freight and passenger trains between Christchurch and Blenheim until it could be cleared. A large volume of rock and soil from the coastal cliff fell across the main north-south highway and railway line, creating an obstruction about 120 m wide (Figure 1).

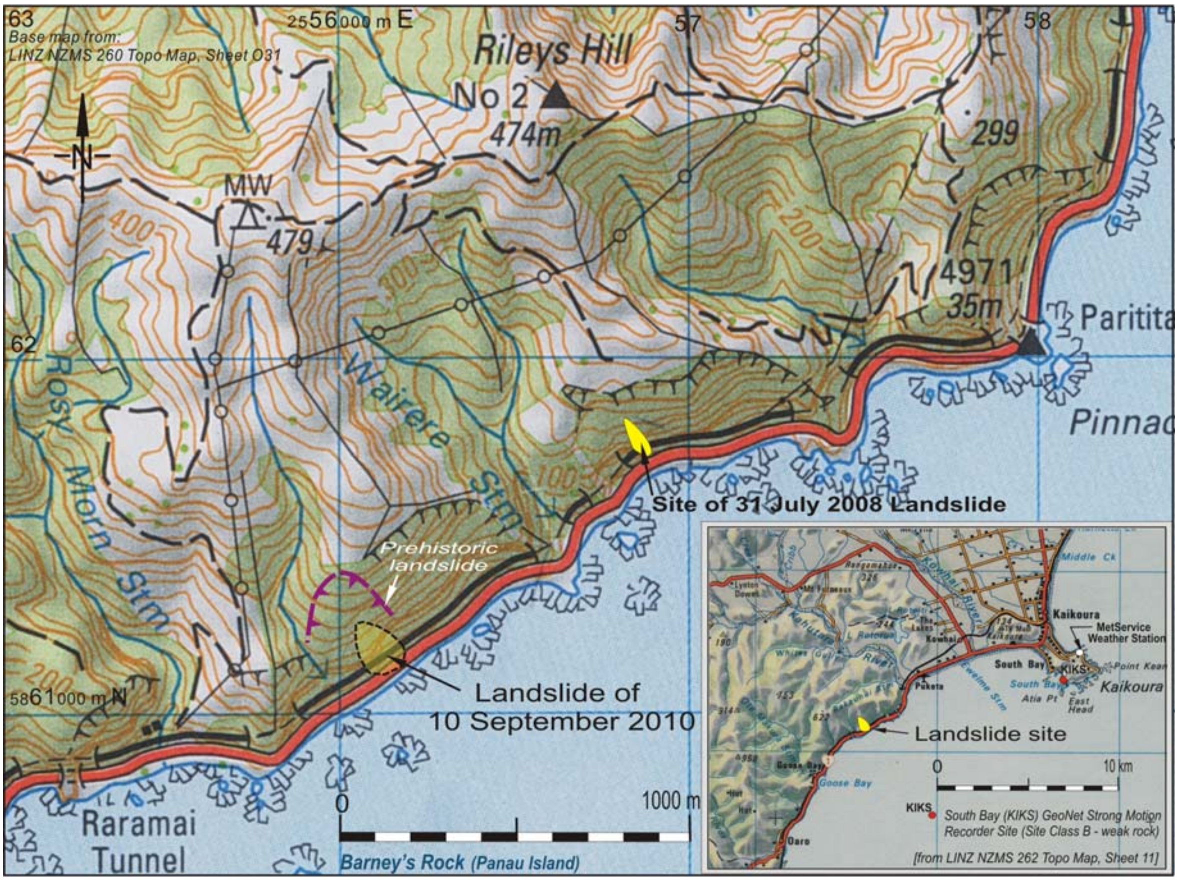

Figure 1 Maps showing the location and topographic setting of the landslide of 10 September 2010 which closed SH 1 and the Main North Railway Line ~12 km southwest of Kaikoura. The locations of the Kaikoura MetService weather station, the GeoNet Strong Motion recorder site (KIKS), and the site of a smaller landslide which blocked the railway line and SH 1 in July 2008 are also shown.

The closure of SH 1 caused light traffic to be diverted to the Inland Kaikoura Route (SH 70), but heavy vehicles were required to use SH 63 through Wairau valley and State Highway 7 through the Lewis Pass. The New Zealand Transport Agency (NZTA) estimated that it could take up to a week to clear the slip and reopen the road. The Picton-Christchurch train and freight service was suspended until the slip was cleared and the line reopened. The road and rail closure occurred at a time when it was important to get supplies to Christchurch following the Darfield earthquake on Saturday 4 September. The landslide was the largest in the Kaikoura area for many years, considerably larger than the landslide about 1km to the north, which blocked the railway line and SH 1 for several days in July 2008 (Figure 1).

Because of the significant infrastructure disruption caused by the landslide, its possible association with the Darfield earthquake sequence, and the 2008 landslide closure of SH 1 and the railway line in the same area, the author was requested to inspect and report on the landslide under the GeoNet Project of GNS Science. This report presents the results of the GeoNet response and assessment of the landslide.

Two photos (Figures 2a and 2b) show the landslide on the morning of Saturday 11 September. Figure 2a is a ground view of the large mass of rocky debris blocking SH 1. Figure 2b shows the landslide location and source area on the steep coastal cliff, and the full extent of the debris cone when earthworks to clear the road had just begun.

After clearance of most of the landslide debris, State Highway 1 and the railway line were reopened to traffic on Thursday 16 September 2010, after being closed for six days. Because debris still covered the tracks, the railway line had to be temporarily relocated out from the base of the slope until it was removed and some safety measures were put in place.

Figure 2 *(a)* Ground view of the southern side of the landslide debris blocking SH 1 on the morning of Saturday 11 September 2010. Angular debris and boulders up to 1.5 m across cover the highway to a depth of about 5 m *(photo NZ Press Association). (b)* Aerial view of the landslide on 11 September, after earthworks to clear the road had just begun. The debris cone extends across SH 1 and sea wall on to the narrow beach below the road *(photo by Wings Over Whales)*.

Because of the prolonged disruption of road and rail traffic and freight between Picton and Christchurch, the landslide received a lot of news media attention, most of which focussed on when the road would be reopened, and what caused the failure. Rainfall was initially blamed for the landslide as it occurred at the end of 3 days of moderate rainfall, during which 32 mm of rain was recorded at Kaikoura, about 13 km east-northeast of the site (Figure 1). However, there was also speculation that the landslide might have been triggered by shaking caused by the Darfield earthquake and the ongoing aftershocks.

Although the landslide did little damage, the transportation disruption it caused and the cost of clearing the slide debris had significant financial implications. Because it was the second landslide to close the railway line and SH 1 south of Kaikoura for several days in the last 2 years, a GeoNet response was initiated to carry out an aerial inspection of the landslide site and adjacent area, and to report on nature and likely cause of the most recent slope failure. After a delay of several days because of bad weather, aerial inspection and high resolution photography of the landslide site was carried out from a helicopter on 27 September 2010. This was followed by a brief ground inspection, which was unfortunately of limited duration because of ongoing earth-moving work to clear debris from the railway line.

The location and nature of the September 2010 landslide are described in this report. Factors that may have contributed to the cause and trigger of the landslide, particularly the role of rainfall and earthquakes, are then examined and discussed. The significance and future behaviour of the landslide and the stability of the slope on which it occurred are also discussed.

2. LANDSLIDE LOCATION

The landslide that occurred on 10 September 2010 is located south of Kaikoura on a steep (~30-50°), 200-300 m high bush-covered coastal slope near Rosy Morn Stream, mid way between Puketa and Goose Bay (Figure 1). Although this landslide appears to be a new (first-time) failure on the slopes adjacent to the coast, SH 1, and the railway line south of Puketa, a 2007 Google Earth satellite image suggests that it occurred on the lower part of one of several old (prehistoric) failures in the area (Figure 3). This image can be compared with an aerial oblique photo of the 2010 landslide site taken on 27 September 2010 when earthworks to remove debris from the railway line were still in progress (Figure 4).

Figure 4 and other aerial photos have been used to plot the 2010 landslide as accurately as possible on a topographic map (Figure 5a) to determine its location and dimensions, and construct a cross section (Figure 5b) to show its position on the slope and relationship to the older landslide on the slope above it. Field mapping was made difficult due to the steep topography and restricted access to the site while earthworks were being carried out.

The slope on which the landslide occurred has an average slope of 45-50°. The new failure has included a 'bulge' of partially-failed material from the old landslide on the lower slope, which had locally oversteepened and loaded the underlying rock mass and colluvium (Figures 3 and 5). The new failure scar and debris cone is roughly 120 m wide, with a slope length of about 180 m long. The crown (head) of the 2010 landslide is about 120 m above sea level, while the subtle, bush-covered scarp of the old landslide is at an elevation of about 260 m. Figures 6 and 8 are close-up aerial photos of the 2010 landslide, which have been annotated to show the main geological and geomorphic features in the landslide source area after much of the landslide debris (body) had been removed.

The dimensions and elevations stated above were determined from a terrestrial laser scan of the landslide scar undertaken by GNS Science on behalf of KiwiRail. The initial scan of the landslide was carried out by Garth Archibald (GNS Engineering Geology Surveyor) on 19 October 2010). The map from the terrestrial laser scan has been used in conjunction with aerial photos to accurately map the extent of the landslide and geological and geomorphic features on the failure scar (Figure 7). Repeated laser scans over time will be used to monitor the slope to detect and measure any further movements that may occur.

Figure 3 Annotated Google Earth 2007 satellite image showing the position of the 2010 landslide on the coastal slope, and scars of older (prehistoric) failures *(shown in red)*. The 2010 failure area on the lower slope seems to be a distinct 'bulge' below the older landslide, the head of which extends to about 260 m above sea level. The railway line *(MNL)* and main highway *(SH 1)* are located close to the toe of the steep coastal slope on a slightly elevated shoreline platform about 3 m above the present storm beach.

Figure 4 Aerial photo of the 2010 landslide, which occurred on the lower part of a much larger old landslide *(head scarp shown by white dashed line)* which extends up to ~260 m above sea level; its direction of movement is shown by the yellow arrow. The toe of the recent landslide is ~120 m across, and its head scarp extends to an elevation of ~120 m, below which is the slide plane *(sp)* of the old landslide, and on the south side of the landslide scar, two prominent joint-controlled wedge failures *(w)*.

