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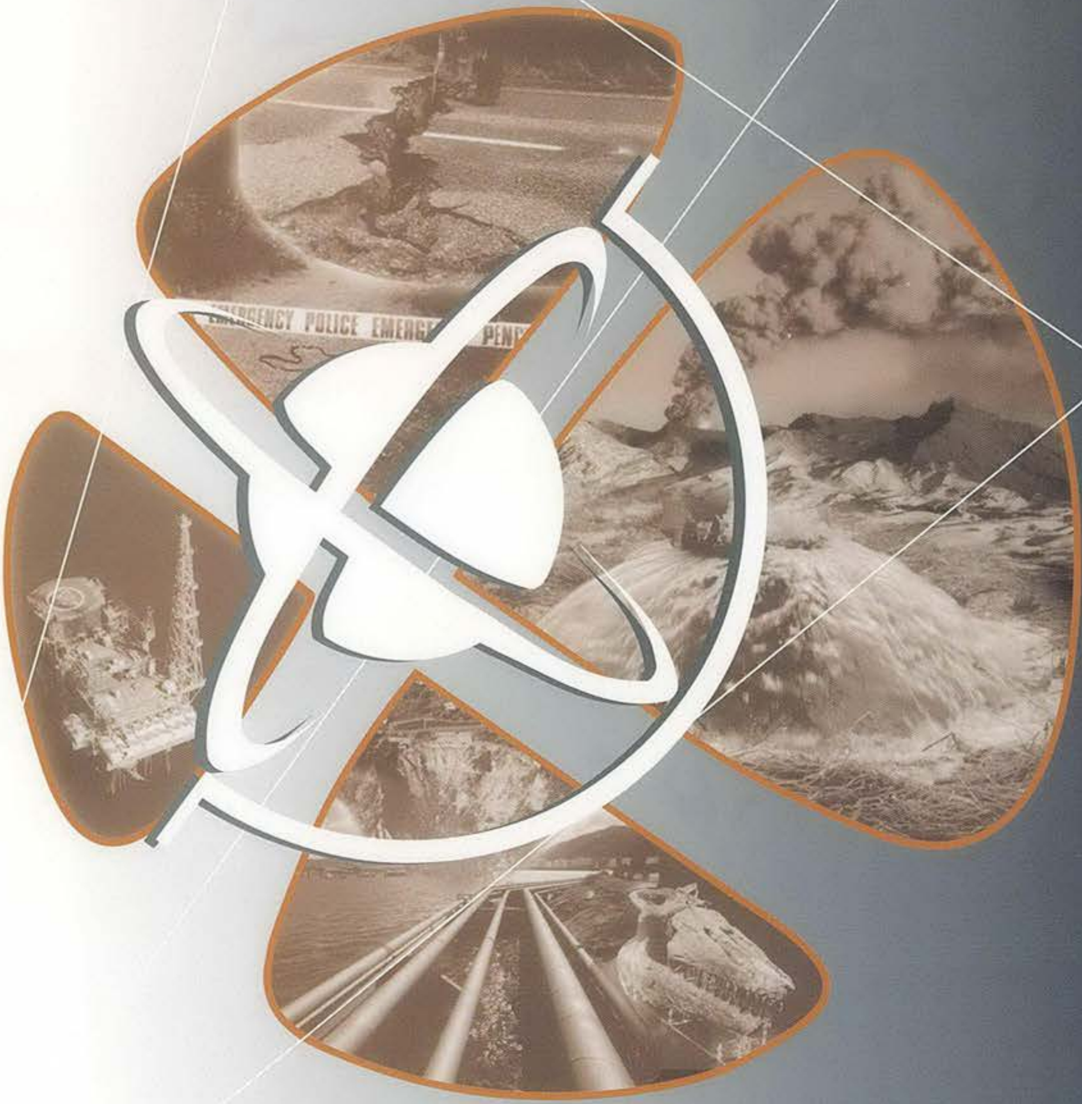

Assessment of urban slope instability in Dunedin, New Zealand, using orbital differential synthetic aperture radar interferometry

Confidential

Client Report
2003/150

December
2003

by NF Stevens, P Glassey & B Smith Lyttle

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Prepared for

Earthquake Commission

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CONTENTS

EXECUTIVE SUMMARY

A number of landslides in Dunedin have affected residential properties, roads and infrastructure. Many of these slides have had, or currently have, surface deformation monitoring networks, with repeat surveys over various periods to measure horizontal and vertical deformation. However, repeated measurements of millimetre- and centimetre-scale slope movement are costly to obtain, and are time-consuming to acquire at a high spatial resolution if using traditional field-based techniques for resurveying, such as levelling and differential GPS (global positioning system) measurements.

In this study, we investigate the viability of orbital differential synthetic aperture radar interferometry (DInSAR) as a potential solution to this problem. DInSAR is a technique developed to measure centimetre-scale surface movement from pairs of remotely sensed synthetic aperture radar (SAR) images collected from orbiting satellites. DInSAR has already proven successful for monitoring slope instability in the French and Austrian Alps.

In this report we collate the survey data made available to us by the Dunedin City Council for comparison, and present comprehensive documentation of landslide motion in the Dunedin urban area. We then provide a detailed review of orbital differential SAR interferometry, and investigate its applicability for measuring slope instability in Dunedin.

In general, we found that the technique worked well over the urban, built-up areas of Dunedin. However, there were relatively few, or only very small, independently documented landslide movements within the intervals of the DInSAR image acquisitions, and ERS DInSAR did not yield the results as we had hoped for. On the other hand, we were able to make several interesting observations, and these results will be invaluable to other groups considering similar studies to this in similar environments and scenarios. Our study is unique, because thus far, as only successful studies applying ERS SAR to landslides have been published, and this study injects some realism into the difficulties of using the technique in areas with moist, variable climates.

1.0 INTRODUCTION

The Dunedin urban area is prone to landslides. A number of these have affected residential properties, roads and infrastructure (Figure 1), and in places landslide movements are continuing. Landslide damage in Dunedin is best illustrated by the Abbotsford landslide of 1979, a catastrophic slope failure following a period of accelerated ground motion (Stuart 1979), which destroyed 69 houses. This slide has since been stabilised, but it was a seminal event in urban planning and legislation for urban development and landslide hazard in New Zealand, resulting from a parliamentary Commission of Inquiry into the causes of the slide (Anonymous 1980).