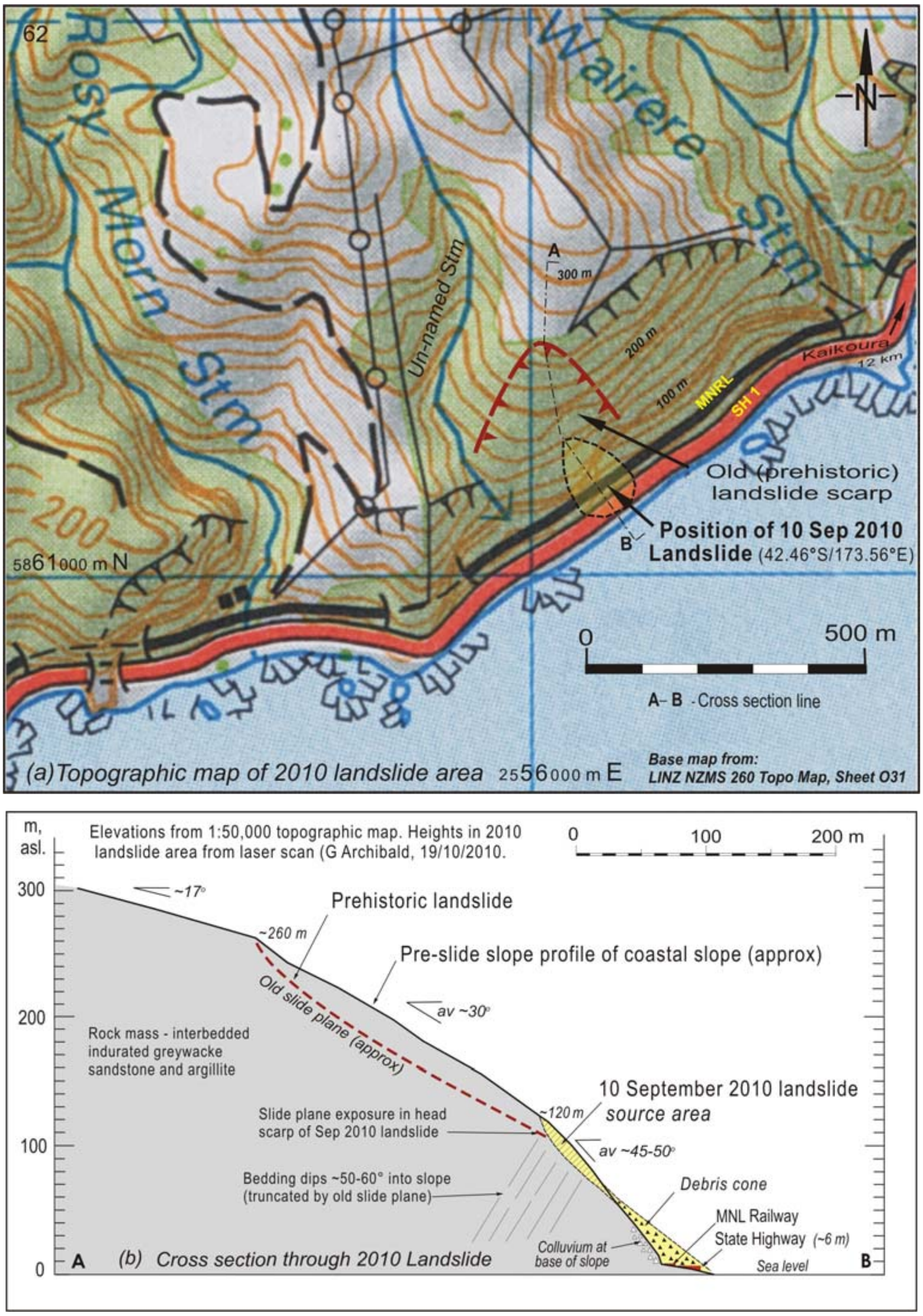

Figure 5 Topographic map *(a)* and cross section *(b)* through the 2010 landslide near Rosy Morn Stream, and the large prehistoric landslide on the slope above.

3. SITE GEOLOGY

The geology of the landslide site comprises Torlesse (Pahua Terrane) bedrock, which is locally dominated by indurated, light grey, thin to medium bedded greywacke sandstone and dark grey mudstone (Rattenbury et al. 2006). Bedrock underlying the coastal slope is mantled in places by angular colluvium 1–3 m thick in the site area, which typically also forms a 'wedge' of debris at the base of the slope (Figure 5b). Bedding at the site dips steeply (~55-60°) to the north (into the slope), and is well exposed near the head of the landslide. Several prominent and persistent, steeply dipping joint sets are also exposed in the new failure scar (Figures 7 and 8).

Figure 6 Aerial photos of the 2010 landslide: *(a)* on 11 September when the full extent of the two debris cones *(d1, d2)* and three main source areas *(sa1, sa2, sa3)* was still visible; *(b)* on 27 September when most of the debris had been removed exposing the bedrock types *(s – sandstone. a – argillite),* structures *(b–bedding, J –prominent joints)*, and two main wedge failure areas *(w1, w2)* on the landslide scar. The area above the slide plane *(sp)* of the old landslide on the upper slope is a ~1 m thick clay layer *(cl)* which appears to dip ~30° southwest towards the un-named stream, and obliquely out of the slope towards State Highway 1 *(SH 1)*. Remnants of old colluvium is exposed at the bottom of the slope below the earthworks trim line. Note the figure in red *(F)* for scale of the landslide scarp.

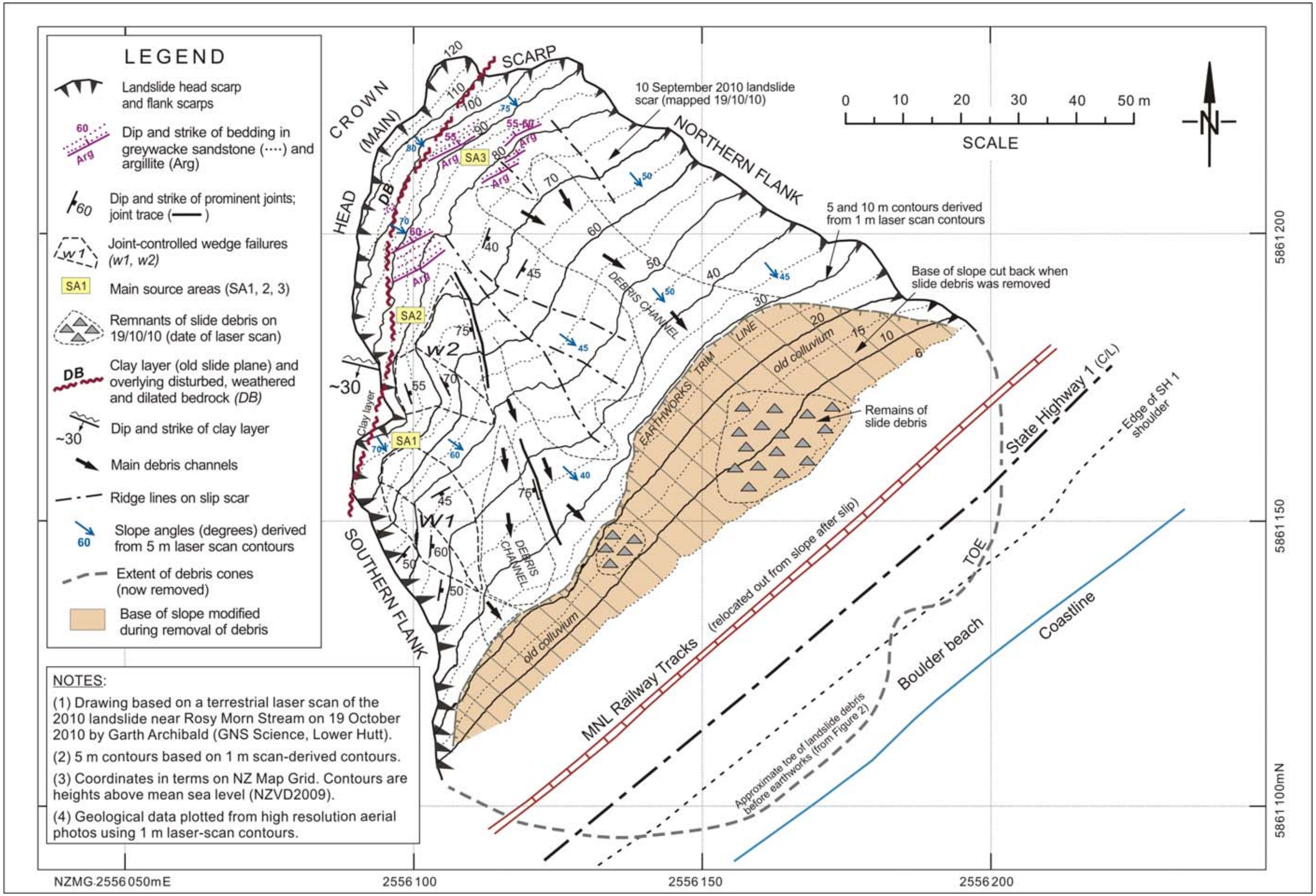

Figure 7 Geomorphic and geological map of the 10 September 2010 landslide near Rosy Morn Stream (plotted on 19/10/10 terrestrial laser scan base map).

4. DESCRIPTION OF THE LANDSLIDE

The 2010 landslide is a moderately large slope failure of soil, angular gravel, and boulders (Figure 2). In landslide terminology of Cruden and Varnes (1996) it may be described as a rock and debris slide. The landslide is about 120 m wide at the toe on SH 1, and it extends about ~180 m up the slope to the steep (65-75°) headscarp and crown ~120 m above sea level (Figures 7 and 8). Slope angles derived from a terrestrial laser scan of the landslide on 19 October 2010 are shown in Figure 9 (provided by Garth Archibald, 2010). Based on the amount of debris removed from the site, the landslide volume is estimated to be about 50,000 m^3 (pers. comm. Scott Ford, Downer EDI Works).