Many of the slides affecting urban Dunedin have had, or currently have, surface deformation monitoring networks, with repeat surveys over various periods to measure horizontal and vertical deformation. Measurements of the surface movement of active landslides are useful for a number of purposes, not only for the obvious monitoring applications. The measurements constrain models of the physical processes causing slope instability, in conjunction with information about the geology and exacerbating conditions that trigger them (e.g. Cruden & Hu 1993), such as climatic events and geomorphic processes.

However, repeated measurements of millimetre- and centimetre-scale slope movement are costly to obtain, and are time-consuming to acquire at a high spatial resolution if using traditional field-based techniques for resurveying, such as levelling and differential GPS (global positioning system) measurements. Commonly, landslide movement is episodic and related to raised groundwater conditions as a result of long wet periods or intense rainstorms (e.g. Johnson 1987a, Glassey 1995). It is thus difficult to obtain the necessary frequency and spatial density of measurements to measure this periodic movement adequately using ground surveys. In engineering geological terms, Dunedin landslides are usually extremely slow moving (< 16 mm/yr), and often survey monitoring has been discontinued because of an apparent lack of movement.

In this study, we investigate the viability of orbital differential synthetic aperture radar interferometry (DInSAR) as a potential solution to this problem. DInSAR is a technique developed to measure surface movement from pairs of remotely sensed synthetic aperture radar (SAR) images collected from orbiting satellites (e.g. Gabriel *et al.* 1989, Massonnet *et al.* 1993). The technique is already proven successful for monitoring slope instability in the French and Austrian Alps (Carnec *et al.* 1996, Fruneau *et al.* 1996, Rott *et al.* 1999). Using data from the European Space Agency ERS satellites, it is possible to measure surface movement to within centimetre accuracy at a high spatial resolution (several tens of metres). DInSAR provides the general advantages of remote sensing: the overview, and the spatial density of measurements, as well being independent of local weather conditions and solar illumination, which limit other field and remote sensing techniques. Results are produced in digital format, allowing swift comparison with data from other measurements, for example, within geographic information systems (GIS).

In this study, we aim: (a) to evaluate the utility of DInSAR techniques to measure centimetre-scale slope creep associated with urban landslides in Dunedin (b) to validate these measurements with existing low-resolution field data collected and collated by Dunedin City Council (c) to look for indicative surface movement on other slopes to pinpoint other areas of slope creep not previously identified or measured, and, (d) to import our observations into a GIS, to look for trends in the data, with the aim of ascertaining how the infrastructure of urban areas of Dunedin will be affected in the short- to medium-term.

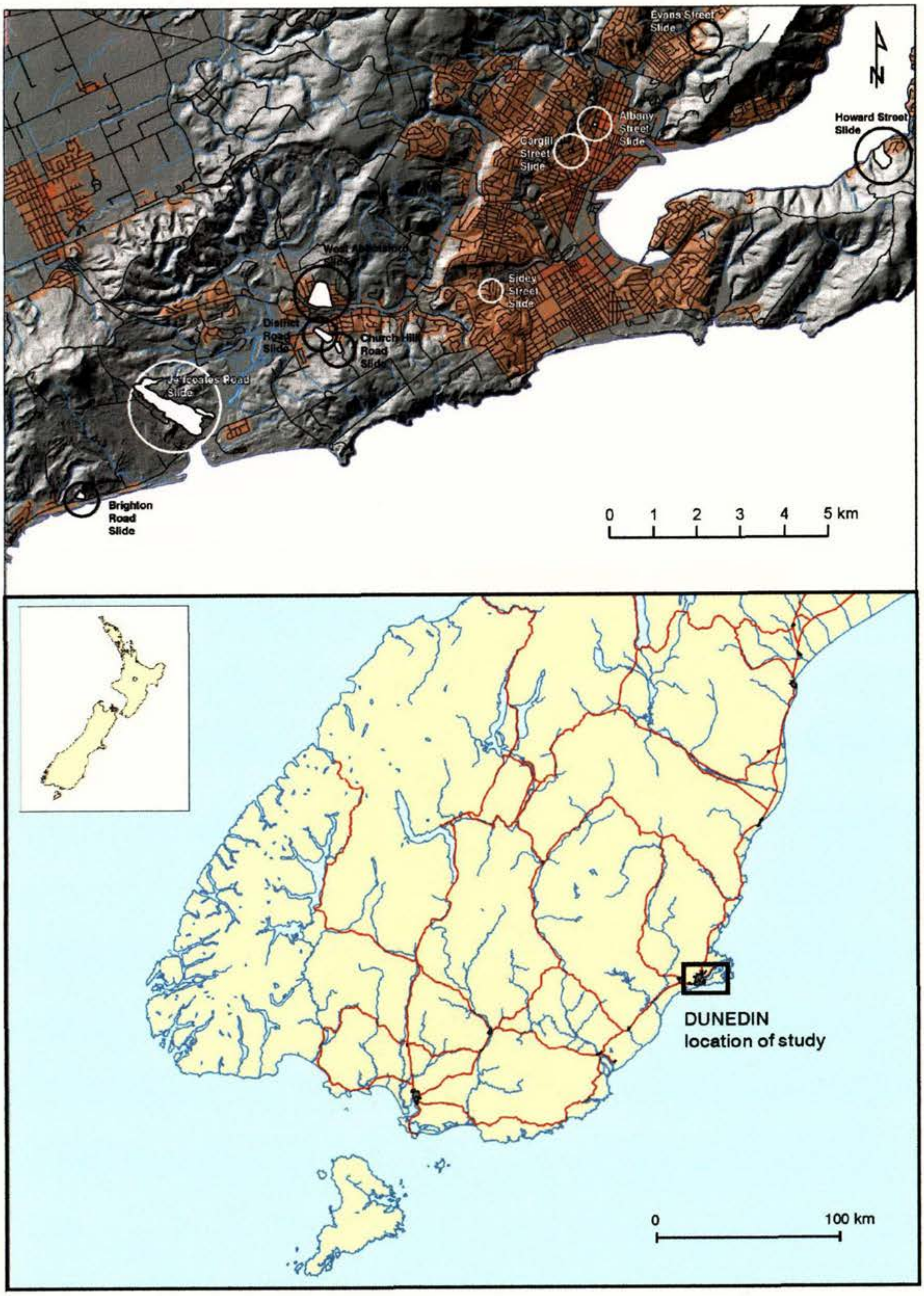


Figure 1 Upper image shows shaded relief plot of Dunedin with urban areas indicated in brown, and locations of known active landslides labelled. Dunedin is located in the South Island of New Zealand, as shown in lower diagram.