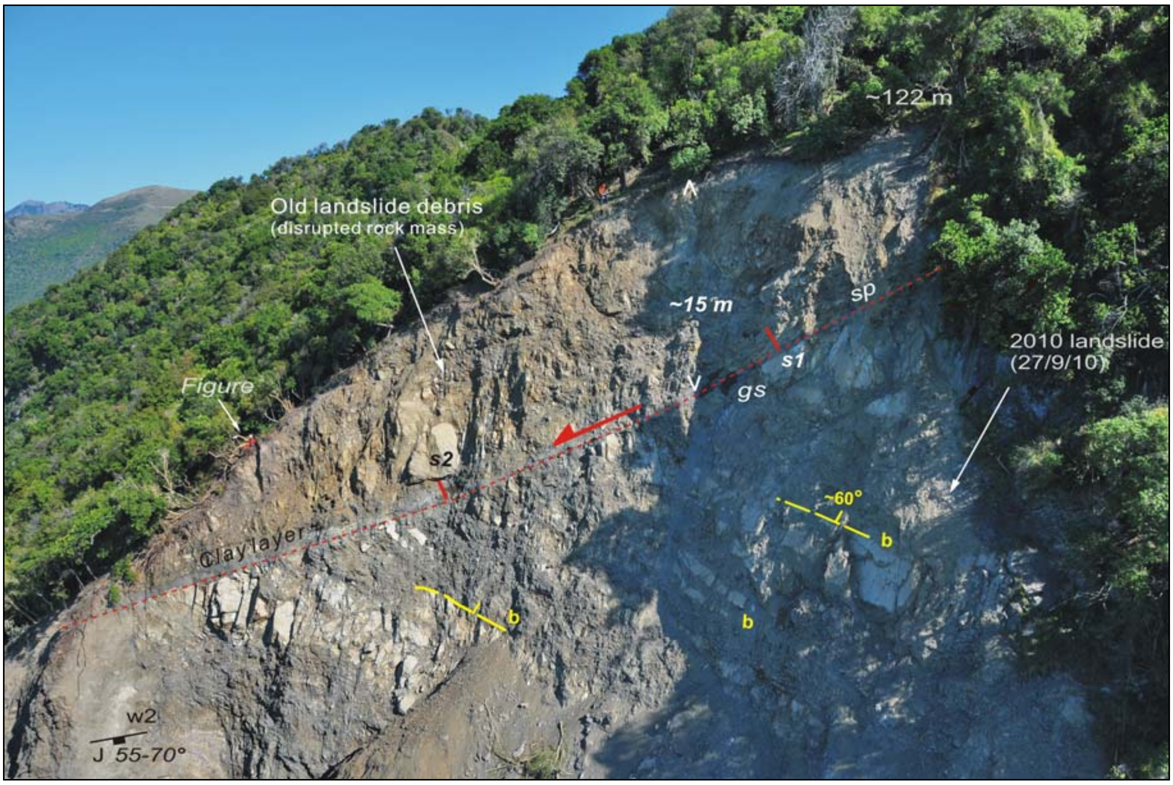

Figure 8 Aerial view of the head of the 2010 landslide showing the clay layer *(cl)*, believed to be the slide plane of the older landslide, above which 10-15 m of the overlying material mass is disrupted and more weathered (brown). A thick sandstone bed *(b)* is displaced ~25 m *(s1–s2)* by the old failure *(note figure in red for scale)*. The rock mass below the clay layer consists of interbedded light grey sandstone and dark grey mudstone. Other features shown here are groundwater seepages *(gs)* associated with the clay layer, and one of the main joint-controlled wedge failures *(w2)*.

The landslide involved the failure of intact rock and old (relict) landslide debris on the lower part of the coastal slope (Figures 6, 7, and 8). The materials in the landslide source area comprise:

(1) <u>Upper section</u>: Old landslide debris ~10–15 m thick overlying a ~1 m thick dark grey clay layer which dips ~30° to the south-southwest towards the Un-named Stream, and obliquely out of the slope. The clay layer is thought to be the basal slide plane of the prehistoric landslide shown in Figure 4. The debris comprises thick, semi-intact beds of sandstone which appears to have been displaced possibly about 25 m (Figure 8). This material is slightly to moderately weathered (brown), with a 'disturbed', open (dilated), and highly permeable appearance.

(2) Lower section: Intact rock comprising slightly weathered, interbedded greywacke sandstone and mudstone (argillite) which dips ~55-60° northwest into the slope. Bedding in the head scarp area is truncated by the failure surface (clay layer) of the old landslide (Figures 7 and 8). The rock mass on the south side of the landslide scar contains persistent joints, which in two places form large wedge failures *(w1, w2).* The old colluvium exposed by earthworks at the base of the slope (Figure 6) was over-ridden by slide debris and was not a significant factor in the failure.

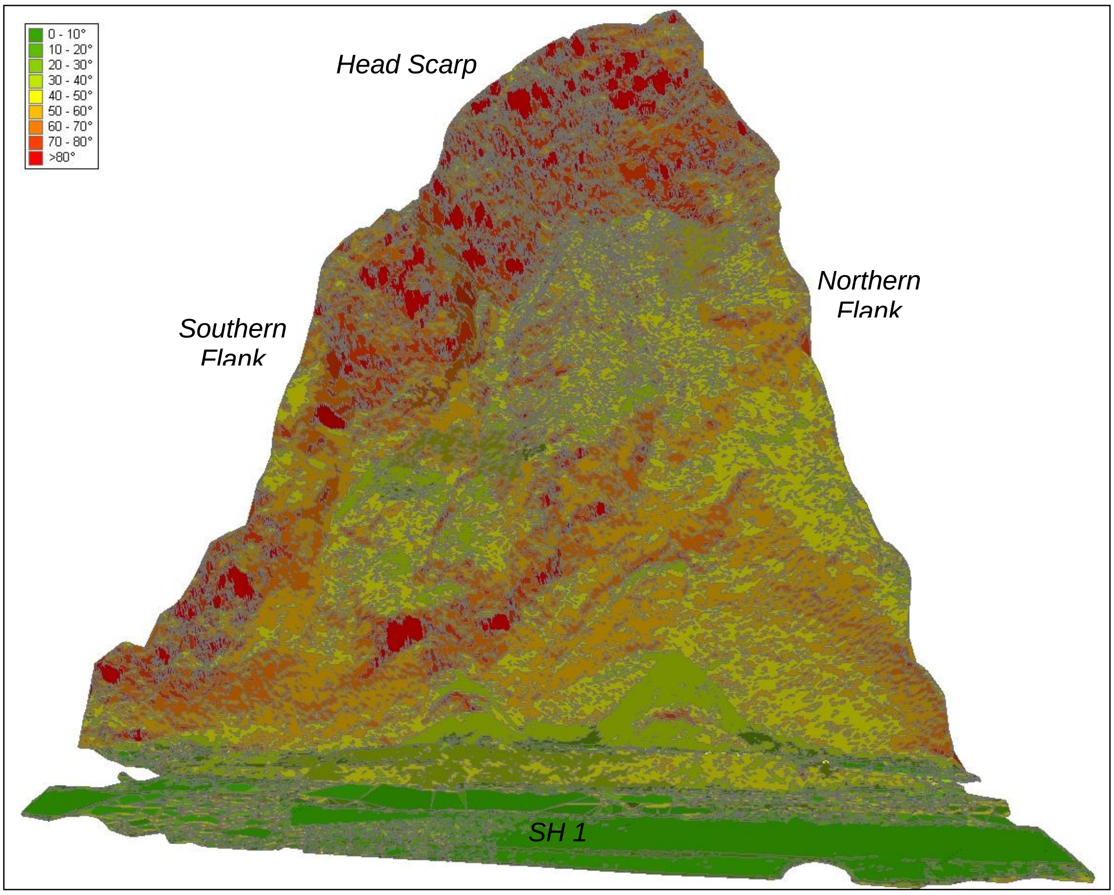

Figure 9 Image of the 2010 landslide showing the slope angles derived from the laser scan model. Red and orange areas are the steeper slopes, and yellow and green areas are less steep; grey areas represent boundaries of slope polygons, and result from the complexity of the model.

The geological features exposed in the landslide scar indicate that the 2010 failure did not occur along the clay layer (old slide plane) which dips obliquely across the slope, or along bedding, which dips into the slope, a condition which generally enhances slope stability. This conclusion is illustrated by the stereonet analysis of the geometrical and kinematic and relationships of the main joints and wedge intersections and bedding in relation to the angle and aspect of the coastal slope (Figure 10). The analysis clearly shows the persistent joint sets which combined to form the joint wedges that controlled the rock mass failure in the lower slope. The plunge of the wedge intersections shown in Figure 10 are within or very close to the daylighting zone on the slope, which makes the slope more susceptible to failure.

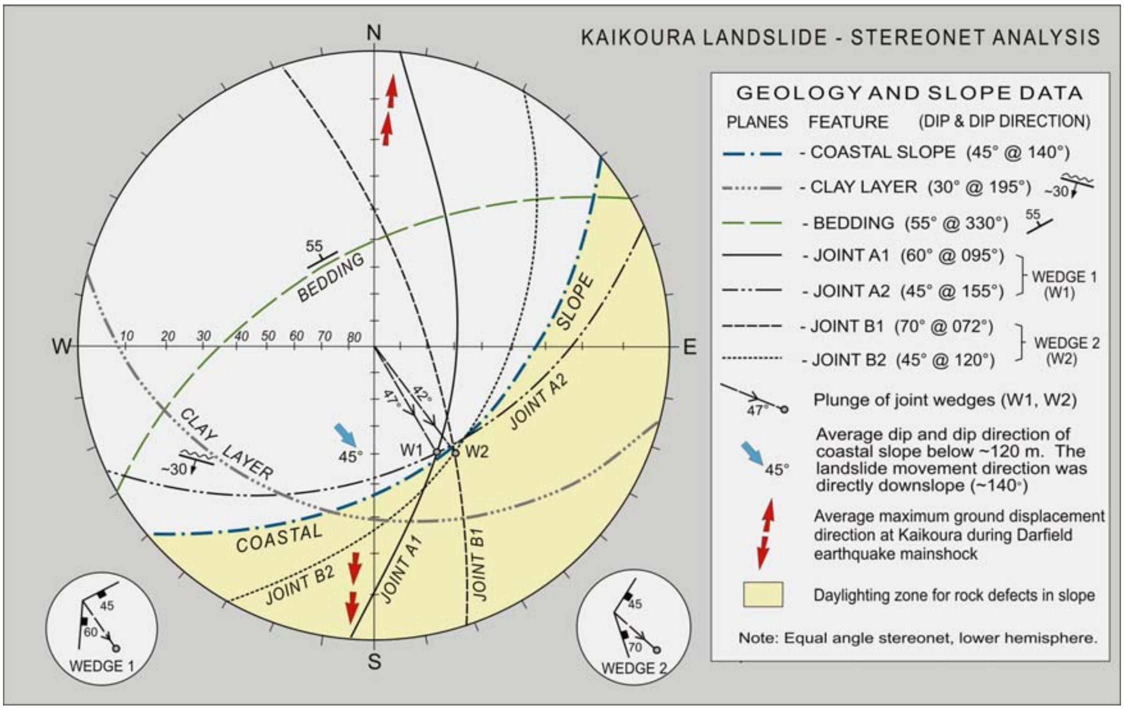

Figure 10 Stereonet analysis of geological structures in the 2010 landslide scar (main joints, wedge intersections (w1, w2), bedding, clay layer or old slide plane) in relation to the slope angle, aspect, and the rock defect daylighting zone on the coastal slope. The directions of landslide movement and earthquake shaking during the Darfield earthquake are also shown.