2.0 LANDSLIDES WITHIN THE DUNEDIN URBAN AREA

The geology of Dunedin (Figure 2) consists of schist basement rock covered by gently eastward-tilted Late Cretaceous to mid-Tertiary sediments that are mainly marine-derived. These are overlain by Miocene volcanic rocks. The long-term effects of river and coastal erosion resulted in dissection of the weathered Miocene volcanic massif and underlying rocks, which explains the considerable topographic relief in the area. Borehole data indicate that the city overlies a highly complex soil stratigraphy (McCahon *et al.* 1993). Unconsolidated Late Quaternary windblown loess, as well as slope-wash colluvium, mantle many of Dunedin's slopes, and alluvial sediments infill the lower reaches of stream valleys (Benson 1968, McKellar 1990, McCahon *et al.* 1993, Glassey *et al.* 2003). This arrangement of geological structure, stratigraphy, a relatively weathered and unconsolidated substrate, combined with the local steep relief on which Dunedin was built, increases the probability of slope movement and/or failure.

The locations of known active, or recently active, landslides in the Dunedin urban area are shown in Figure 1 and include, but are not limited to, Howard Street (Macfarlane 1990, Glassey 1991a, Glassey 1995), Albany Street (Johnson 1987a, Glassey 1991b), Cargill Street (Macfarlane 1989b), District Road and Church Hill Road landslides (E.R.Garden 1977, 1981), and the West Abbotsford landslide (McKellar, 1968). These slides range in area from about 0.2 ha to 10 ha or more.

The field survey data for these slides was collected at various times by the Dunedin City Council (DCC) and predecessor councils. The data were made available for this study by DCC, and were provided mostly in hard copy format. The surveys used different techniques (levelling, electronic distance measurement (EDM) and GPS) with various degrees of survey error, and data were provided in various formats, including: (a) relative levelling of marks only, (b) measurement of positive or negative horizontal departures from a baseline, and (c) full x, y, z determination. A number of different reference frames were used for surveys, but most were recorded in New Zealand Map Grid (NZMG), Taieri Circuit. Over the period of the surveys, many marks were destroyed either by landslide movement or by road construction and other activities, and replacement marks were installed. Therefore many slides have discontinuous data over the survey period.

The coordinates of the survey points derived from the various survey types were transformed to a common reference grid using transformation software in ESRI ArcGIS^{TM}. We entered data from repeat surveys into a Microsoft Access database, and calculated the horizontal and vertical deformation between surveys. The movements of key landslides where data has been obtained consistently over the years is summarised in Table 1. Individual slides are described in more detail in Section 3.

Table 1 Summary of measured ground deformation, Dunedin landslides

Landslide	Measurement period	Years	Maximum Horizontal Displacement (mm/year)	Maximum Vertical Displacement (mm/year)
Albany St	1986 - 1991	14	9	3
Brighton Road	1998-2001	3.1	113	31
Cargill St	1987-1988	1.3	12	15
Church Hill/District Road	1997 – 2001	3.25	29	4
Evans St	1988 – 1993	4.2	-	12
Howard St	1987 – 1998	8.3	15.3	14.4
Sidey St	1997 - 2000	3.8	3	3.7
West Abbotsford	1984 - 1991	7	1.6	-

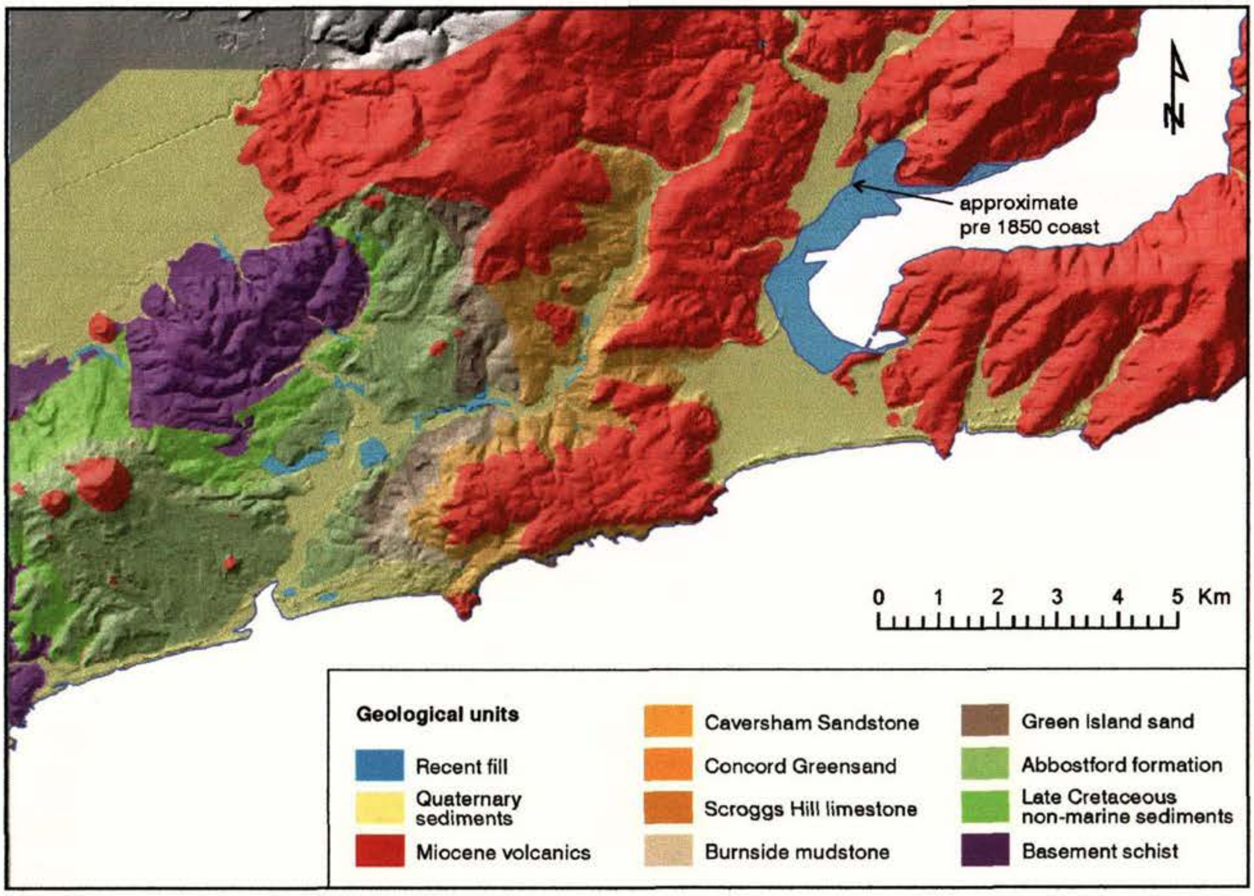


Figure 2 The geology of Dunedin plotted over a shaded relief image depicting the surface relief.

3.0 DETAILED DESCRIPTIONS OF KNOWN ACTIVE LANDSLIDES IN DUNEDIN

3.1 Albany Street slide

The Albany Street slide, located in Central Dunedin (Figures 1 and 3-1), affects 14 residential properties, and was first recognised in 1986 (Johnson 1986), at which time a ground deformation survey network was established on the site. Between 1986 and 1991, the total maximum horizontal displacement measured was 357 mm (71 mm/yr) and a vertical displacement of 59 mm (11 mm/yr) (Glassey 1991b). Remedial drainage measures were installed in 1987 and movement since then has slowed to about 9 mm/yr horizontal deformation and 3 mm/yr vertical. Some accelerated vertical movement occurred after the drainage which may be settlement that is related to the drainage.

3.2 Brighton Road slide

The Brighton Road slide is a regressive failure an old coastal cliff (Figures 1 and 3-2). A number of houses are located at the toe of the slide. Survey data provided by the DCC indicate horizontal deformation between 0 – 352 mm, and vertical displacement of 2 – 96 mm in the period 1998 – 2001. The horizontal displacement rate is 131 mm year with the vertical displacement rate of 30 mm per year.

3.3 Cargill Street slide

The Cargill Street slide is located in the city centre (Figures 1 and 3-3) and affects 8 residential properties (Macfarlane 1989b). Only levels and horizontal offsets either downslope (-) or upslope (+) were recorded. Total horizontal displacements of up to 12 mm were measured between 1987 and 1988, with vertical deformation of up to 20 mm recorded in a similar period. Although survey monitoring pin markers were installed in 1990 and resurveyed by DCC at irregular intervals, we have not been able to locate this survey information.

3.4 Church Hill Road and District Road slides

These slides are located in the Green Island suburb, and affect a dozen or so residential properties (Figures 1 and 3-4). Although we do not present these data here, investigation into these slides was carried out in the late 1970s and early 1980s, with two independent surveys on the two slides were being carried out before they were combined in 1997.

At the Church Hill Road slide, horizontal movement between 1997 and 2001 ranges from 3 mm to 95 mm, which equates to rates of 0.8 to 23 mm per year. Vertical displacement ranges from 3 – 30 mm. A separate survey of other marks on the slide between 2000 and 2001, has measured horizontal displacement of between 3 and 28 mm and vertical displacements of 1 to 74 mm. The 74 mm upward movement at is IS 3/00 in 1 year is extraordinary given that the landslide model postulated by ER Garden & Partners (1977, 1981) indicates that this mark is not within the landslide. It is likely that the zone of landslide toe deformation is more extensive than assumed, because the horizontal movement vector of this mark is consistent with landslide displacement. However we cannot discount that the mark was displaced as a result of human activity.

3.5 Evans Street slide

The Evans Street Slide, located in North East Valley (Figure 1, Figure 3-5) was first identified in 1980, when an area on the slope was scoured out during a rainstorm and retrogressive scarps developed. Between 1981 and 1988 approximately 700 mm of vertical and 800 mm of horizontal displacement is thought to have occurred. (Johnson 1987b, 1988). Following investigation in 1987, a levelling survey network was established in January 1988, which measured vertical deformation only. Repeat surveys over a 5 year period indicate up to 50 mm of cumulative vertical displacement, implying a maximum average rate of about 12 mm/year downward movement (Glassey 1993).

3.6 Howard Street slide

The Howard Street slide, located at Macandrew Bay on the Otago Harbour (Figures 1 and 3-6), is an area of multiple rotational slumping divided into an “inactive” primary area and an “active” secondary area. Urban development of the slide area started in the 1930s, and now contains up to 60 houses constructed within the slide boundaries.

Investigations into the slide were conducted between 1987 and 1989 and included geotechnical drilling and the installation of peizometers to monitor groundwater levels (Macfarlane 1989a, 1990, Glassey 1991a). A survey monitoring network was established in 1987 with repeat surveys carried out on a yearly basis (figure 3-6). The maximum total horizontal deformation measured between 1987 and 1998 is 130 mm (~12 mm/yr), and 120 mm (~11mm/yr) maximum total vertical deformation. Significant movement (54 mm horizontal and 16 mm vertical) was measured (which points?) between May 1993 and May 1994 and is inferred to be related to a rainstorm event that occurred in March 1994 (Glassey 1995).

Engineering geological investigations indicate that the slide has a “stick-slip” style of movement, with episodes of displacement usually occurring after a period of intense rainfall that follows a season of high antecedent rainfall which has generally elevated groundwater. Damaging movement was recorded in 1949, 1968 and 1994. Rainfall conditions conducive to movement also occurred in August 2000 but no reports of damage were received and the survey network was not re-measured.