The recent failure involved collapse of the more weathered and dilated older slide debris with displaced sandstone beds in it above the clay layer (Figure 8), and the underlying jointed bedrock. Some of the debris from the older landslide on the upper slope appears to have moved about 25 m in a southwest direction, probably several thousand years ago. The displaced mass formed an oversteepened ‘bulge’ on the lower slope, and locally loaded the underlying rock mass containing persistent joints dipping out of the slope (Figures 7 and 10). The slope is then inferred to have become progressively more unstable over time as it was undercut by wave action, and later by cuts for the railway line and highway. Despite the adverse rockmass condition in the slope it apparently survived for a very long time after the initial slope failure. This was possibly because the joint wedges dipping out of the lower slope were relatively steep in relation to the slope angle, and only the northern wedge (w2) actually daylighted on the cliff face (Figure 10).

Groundwater is also likely to have played at part in the slope failure, but to what extent is uncertain. Water seepages associated with the old slide surface in the headscarp (Figure 8) suggest that the clay layer forms a permeability boundary on the slope, which would have ponded water above it, within the weakened, dilated material. During periods of rainfall these conditions would probably have resulted in locally elevated pore water pressures and increased loading on the lower slope. This would have reduced the overall stability of the slope and increased its likelihood of failure.

The 2010 landslide debris comprises mainly angular rocks (gravel) with boulders up to 1.5 m across, mixed in with colluvial deposits, stony top soil, and vegetation debris. When observed immediately after the failure (Figure 2), most of the surface debris appeared to have been derived from later failures from the head scarp area, rather than the initial main collapse. The distribution of debris suggests there were three source areas, resulting in two overlapping debris cones, with the southern cone formed first and the northern cone, derived from the head scarp, slightly later (Figure 6a).

A number of small rock falls from all three source areas occurred during removal of the debris from the toe of the slope to reopen SH 1 and the railway line, making the earthworks more dangerous and difficult to accomplish. Sluicing with a helicopter monsoon bucket was also carried out to remove loose debris and help stabilise the failure scar. Most of the debris has now been removed and the landslide toe and body has been cut back into in-situ ground (mainly weathered bedrock and old colluvium) at the base of the slope (Figure 7).

5. CAUSE OF THE LANDSLIDE

The rock mass forming the slope that failed (from ~30-100 m a.s.l.) is of relatively poor quality – variably bedded and closely jointed, with several adversely-oriented joints dipping ~40-70° obliquely out of the slope. Persistent joints extending 10-20 m through the rock mass have resulted in large wedge failures in some areas (Figure 7). The rock mass also appears to be somewhat dilated and disturbed, especially in the head scarp area above the extensive clay layer. The poor rock condition in the head scarp is consistent with that part having been affected by an earlier (prehistoric) slope failure a long time before the 2010 landslide. The absence of any old landslide debris at the site suggests that the older failure occurred when the toe the steep slope was actively being eroded by the sea during the mid Holocene optimum, a period of relatively higher sea levels in New Zealand about 3000-5000 years ago (Gibb 1986, Kennedy 2008). The combination of these unfavourable factors indicates that the slope on which the landslide occurred was susceptible to failure under appropriately adverse conditions or triggering events, which in this case could be either earthquake shaking or rainfall. The roles of these potential triggers are discussed below.

5.1 Earthquake shaking

Over the 6 days between the M_w 7.1 Darfield earthquake of 4 September 2010 and the landslide on 10 September there were many aftershocks, including 120 of magnitude 4.0 – 4.9, and 11 of magnitude 5.0 – 5.4 (local magnitude). A list of aftershocks greater than magnitude 4.3 and estimated MM intensities and peak ground accelerations (PGA) at the slip site correlated against rainfall and rockfall activity at the landslide site is presented in Table 1.

Table 1 shows that the Darfield earthquake mainshock on 4 September 2010 was strongly felt (intensity MM 5) at Kaikoura, and may have reached ~MM 6 at the 2010 landslide site, with a peak ground acceleration (PGA) about 0.021 g (pers. comm. G. McVerry). However that level of shaking did not cause the slope to fail, or any significant or apparent instability at the site. Between 4 and 10 September felt intensities during 11 aftershocks of M 5.0–5.4 were all less than MM 4 in the Kaikoura area (pers. comm. W Smith). The estimated PGA values for these events range from ~0.005 – 0.007 g (pers. comm. G. McVerry), all much weaker than the mainshock. The shaking caused by 42 aftershocks of M 4.3–4.9 over the same period would have been considerably less (about 0.002 – 0.004 g). There were no felt intensity reports from Kaikoura during any of the recorded aftershocks, and none can be directly correlated with the time of the landslide which blocked the railway line and SH 1, which is estimated to have been between 9:57 and 10:16 pm on 10 September.

Precedent evidence from New Zealand shows that shaking of MM 5 or 6 would not normally be high enough to trigger a failure like the 10 September landslide, despite any topographic amplification of shaking at the site. Recent studies of landslides triggered by historical earthquakes in New Zealand (Hancox et al, 1997, 2002; Dowrick et al. 2008) have shown that the minimum MM intensity for landsliding in New Zealand is MM 6 (rocks dislodged on steep slopes, a few very small ($\leq 10^3$ m^3) soil and regolith slides and rock falls on steep banks and cuts. Widespread landsliding and larger landslides (10^4–10^5 m^3 or >) similar to the Kaikoura landslide, generally only occur at MM 7 or greater *(see Appendix 2)*.

Table 1 Aftershocks of magnitude 4.3 or greater associated with the Darfield earthquake, rainfall at Kaikoura, and rock fall activity at the Rosy Morn Stream landslide site from 4 to 10 September 2010.

EARTHQUAKE DATA			Comments on Earthquakes (MMI & PGA at LS Site)	KAIKOURA RAINFALL DATA			
Date	Time (NZ Standard)	Magnitude (M_w, M_L)	Comments on Landslide Activity at 2010 Landslide Site	Rainfall (mm) in 24 hrs to			
				09:00	24:00	Deficit	Runoff
30 Aug 2010			Note: No landslide/rock fall activity noted at site prior to 8/9/10	1.4	34.8		
31 Aug 2010				33.4	0.2		
1 Sep 2010				0.4	0.2		
2 Sep 2010							
3 Sep 2010					3.0		
4 Sep 2010	04:35	7.1 (M_w)	**Darfield Mainshock – MM 4-5 at Kaikoura (PGA 0.012-0.026 g).**	3.0			
4 Sep 2010	04:56	5.3	**Aftershock 5.0 or >**				
4 Sep 2010	05:06	4.8					
4 Sep 2010	5:26	4.7					
4 Sep 2010	05:38	4.4					
4 Sep 2010	05:46	4.3					
4 Sep 2010	05:55	4.6					
4 Sep 2010	06:01	4.5					
4 Sep 2010	06:17	4.3					
4 Sep 2010	06:18	4.5					
4 Sep 2010	07:04	4.3					
4 Sep 2010	07:07	4.8					
4 Sep 2010	07:13	4.6					
4 Sep 2010	07:56	5.2	**Aftershock 5.0 or >**				
4 Sep 2010	08:15	4.6					
4 Sep 2010	10:17	4.4					
4 Sep 2010	11:12	5.3	**Aftershock 5.0 or >**				
4 Sep 2010	13:52	4.4					
4 Sep 2010	14:01	4.4					
4 Sep 2010	16:55	5.4	**Aftershock 5.0 or >**				
4 Sep 2010	19:03	4.5					
4 Sep 2010	19:07	4.7					
4 Sep 2010	20:54	4.7					
4 Sep 2010	22:34	4.6					
4 Sep 2010	22:38	5.0	**Aftershock 5.0 or >**				
5 Sep 2010	04:23	4.4					
5 Sep 2010	05:17	4.9					
5 Sep 2010	05:20	5.1	**Aftershock 5.0 or >**				
5 Sep 2010	05:53	4.4					
5 Sep 2010	06:36	4.3					
5 Sep 2010	06:59	4.3					
5 Sep 2010	08:13	4.3					
5 Sep 2010	09:46	4.4				6.4	0
5 Sep 2010	13:04	5.0	**Aftershock 5.0 or >**				
5 Sep 2010	13:55	4.4					
6 Sep 2010	12:35	4.4				8.5	0
6 Sep 2010	15:07	4.4					
6 Sep 2010	15:34	4.3					
6 Sep 2010	18:01	4.5					
6 Sep 2010	23:24	5.2	**Aftershock 5.0 or >**				
6 Sep 2010	23:25	4.5					
6 Sep 2010	23:40	5.4	**Aftershock 5.0 or >**				
7 Sep 2010	00:21	4.6					
7 Sep 2010	03:24	5.4	**Aftershock 5.0 or >**			10.5	0
8 Sep 2010	00:41	**4.6**					
8 Sep 2010	03:59	4.8					
8 Sep 2010	07:49	5.1	**Aftershock 5.0 or >**	5.6		7.0	0
8 Sep 2010	09:01	4.3					
8 Sep 2010	14:50	4.3	(1) 16:05 – Police report rocks across MNL Track at 176 km (LS site). (2) 16:29 – KiwiRail report slip cleared. (3)23:20 – MNL Track blocked by slip at 176 km (LS site).		11.2		
9 Sep 2010	02:49	4.3	(1) 09:56 – Slip cleared, MNL reopened.	5.6		3.5	0
9 Sep 2010	06:14	4.3			13.8		
10 Sep 2010	00:25	4.3		21		0	15.4
10 Sep 2010	07:10	4.6	(1) 7:51 – Rockfall reported at MNL 176 km. line closed. (2) 0921 – Slip cleared, track reopened.				
10 Sep 2010	22:04	4.3	(3) 21:57 – Boulders reported on SH 1 and MNL railway at 176 km. (4) 22:16 – Large landslide reported at slip site, SH 1 closed. (5) 22:45 – MNL closed (both reopened 16 Sep after slip cleared).		7.2		

Notes:
(1) Earthquake data from GeoNet website (*www.geonet.org.nz*). 2) Rainfall data from NZ MetService. (3) MNL railway line information from KiwiRail. (4) SH 1 information from NZTA. (5) Earthquake magnitudes are M_W (moment magnitude) for the mainshock and M_L (local magnitude) for aftershocks.

5.1.1 Darfield earthquake strong motions

The magnitude 7.1 Darfield earthquake of 4 September 2010 UT yielded New Zealand's richest and strongest set of strong motion data since recording began in the early 1960s. Mainshock accelerograms were returned from 130 sites in the GeoNet recorder network (www.geonet.org.nz), ten or which had peak horizontal accelerations in the range 0.3 to 0.82 g. One near-fault record, from Greendale, had a peak vertical acceleration (PGA) of 1.26 g. Eighteen records showed peak ground velocities exceeding 0.5 m/s, with three of them exceeding 1 m/s (Cousins and McVerry, 2010).

A feature of the mainshock records was the long-period content, even in records as distant as a strong motion recording site on weak rock (Site Class B) at South Bay in Kaikoura, 12 km east-northeast of the landslide site (Figure 1), and about 175 km from the earthquake's epicentre (Figure 11). A consequence of the long-period content of the motions was that the peak ground displacement at South Bay, 44 mm, was very large in relation to the peak ground acceleration of about 0.01 g, and there was also a marked north-south polarisation to the motion (Figure 12, pers. comm. Jim Cousins, 2010). The mainshock was also notable for its long duration (~150 seconds) and relatively high peak velocity (~45 mm/s) which coincided with peak displacement (Figure 11). All of these factors would have increased the significance of the mainshock at the landslide site.

The motions described above equate to a felt intensity of MM 5 in the South Bay area (GeoNet Website). However, at the landslide site on the steep coastal cliff south of Kaikoura the ground motions are likely to have been amplified to some extent by topographic effects, and may have reached ~MM 6 high on the cliff face. The dominant north-south direction of the long-period ground displacement is also likely to have had a destabilising effect on the landslide as these motions are slightly oblique to aspect of the slope and the south-southeast (~140°) direction of the landslide movement (see Figures 10 and 12).

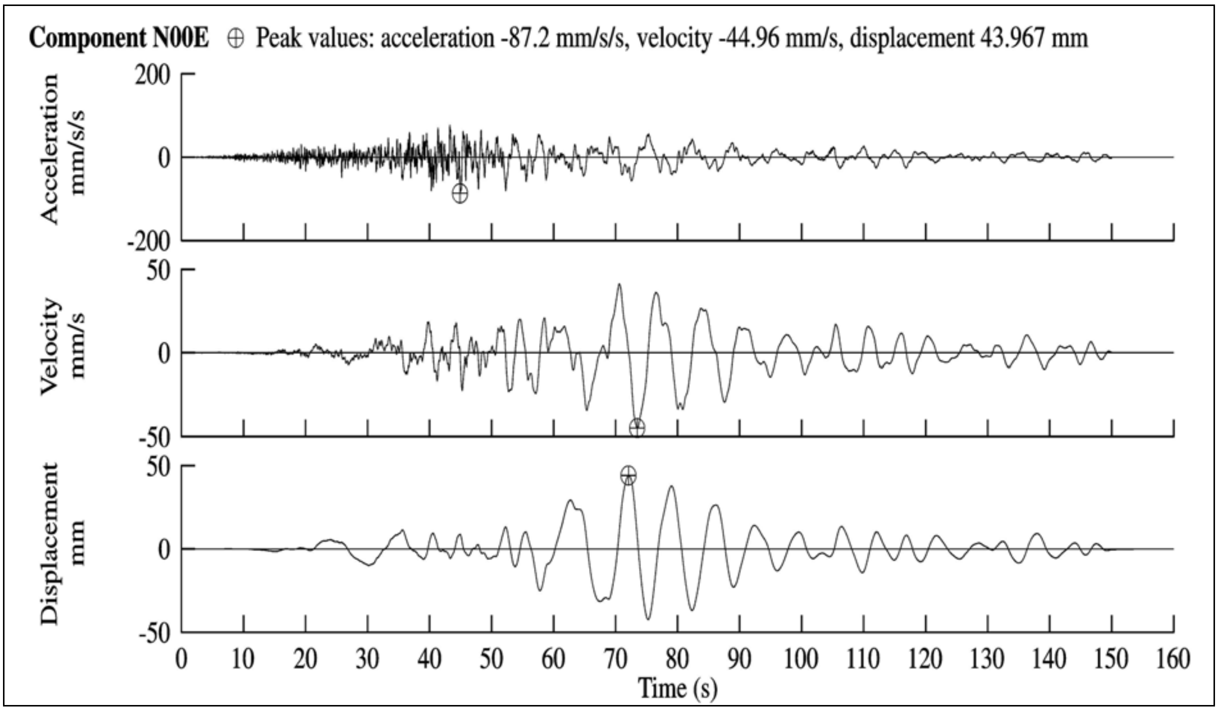

Figure 11 North-south motions computed from strong-motion recording from South Bay, Kaikoura.

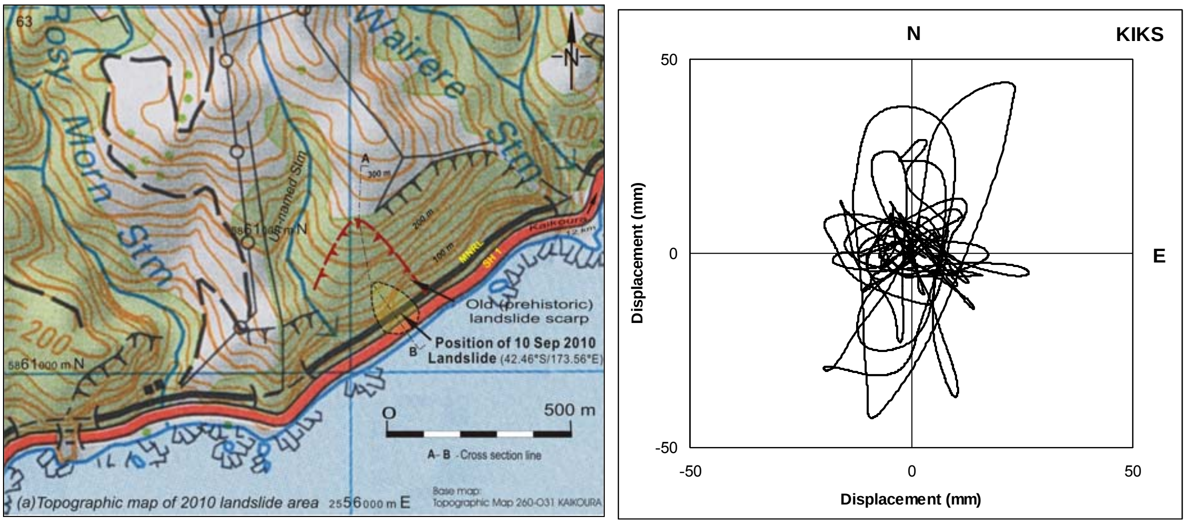

Figure 12 Horizontal ground displacements at Kaikoura *(right)* shown in relation to the landslide site *(left)*.

One of the larger aftershocks also was recorded at Kaikoura, a magnitude 5.4 event on September 4th (the other aftershocks were too small to trigger the strong motion recorder). The record for that event is very different to that from the mainshock, being much smaller and having very little long period content. The PGA recorded at Kaikoura during that event was 0.001 g (one tenth of that from the mainshock) and the peak ground displacement was 0.1 mm (one four-hundredth of that from the mainshock - pers. comm. Jim Cousins, 2010). The mean peak ground accelerations estimated at the landslide site during the magnitude 4.3 to 5.4 aftershocks range from 0.003-0.007 g at (pers. comm. G McVerry).

The weaker motions associated with many aftershocks of ~M4–5.4 over six days following the Darfield earthquake (Table 1) were probably far less important at the 2010 landslide site than the much stronger mainshock on 4 September. However, the greater incidence of rocks on SH 1 and railway line in the Kaikoura area which occurred during the aftershock phase (pers. comm. Mike Connors, NZTA) suggests that the shaking was strong enough to have affected slopes in the area. Therefore, although the Darfield mainshock on 4 September did not trigger the landslide immediately, it may have initiated the slope failure process. The low intensity shaking caused by the aftershocks is likely to have enhanced the destabilisation of the slope and advanced its progress towards the rapid slope collapse on 10 September.

5.1.2 Significance of the aftershock sequence

One of the significant aspects of the Darfield earthquake was the aftershock sequence. Between the mainshock on 4 September and 31 October 2010 there were about 1000 aftershocks of magnitude 3.0 and greater, with the largest of these being magnitude 5.4. Between 4 and 10 September, when the landslide occurred near Rosy Morn Stream, there were over 500 aftershocks of magnitude 3.0 or greater, 90 of magnitude 4.0 or greater, 28 of magnitude 4.5 or greater, and 11 of magnitude 5.0. The length of the aftershock sequence and the resulting damage was possibly unique in New Zealand. This may be related to the long recurrence interval of the Greendale Fault (~16,000 years, www.geonet.org.nz) which was responsible for the Darfield earthquake (pers. comm. Martin Reyners, 2010).

Unrelated to the aftershock sequence, three earthquakes of magnitude 2.3 to 2.7 occurred near Kaikoura on 9 and 10 September, within ~7–21 km of the slip site (www.geonet.org.nz). These very small earthquakes are unlikely to have had a significant affect on the landslide site.

5.1.3 Effects of historical earthquakes

The 2010 landslide site has experienced MM 6–7 or greater shaking 8 times since 1848, and on 4 occasions reached MM 5, the same as the Darfield earthquake mainshock (Table 2). There are no records on any slope instability at the landslide site during any of these historical earthquakes, or at any time prior to 8 September 2010.

Table 2 Earthquakes that have caused MM 4-7 intensity shaking at the 2010 landslide site since 1948.

Earthquake Date and Name (Magnitude and Fault source if known)	Approximate MM intensity at landslide site south of Kaikoura
1848 Marlborough (M 7.1, Wairau Fault)	7
1855 Wairarapa (M 8.1, West Wairarapa Fault)	6
1888 North Canterbury (M 7.0-7.3, Hope Fault)	6
1922 Motunau, North Canterbury (M 6.4)	5
1929 Arthur's Pass (M 7.1, Kakapo Fault)	5
1929 Murchison (M 7.8, White Creek Fault)	6
1931 Napier (M 7.8)	4
1934 Pahiatua (M 7.6)	4
1942 Masterton (M 7.2)	5
1965 Chatham Rise (M6)	5
1966 Seddon (M 5.8)	4
1968 Inangahua (M 7.1, Inangahua Fault)	5
2010 Darfield (M 7.1, Darfield Fault)	5
Note: Earthquakes and MM intensity data 1848-1968 from Downes 1995; Dowrick and Cousins, 2003.	