3.7 Jeffcoates Road slide

Jeffcoates Road Slide is located on the flanks of Saddle Hill (Figures 1 and 3-7) just on the fringe of urban Dunedin. It is a large earth flow within the Abbotsford formation (Figure 2), with typical hummocky debris and a 15 m high head scarp. The Old Brighton Road crosses the slide at the mid point of the slide, and the centre line of the road has a distinct down slope warp. Deer fences and telephone poles that cross the slide also show distinct down slope movement relative to those off the slide.

No official survey network has been set up for monitoring the Jeffcoates Road slide (Figure 3-7). However, a short period of measurement of the offset of the centre line of Old Brighton Road (before being resealed) indicated horizontal displacement of between 5 and 15 mm per year (P. Glassey, unpublished data).

3.8 Sidey Street slide

The Sidey Street slide (Figure 1 and 3-8) was first identified in 1997 when movement caused damage to a few houses. Remedial work was carried out that year. There has been a maximum of 12 mm horizontal and 14 mm vertical displacement between the first survey in July 1997, shortly after the remedial work was completed and September 2000. The movement appears to be at a rate of about 3 mm per year. The vectors of horizontal movement are not shown in Figure 3-8 as they were measured a downslope (-) or upslope (+) movement from a baseline bearing.

3.9 West Abbotsford slide

The West Abbotsford landslide is a large prehistoric slump/earth flow complex whose existence was first recognised during design investigations for the Dunedin Motorway in the early 1960s. Part of the slide area was reactivated in 1968 during of motorway construction. More than 60 residential properties are located on the reactivated part of the landslide. Remedial measures instigated during the motorway construction seem to have largely arrested the slide movement with surveys from 1984 – 1991 indicating 11 mm total horizontal displacement, an annual rate of 2 mm/yr (figure 3-9). Monitoring has not been carried out since 1991.

Figure 3.1: Albany St Slide affecting Queen St, Albany St and George St as well as about 20 houses. The survey markers are shown but no azimuth of horizontal displacement has been measured. It is assumed that the horizontal displacement is downslope (west to east). Total horizontal and vertical displacement (mm) at the Albany St Slide, 1986 – 2000 are summarised in the graph below. Orange line represents approximate extent of slide in this, and in following diagrams.

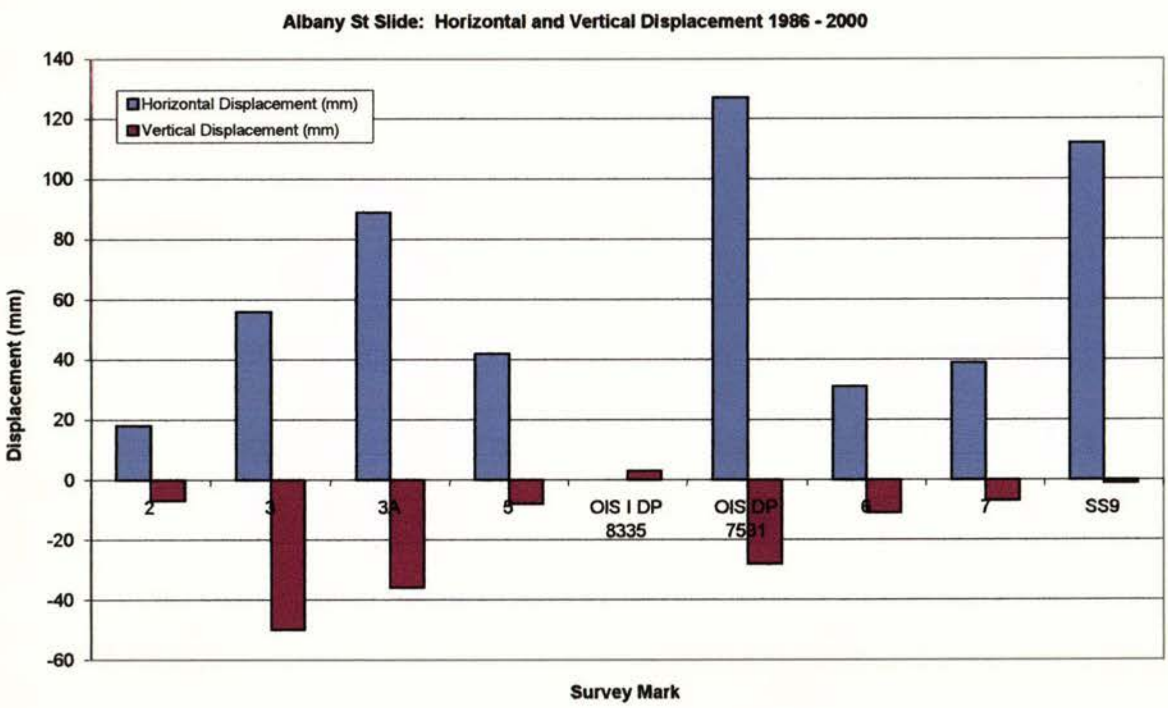


Figure 3.2: The Brighton Road Slide with survey marks and horizontal displacement in mm shown as vectors. The graph below summarises the displacement a Brighton Road Slide 1998 – 2001.

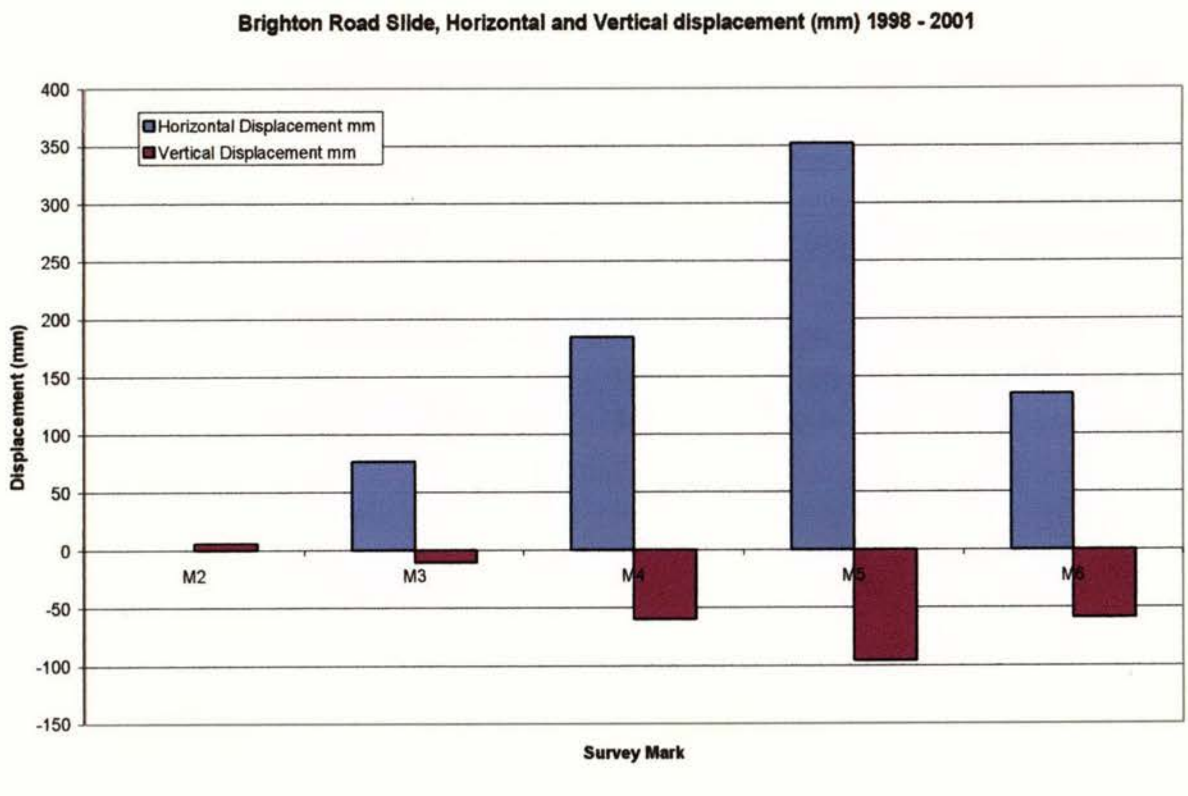


Figure 3.3: Approximate extent of the Cargill St Slide, Central Dunedin. The survey marks are shown. Only levels and offset, either downslope (-) or upslope (+), were recorded. The graph below summarises the displacement recorded at survey marks 1987 to 1988