Based on historical earthquake-induced landslide data in New Zealand, the 10 September landslide seems unlikely to have been triggered by the Darfield earthquake, centred ~160 km to the southwest, or any of the aftershocks. No large landslides were triggered by the earthquake on susceptible slopes in the Christchurch and Lyttelton areas, or on slopes to the north. There is, however, evidence from to show that steep coastal slopes in the Kaikoura area were adversely affected by the long earthquake sequence, as the NZTA reported a noticeable increase in the frequency of rocks falling on to SH 1 during the week after the earthquake when the weather was mainly fine.

Although seismic shaking during the Darfield earthquake did not trigger the landslide, evidence suggests that some slopes in the Kaikoura area were affected by the earthquake and the associated aftershock sequence. These earthquakes subjected the landslide site on the coastal slope to repeated, low intensity shaking which may have slightly reduced its stability, making it more likely to fail during adverse conditions, such as rainfall. It is possible that the cumulative effects of the earthquakes, combined with moderate rainfall over three days reduced the stability of the slope to a level where rapid failure occurred.

The fact that a small failure occurred on the southern flank of the landslide on Wednesday 8 September, two days before the main failure (Table 1), suggests that the slope was already close to complete failure at that stage. Therefore, it may be reasonable to conclude that the timing of the main failure on Friday 10 September was not controlled by a single triggering event, but by the combined effects of several contributing factors including: the slowly deteriorating rock mass weakened by an earlier failure, the long sequence of low level earthquake shaking associated with the Darfield earthquake, and the 32 mm of rain that fell over the preceding 72 hours. The relative contributions of these factors are examined next.

5.2 Rainfall

The Kaikoura coast is noted for its rapid weather changes and associated high intensity rainstorms, many of which have resulted in widespread erosion, landslides, and flooding problems that have caused disruption to roads and rail services (Bowring et al. 1979). Foremost amongst these storms was Cyclone Alison, which occurred in March 1975, bringing heavy rain to large areas of the country. The Kaikoura region was hit particularly hard by the storm, with intense rainfalls of 40-70 millimetres per hour in some catchments. In the area of the 2010 landslide near Rosy Morn Stream, 200–300 mm rain fell over 48 hours on 11-12 March 1975 (Bell, 1976).

During Cyclone Alison, floods and debris flows poured down many streams in the Seaward Kaikoura Range, and flowed out onto the coastal plain. Many parts of SH 1 and the MNL railway line were washed out or buried under gravel. One diesel locomotive was stopped and partly buried by a debris flow (debris flood). There were also several wedge-controlled “chute” failures in jointed greywacke strata along the coastal section south of Kaikoura (Bell 1976). These failures were similar to the landslide triggered by a rainstorm on 31 July 2008 landslide 1 km north of the 2010 landslide (Figure 13), which closed SH 1 and the railway line for several days (Opus Consultants, 2008). The slope on which the 2010 landslide occurred seems to have been unaffected by either of these rainstorms.

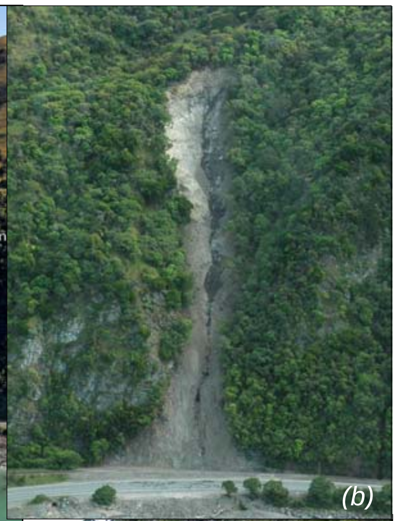

Figure 13 (a) The 31 July 2008 landslide ~1 km north east of the 2010 landslide near two railway tunnels; (b) the wedge failure source of the 2008 landslide at the top of a narrow "chute" scour channel which funnelled debris down the slope; (c) SH 1 and the railway line blocked by a large debris fan comprising ~10,000 m^3 of soil, angular gravel, boulders, and other slope debris on 31 July 2008.

(Photos (b) and (c) from Opus, 2008).

The July 2008 landslide occurred after record 1-day rainfall (144 mm) was recoded at Kaikoura on 30 July, and most of the Marlborough to Canterbury region received 200-300% of the mean July rainfall (data from NIWA Monthly Climate Summaries). Although that storm resulted in a significant landslide in the vicinity of the 2010 landslide, the slope on which the 2010 failure occurred was not significantly affected, although the small superficial slip scar just to the north is believed to have occurred during the 2008 storm.

Considering the climatic history of the Kaikoura coast, the 32 mm of rain that fell over three days just prior to the landslide (Table 1) is unlikely to have caused the large landslide that occurred. As discussed earlier, the landslide site has been subjected to and survived more intense rainfall in the past. The most recent example of this type of event occurred a few days before the Darfield earthquake, when 35 mm rain fell at Kaikoura on 30 August without causing any noticeable instability at the 2010 landslide site (Table 1).

The long term rainfall data on the NZ Metrological Service website (www.metconnect.co.nz) show that there was an increase in monthly rainfall at Kaikoura over three months prior to the September 2010 landslide, particularly May and June during which the monthly rainfall totals were significantly greater than the mean (Figure 14). Although such a trend can lead to increased antecedent soil moisture on some slopes, there is no evidence this was a significant factor at the landslide site or elsewhere on the slope. When the 2010 landslide occurred the cumulative deviation from the mean rainfall at Kaikoura was still negative, after less than average rainfall over 12 of the last 16 months (Figure 14).

Steep, well drained jointed rock slopes tend to enhance surface runoff and reduce rainfall infiltration into a slope, which consequently lessens the potential for increased antecedent moisture levels on the coastal slopes south of Kaikoura. The absence of any increase in landsliding in the area over the four months prior to September 2010, and the lack of a response to 35 mm rainfall on 30 August, suggests that increased monthly rainfall over three of the preceding four months was probably not, on its own, a significant factor in the initiation of the 2010 landslide. However, in combination with the Darfield earthquake sequence, the longer-term rainfall may have been important contributing factors.

KAIKOURA RAINFALL: Monthly Totals, Long Term Monthly Mean, Cumulative Deviation from Mean (mm) for Jan 2009 to Sep 2010

Rainfall (mm)	Jan-09	Feb-09	Mar-09	Apr-09	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10	May-10	Jun-10	Jul-10	Aug-10	Sep-10
Long Term Monthly Mean	58.1	41.9	67.1	54.8	45.1	79.4	101.5	48.7	56.5	57.7	69.5	48.3	58.1	41.9	67.1	54.8	45.1	79.4	101.5	48.7	56.5
Montlly Rain Totals (mm)	15.0	113.4	13.4	28.4	82.0	52.0	34.2	30.2	40.4	100.0	33.8	31.2	20.2	21.6	68.4	10.2	184.6	132.4	98.0	75.0	39.4
Cumulative Deviation from Mean (mm)	-43.1	28.4	-25.3	-51.7	-14.8	-42.2	-109.5	-128.0	-144.1	-101.8	-137.5	-154.6	-192.5	-212.8	-211.5	-256.1	-116.6	-63.6	-67.1	-40.8	-57.9
Deviation from Mean	-43.1	71.5	-53.7	-26.4	36.9	-27.4	-67.3	-18.5	-16.1	42.3	-35.7	-17.1	-37.9	-20.3	1.3	-44.6	139.5	53.0	-3.5	26.3	-17.1

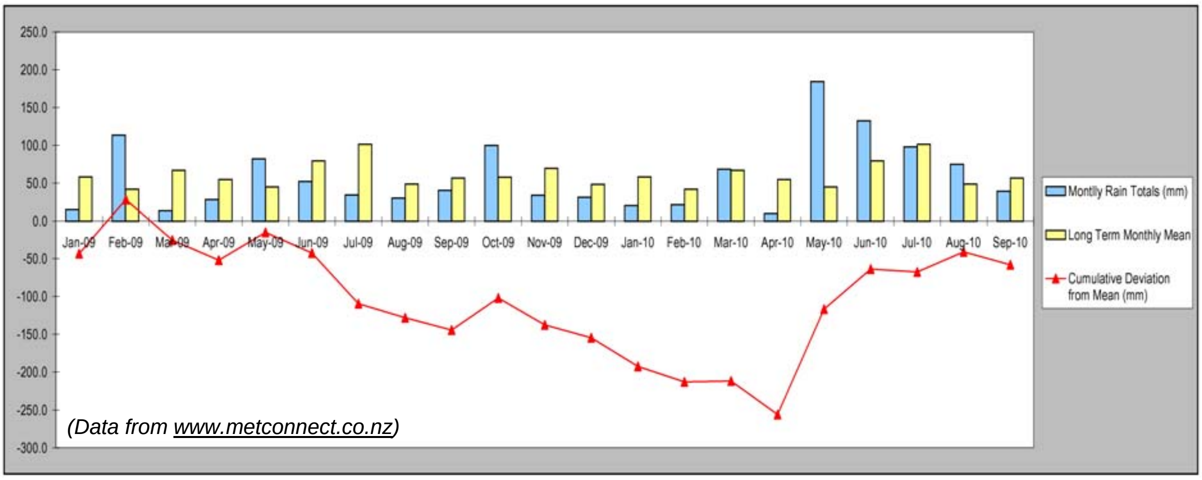

Figure 14 Monthly rainfall totals and cumulative deviation from mean at Kaikoura 2009-2010.

6. DISCUSSION

6.1 Cause and trigger of the landslide

When a number of factors or preconditions contribute to the cause of a landslide it is often difficult to identify the principal ‘trigger’ of a slope failure with certainty, unless an eye witness account links it to a specific event or process. There was no eye witness to the landslide that blocked the railway and SH 1 on 10 September, so the ‘trigger’ for that event is not clear-cut. However, the geological history of the slope and the time line of events laid out in Table 1 make it possible to establish the contributing factors and most likely trigger for the event. A graphical representation of the timeline of geological and historical events that are relevant to the coastal slope and the 2010 landslide is presented in Figure 15.