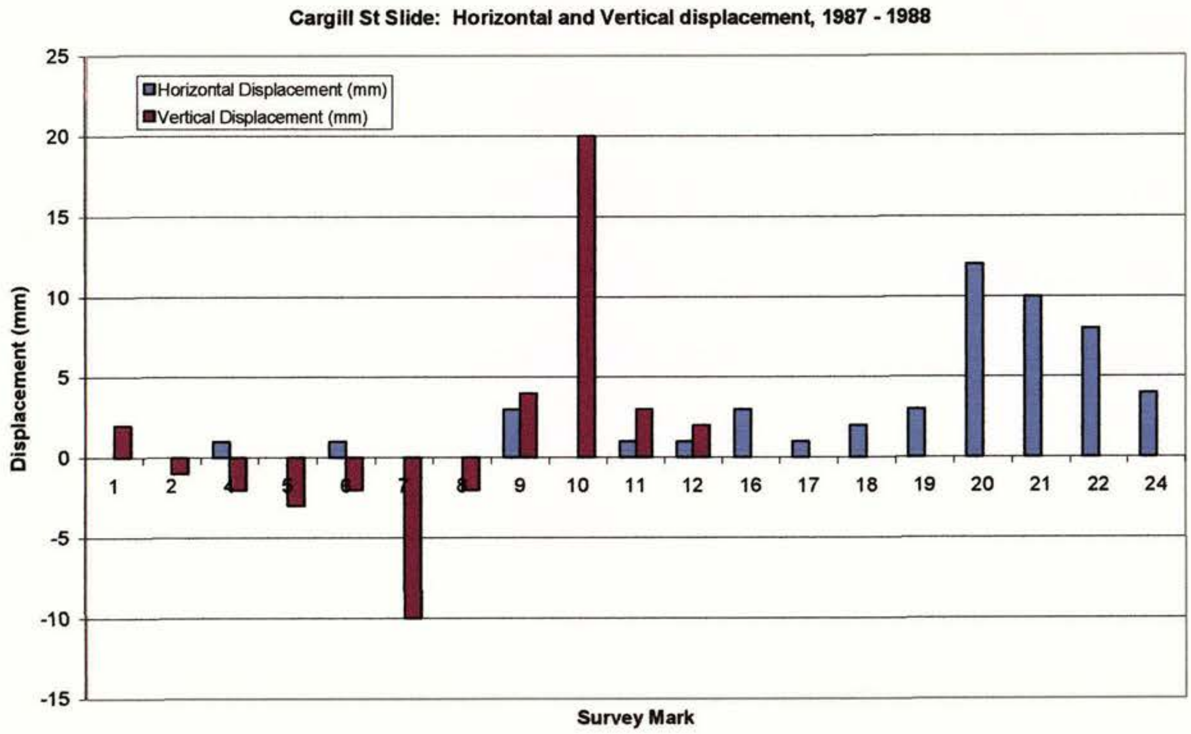
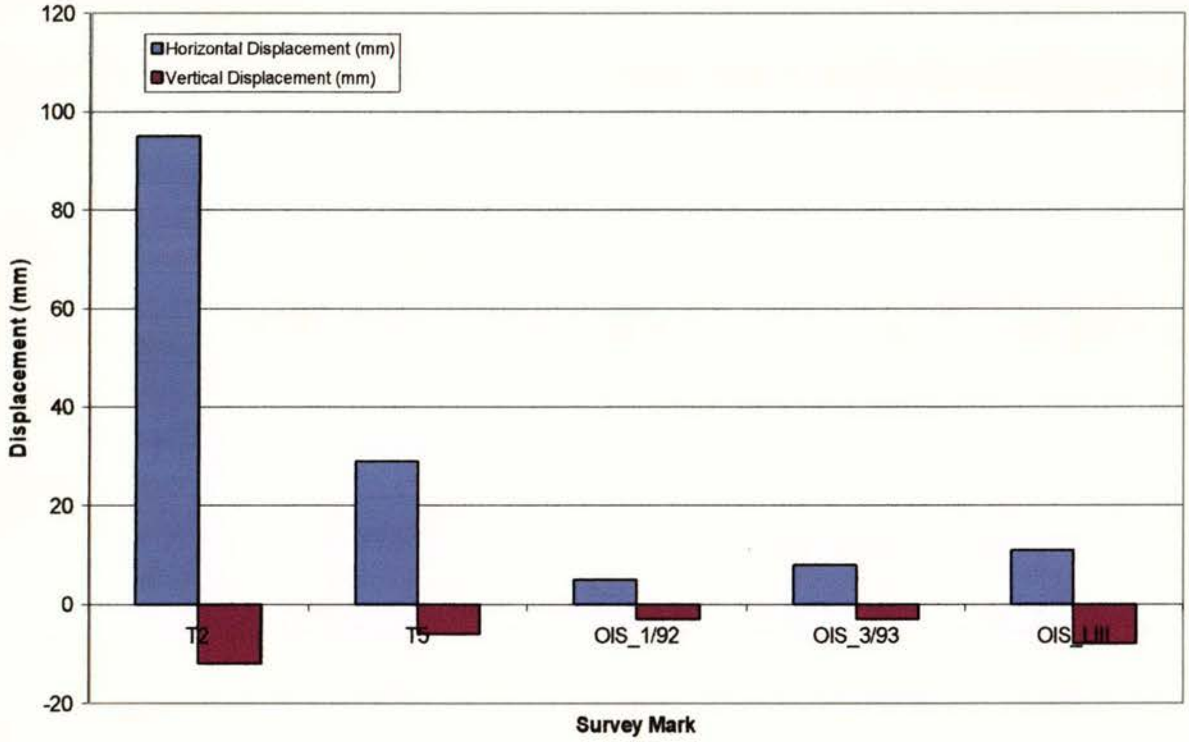
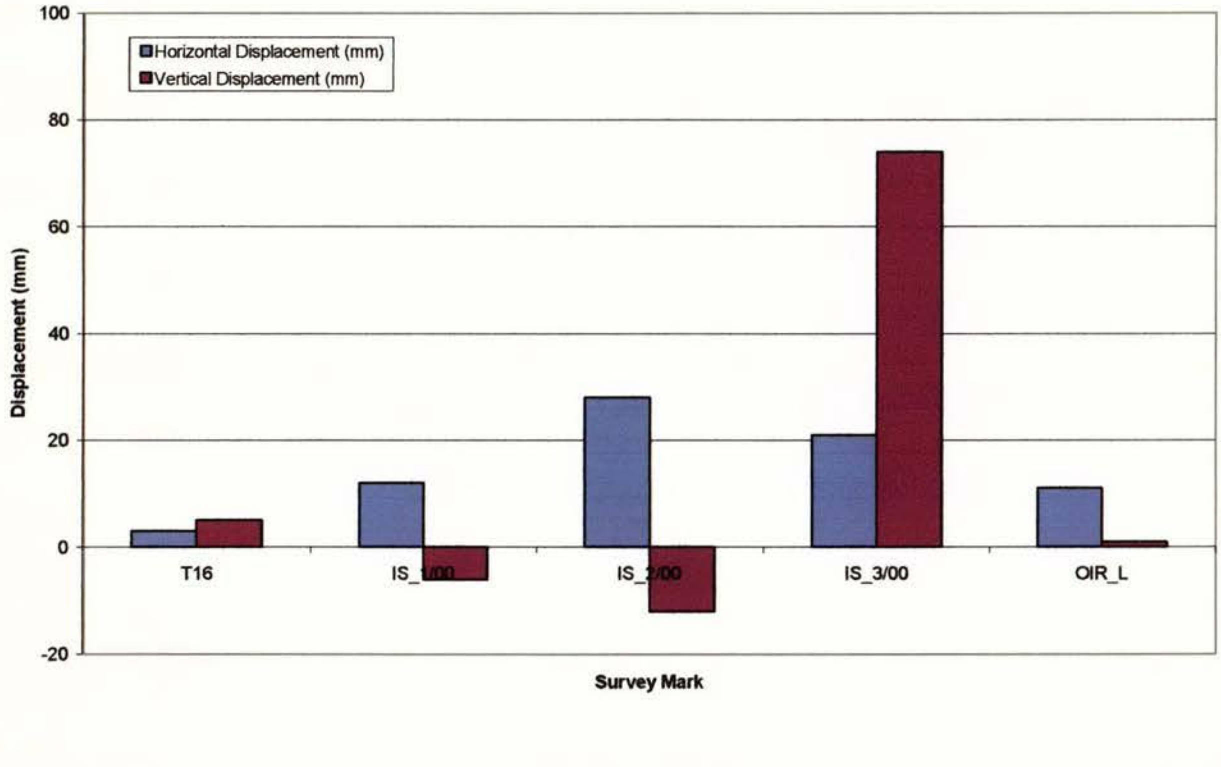


Figure 3.4: The Church Hill Rd and District Rd slides, Green Island, with survey marks showing horizontal displacement vectors (mm) for rationalised survey points. The total horizontal and vertical displacements are given in the graphs below (overleaf).