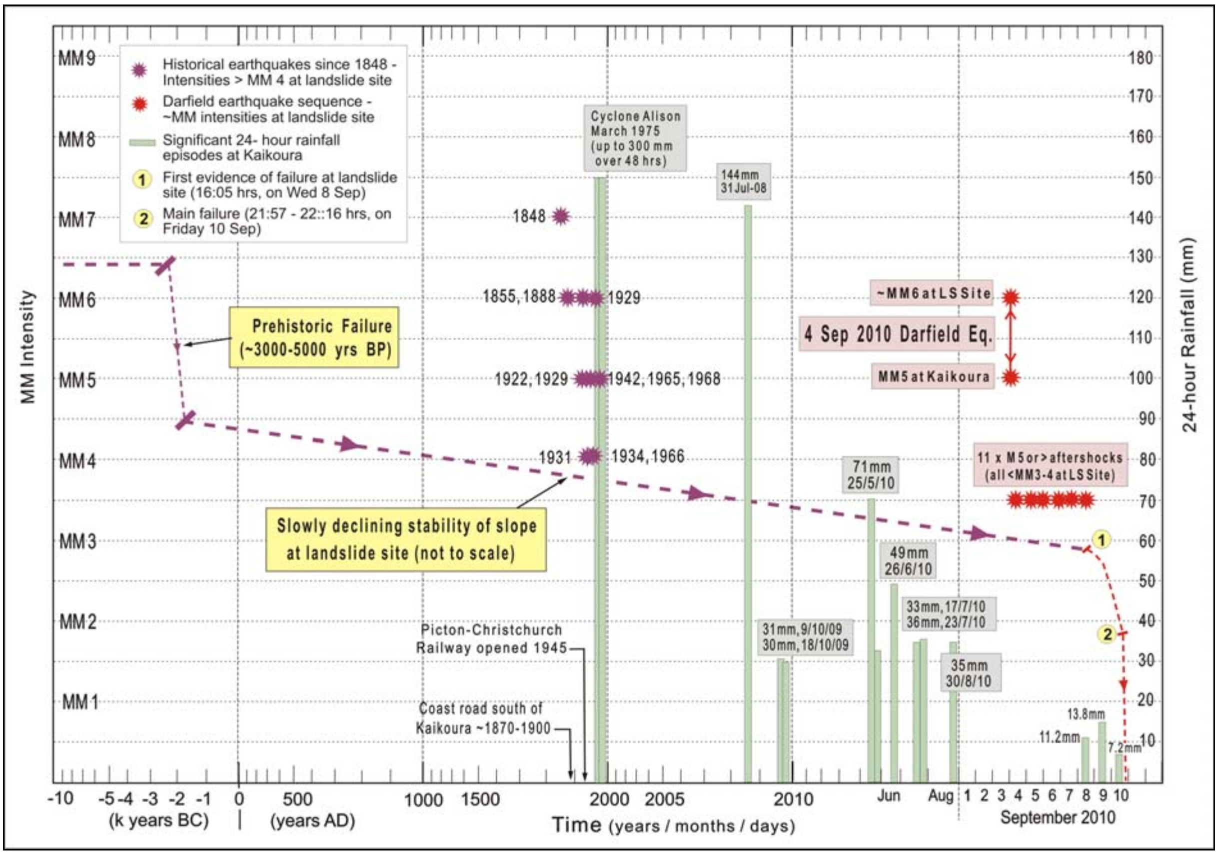

Figure 15 Graphical representation of the timeline of large earthquakes, significant rainfall episodes, and other events that may be relevant to the triggering of the September 2010 landslide.

Given the previously described unfavourable geological conditions and failure history of the slope on which the landslide occurred, greater than average rainfall over the preceding four months, prolonged low intensity shaking associated with the Darfield earthquake and the numerous aftershocks, and low to moderate rainfall over three days appear to have combined to trigger the landslide on 10 September 2010. Long-term weathering processes ('slope ripening') over several thousands of years will also have played an important role in weakening and preparing the slope for another failure after its partial prehistoric collapse, as will the excavation for the railway line at the toe of the slope in the late 1800's (Figure 15).

After considering the effects of past rainstorms and earthquakes in the Kaikoura area, and the sequence of events before the landslide occurred (Table 1, Figure 15), the Darfield earthquake mainshock and its long sequence of aftershocks appear to have an increased importance in the initiation of the 2010 landslide. The key details of the process contributing to the failure are:

(1) The Darfield earthquake on 4 September 2010 caused moderately strong, long-duration shaking (~MM 6, PGA 0.01g or >) at the slip site, with relatively large ground displacements of up to 44 mm, polarised in a north-south direction. This level of shaking would have been unfavourable for the slope, and may have been responsible for initiating the process that culminated in the rapid collapse on 10 September.

(2) The slope may have been more susceptible to failure at the time of the earthquake due greater than average rainfall over the preceding four months, as shown by the steep rise in the cumulative deviation from the mean monthly rainfall curve over that period (Figure 14).

(3) Between 4 and 10 September 2010, there were about 120 earthquakes of magnitude 4.0 to 4.9, and 11 of magnitude 5.0 or greater, causing prolonged low intensity shaking at the slip site (<MM 4 with PGAs of ~0.001–0.007 g). It is inferred that this shaking further reduced slope stability to a point where observable slope failure was imminent.

(4) A magnitude 5.1 aftershock occurred at 07:49 on Wednesday 8 September, and was followed at 16:05 on the same day by the first rock fall from the southern side of landslide site *(MNL Distance 176 km, Appendix 1)*. The failure on Wednesday afternoon was the first indication of slope instability at the site, and is interpreted to be the first visible evidence of the start of the recent landslide development process.

(5) The failure on Wednesday afternoon occurred just after it had started raining, with 11 mm recorded at 24:00 on 8 September. At 23:20 that day the railway line was blocked by another slip at the same site. A further 21 mm of rain fell over the next 48 hours to 09:00 on Friday 10 September.

(6) On Friday 10 September at 07:51 a rock fall from the centre of the landslide site closed the railway line for 1½ hours. That failure occurred during light rain, but there was no significant rainfall after 9 am. At 9:57 pm that evening, about 13 hours after it stopped raining, the Police advised the NZTA that there were boulders on SH 1 and railway line.

(7) When the site was inspected by NZTA contractors at 10.16 pm, both SH 1 and the railway line were found to be blocked by a large landslide. The main (large) failure must have occurred some time between 9:57 and 10:16 pm. Within that window of opportunity a magnitude 4.3 aftershock occurred at 10:04 pm. There is no eye witness account or any other evidence to indicate that the very weak shaking (PGA ~0 003 g) associated with that event was responsible for the main collapse.

From the time line of aftershocks, rainfall data, and rock falls at the landslide site discussed above it is concluded that the Darfield earthquake and the aftershocks probably contributed significantly to the weakening of the rock mass in the slope, which was probably already more susceptible to failure due to greater then average rainfall over the preceding four months. Low to moderate rainfall just before the main failure occurred would also have contributed to the development of the failure. On its own, however, the 32 mm of rain over the three days prior to the landslide was probably not very significant, as the slope had survived more intense rainfall ten days before failure, and on numerous previous occasions. The precursory failures at the landslide site show that the slope was in the process of failing and close to a large-scale failure at 9.57pm on Friday 10 September. It is likely therefore that the Darfield earthquake mainshock on 4 September and the prolonged sequence of aftershocks combined with greater than average rainfall over the preceding four months to trigger the landslide. In this context, the earlier prehistoric failure, adverse geological structures within the slope and greater than average longer-term rainfall are regarded as factors that pre-conditioned the slope and made it susceptible to failure on 10 September, whereas the Darfield earthquake and aftershock sequence acted more in a triggering role.

Because the slope had survived much greater rainfall on many occasions in the past, the cumulative effects of the strong mainshock and the long sequence of low intensity aftershocks are believed to have been the most significant factors in the timing or triggering of the landslide. Looking at the available evidence there is a strong possibility that the slope would not have failed on 10 September 2010 if the Darfield earthquake and aftershocks had not occurred. However, given the poor rock condition and earlier failure history of the slope, it probably would have failed at some time in the future.

6.2 Significance of the landslide

The 10 September landslide near Rosy Morn Stream was probably the largest and most significant failure on the Kaikoura coast in the last 35 years. Although it was not a particularly large landslide (only ~50,000 m^3) it was very important because of the disruption it caused to transport. The slip closed SH 1 and the railway line, and blocked usual road and rail access from Picton to Christchurch for one week. That closure occurred at a vital time when supplies were urgently needed in Christchurch after the Darfield earthquake. The extensive earthworks needed to clear the landslide debris and reopen the main highway and railway line also incurred considerable expense. Other costs were incurred by the diversion of rail, freight, and road traffic through alternative routes such as the Lewis Pass or Inland Kaikoura highways.

The other noteworthy aspect is that the recent failure has significantly oversteepened the lower slope, especially in the head scarp area, making highly susceptible to further collapses in the future. Some of these failures might only be small, but there is potential for large failures of the weak old slide debris above the clay layer, and some of these might be large enough to again close the railway line and SH 1. Another laser scan of the landslide scar will be carried out by GNS Science in the near future to see if there has been further movement on the slope, and if necessary the scan data could be used in the design of mitigation measures at the site.

The landslide was also significant from a geotechnical perspective as it provides reasonably convincing evidence that prolonged, cumulative low intensity earthquake shaking can initiate (trigger) a landslide in some steep, susceptible slopes that are approaching failure. This process has not previously been observed in New Zealand, as the very low shaking intensities involved (< MM 3-4) are well below the ~MM 7 intensity threshold normally associated with a failure of this type and size *(Appendix 2)*. The September 2010 landslide near Kaikoura demonstrates the hazard potential of aftershocks associated with large earthquakes on some highly susceptible slopes, even at distances greater than 100 km from the epicentre.

7. CONCLUSIONS

(1) The landslide which blocked SH 1 and the railway line near Rosy Morn Stream 12 km south of Kaikoura on 10 September 2010 is a moderately large (~50,000 m3) debris and rock slide. The failure occurred on the toe of a large prehistoric landslide on the steep coastal slope, which is formed of indurated, interbedded, well jointed greywacke sandstone and mudstone bedrock, and is overlain by thin colluvial deposits.

(2) The results of this study indicate that landslide cannot be attributed to any one triggering event, but instead it appears to have been caused by a combination of factors. These factors include unfavourable geological conditions on the previously failed slope, shaking caused by he Darfield earthquake mainshock and the long sequence of aftershocks, greater than average rainfall over the preceding four months, and low to moderate rainfall over three days before the failure, all combined to cause the landslide on 10 September. Because of the timing of the aftershocks, rock falls at the landslide site, and rainfall in the area, which stopped about 12 hours before the main failure, the cumulative effect of the mainshock and aftershocks is seen as a particularly important factor in the initiation of the landslide and in bringing the slope to failure.

(3) The Darfield earthquake on 4 September 2010 caused moderately strong, long-duration shaking (~MM 6, PGA 0.015g) at the slip site, with relatively large ground displacements of up to 44 mm, polarised in a north-south direction. This level of shaking would have been unfavourable for the slope, and may have been responsible for starting the slope failure process. From 4 to 10 September 2010 when the landslide occurred there were 120 earthquakes of magnitude 4.0 to 4.9, and 11 of magnitude 5.0 or greater, which caused low intensity shaking at the landslide site (<MM 3-4, with peak ground accelerations of ~0.001–0.007 g).

(4) Earthquake shaking is believed to have further weakened the rock mass in the slope, which was probably made more susceptible to failure due to greater than average longer-term rainfall. On its own the 32 mm of rain that fell over three days prior to the landslide was probably not very significant, as the slope had survived more intense rainfall ten days before the failure, and considerably more several times over the last 35 years or more. In the context of the overall slope failure process, the earlier prehistoric failure, adverse geological structures within the slope and greater than average longer-term rainfall are therefore seen as factors that pre-conditioned the slope and made it susceptible to failure on 10 September. The Darfield earthquake and the aftershock sequence are believed to have acted more in a triggering role.

(5) The cumulative effect of the Darfield earthquake mainshock and the prolonged sequence of low intensity aftershocks are therefore believed to have been the most significant factor in triggering the landslide. There is a strong possibility that the slope would not have failed on 10 September 2010 if the Darfield earthquake and aftershocks had not occurred. However given the poor rock condition and earlier failure history of the slope, it probably would have failed at some time in the future.

(6) Despite its modest size, the 2010 landslide was a significant event, mainly because of the disruption it caused to transport by closure of an important road and rail link to Christchurch at a time when supplies were urgently needed there after the Darfield earthquake. Normal road and rail access was blocked for one week while the debris was cleared away. However, the recent failure also oversteepened the slope, making it more susceptible to further collapses in the future, some of which might be large enough to again close the railway line and SH 1.

(7) The 2010 landslide was also of geotechnical significance, as it provided reasonably convincing evidence that under some conditions cumulative low intensity shaking can trigger moderately large landslides on some highly susceptible slopes at distances greater than 100 km from the epicentre. This possibility should be taken into account in future earthquake and landslide hazard and risk assessments in New Zealand.

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9. ACKNOWLEDGEMENTS

This study was funded under the GNS Science GeoNet and FRST landslide research projects. The author wishes to thank his GNS colleagues Grant Dellow, Chris Massey, and Stuart Read for helpful reviews of the report, and also Garth Archibald for the laser scan model, and Jim Cousins and Graeme McVerry for the strong motion data presented in the report. GNS Science colleagues Pilar Villamor, Nick Perrin, and Martin Reyners, Greg Saul (Opus Consultants), and David Hopkins, Bruce Riddolls, and Ed Ladley, are also acknowledged for providing information and valuable discussions during the study.

APPENDIX 1 KIWIRAIL SMS REPORTS RELATING TO SLIP AT MNL DISTANCE 176KM

The following extracts from KiwiRail SMS (Short Message Service) message records were sent:

From: +642704580985897
Sent: Sep 8, 2010 4:05 PM
MNL Oaro to Kkura police have reported a rock slip across track at 176km . Staff on way to site. 701 held at Kkura
NCM.

From: +642704580985898
Sent: Sep 8, 2010 4:29 PM
MNL 176km update Staff on site cleared slip. Staff will stay on site and watch 701 pass thru at reduced speed
NCM

From: +642704580985899
Sent: Sep 9, 2010 6:47 AM
At 2320 hours advice received that MNL is blocked by a slip @ 176km Oaro - Kaikoura. Due to falling rocks ETA on track assessment 0800 hrs., Thurs.
NCM, KIWIRAIL

From: +642704580985903
Sent: Sep 9, 2010 8:24 AM
Update slip MNL track clearance expected at 1000hrs.
NCM

From: +642704580985904
Sent: Sep 9, 2010 10:14 AM
Track Clearance for slip 176km MNL received at 0956hrs.
NCM

From: +642704580985911
Sent: Sep 10, 2010 7:51 AM
Another rockfall 176km MNL between Kaikoura - Oaro
have closed the line. Staff on site in 10".
NCM

From: +642704580985914
Sent: Sep 10, 2010 9:59 AM
Rockfall MNL cleared track re-opened with restrictions at 0921hrs.
NCM

From: +642704580985916
Sent: Sep 10, 2010 10:45 PM
Subject: MNL closed between Oaro & Kkura

From: +642704415021920
Sent: Sep 11, 2010 12:31 PM
MNL still closed at OARO. 735S/11, 737S/11, 721S/11, 739/12, 701/12, 722S/11, 700/12, 734S/12 will not run. No rail on RF07/11 & RF10/11. DE-LSM
Mnl closed between Oaro & Kkura slip across track & road at 176km. possible closed up to 24hrs or more update Saturday am
NCM

From: +642704580985925
Sent: Sep 11, 2010 6:54 PM
Update MNL slip. Work finished for day unable to work at night to dangerous. Work restart first light. Update 1100hrs Sunday
NCM

Data from KiwiRail by courtesy of David Hopkins Consulting.

APPENDIX 2 LANDSLIDE AND ENVIRONMENTAL CRITERIA FOR THE MODIFIED MERCALLI INTENSITY SCALE – NZ 2007

Landslide and Environmental Criteria for the Modified Mercalli Intensity Scale – NZ 2007	
MM5	▪ Loose boulders may occasionally be dislodged from steep slopes.
MM6	▪ Trees and bushes shake, or are heard to rustle. ▪ Loose material may be dislodged from sloping ground, e.g. existing slides, talus and scree slopes. ▪ A few very small ($\leq 10^3$ m^3) soil and regolith slides and rock falls from steep banks and cuts. ▪ A few minor cases of liquefaction (sand boil) in highly susceptible alluvial and estuarine deposits.
MM7	▪ Water made turbid by stirred up mud. ▪ Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings common. ▪ Instances of settlement of unconsolidated, or wet, or weak soils. ▪ A few instances of liquefaction (i.e. small water and sand ejections). ▪ Very small ($\leq 10^3$ m^3) disrupted soil slides and falls of sand and gravel banks, and small rock falls from steep slopes and cuttings are common. ▪ Fine cracking on some slopes and ridge crests. ▪ A few small to moderate landslides (10^3 –10^5 m^3), mainly rock falls on steeper slopes (>30˚) such as gorges, coastal cliffs, road cuts and excavations. ▪ Small discontinuous areas of minor shallow sliding and mobilisation of scree slopes in places. ▪ Minor to widespread small failures in road cuts in more susceptible materials. ▪ A few instances of non-damaging liquefaction (small water and sand ejections) in alluvium.
MM8	▪ Cracks appear on steep slopes and in wet ground. ▪ Significant landsliding likely in susceptible areas. ▪ Small to moderate (10^3-10^5 m^3) slides widespread; many rock and disrupted soil falls on steeper slopes (steep banks, terrace edges, gorges, cliffs, cuts etc). ▪ Significant areas of shallow regolith landsliding, and some reactivation of scree slopes. ▪ A few large (10^5-10^6 m^3) landslides from coastal cliffs, and possibly large to very large ($\geq 10^6$ m^3) rock slides and avalanches from steep mountain slopes. ▪ Larger landslides in narrow valleys may form small temporary landslide-dammed lakes. ▪ Roads damaged and blocked by small to moderate failures of cuts and slumping of road-edge fills. ▪ Evidence of soil liquefaction common, with small sand boils and water ejections in alluvium, and localised lateral spreading (fissuring, sand and water ejections) and settlements along banks of rivers, lakes, and canals etc. ▪ Increased instances of settlement of unconsolidated, or wet, or weak soils.
MM9	▪ Cracking of ground conspicuous. ▪ Landsliding widespread and damaging in susceptible terrain, particularly on slopes steeper than 20˚. ▪ Extensive areas of shallow regolith failures and many rock falls and disrupted rock and soil slides on moderate and steep slopes (20˚-35˚ or greater), cliffs, escarpments, gorges, and man-made cuts. ▪ Many small to large (10^3-10^6 m^3) failures of regolith and bedrock, and some very large landslides (10^6 m^3 or greater) on steep susceptible slopes. ▪ Very large failures on coastal cliffs and low-angle bedding planes in Tertiary rocks. Large rock/debris avalanches on steep mountain slopes in well-jointed greywacke and granitic rocks. Landslide-dammed lakes formed by large landslides in narrow valleys. Damage to road and rail infrastructure widespread with moderate to large failures of road cuts and slumping of road-edge fills. Small to large cut slope failures and rock falls in open mines and quarries. ▪ Liquefaction effects widespread with numerous sand boils and water ejections on alluvial plains, and extensive, potentially damaging lateral spreading (fissuring and sand ejections) along banks of rivers, lakes, canals etc). Spreading and settlements of river stop-banks likely.

MM10	▪ Landsliding very widespread in susceptible terrain. ▪ Similar effects to MM9, but more intensive and severe, with very large rock masses displaced on steep mountain slopes and coastal cliffs. Landslide-dammed lakes formed. Many moderate to large failures of road and rail cuts and slumping of road-edge fills and embankments may cause great damage and closure of roads and railway lines. ▪ Liquefaction effects (as for MM9) widespread and severe. Lateral spreading and slumping may cause rents over large areas, causing extensive damage, particularly along river banks, and affecting bridges, wharfs, port facilities, and road and rail embankments on swampy, alluvial or estuarine areas.

Notes:

(1) "Some or 'a few' indicates that threshold for response has just been reached at that intensity.

(2) Environmental damage (response criteria) occurs mainly on susceptible slopes and in certain materials, hence the effects described above may not occur in all places, but can be used to reflect the average or predominant level of damage or MM intensity in an area.

(3) Environmental criteria not defined for MM11 and 12, as those intensities have not been reported in New Zealand. Earlier versions of the MM intensity scale suggest that environmental effects at MM11-12 are similar to MM9- 10, but possibly more widespread and severe.

(4) This appendix is based on Hancox et al. 1997, 2002, and Dowrick et al., 2008.

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