Church Hill and District Road Slides: Horizontal and Vertical displacement, 1997 - 2001



Church Hill and District Road Slides: Horizontal and Vertical displacement, 2000 - 2001



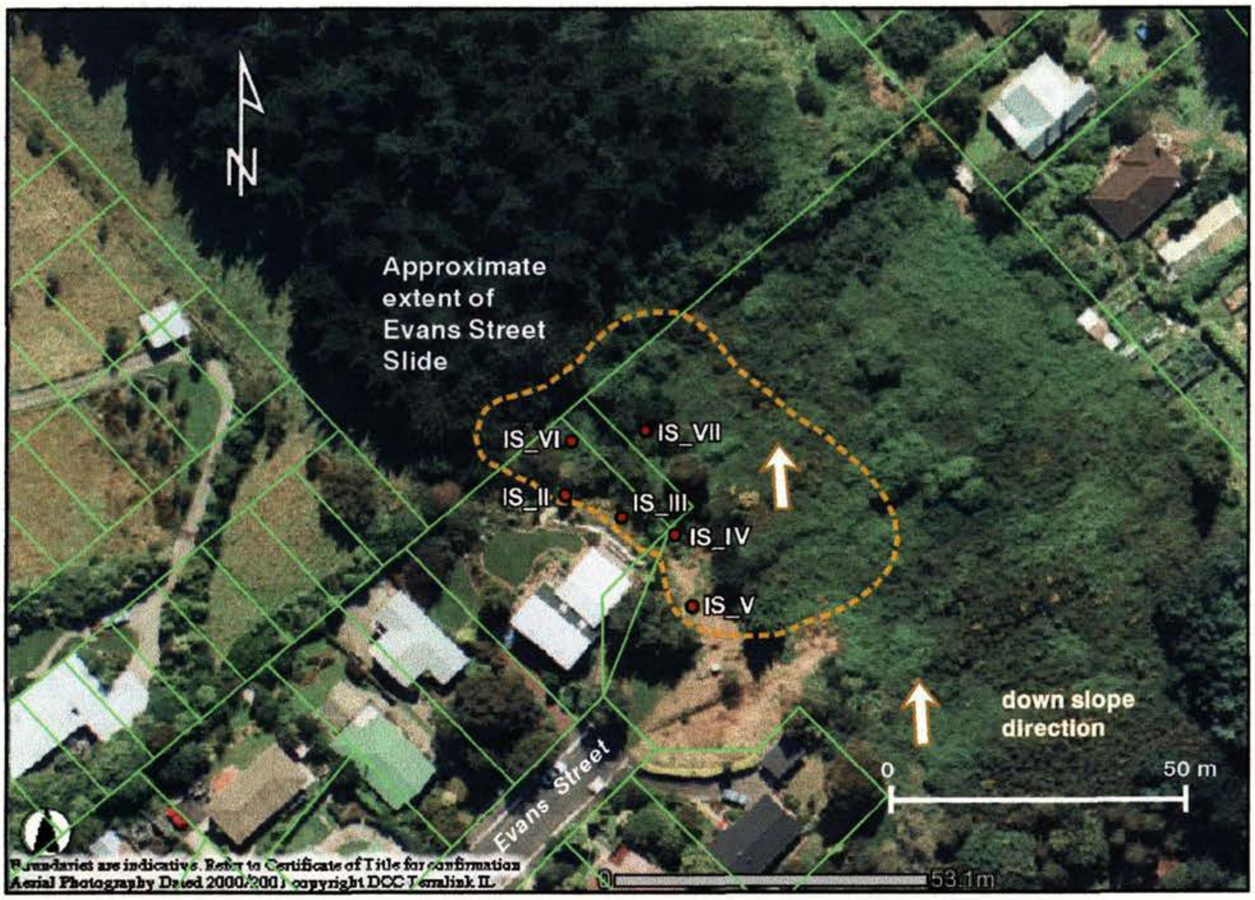
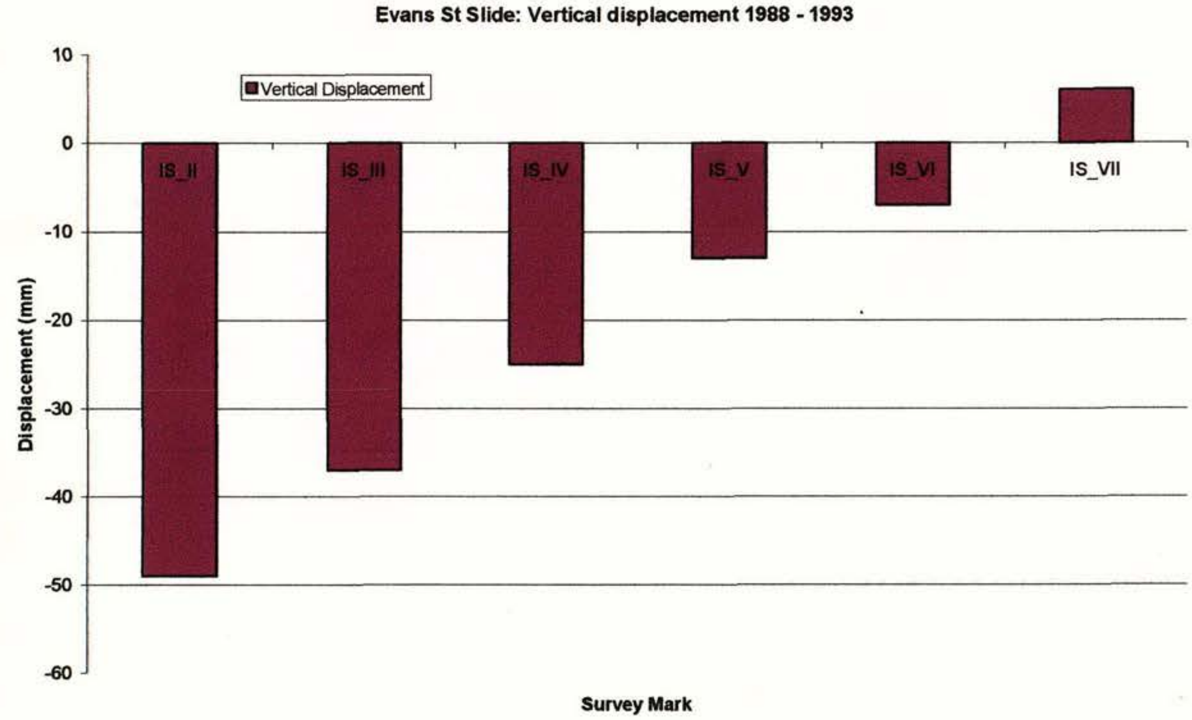


Figure 3.5: Approximate extent of the Evans St slide showing survey markers. Total vertical displacement (mm) of survey marks 1988 – 1993 are given in the graph below



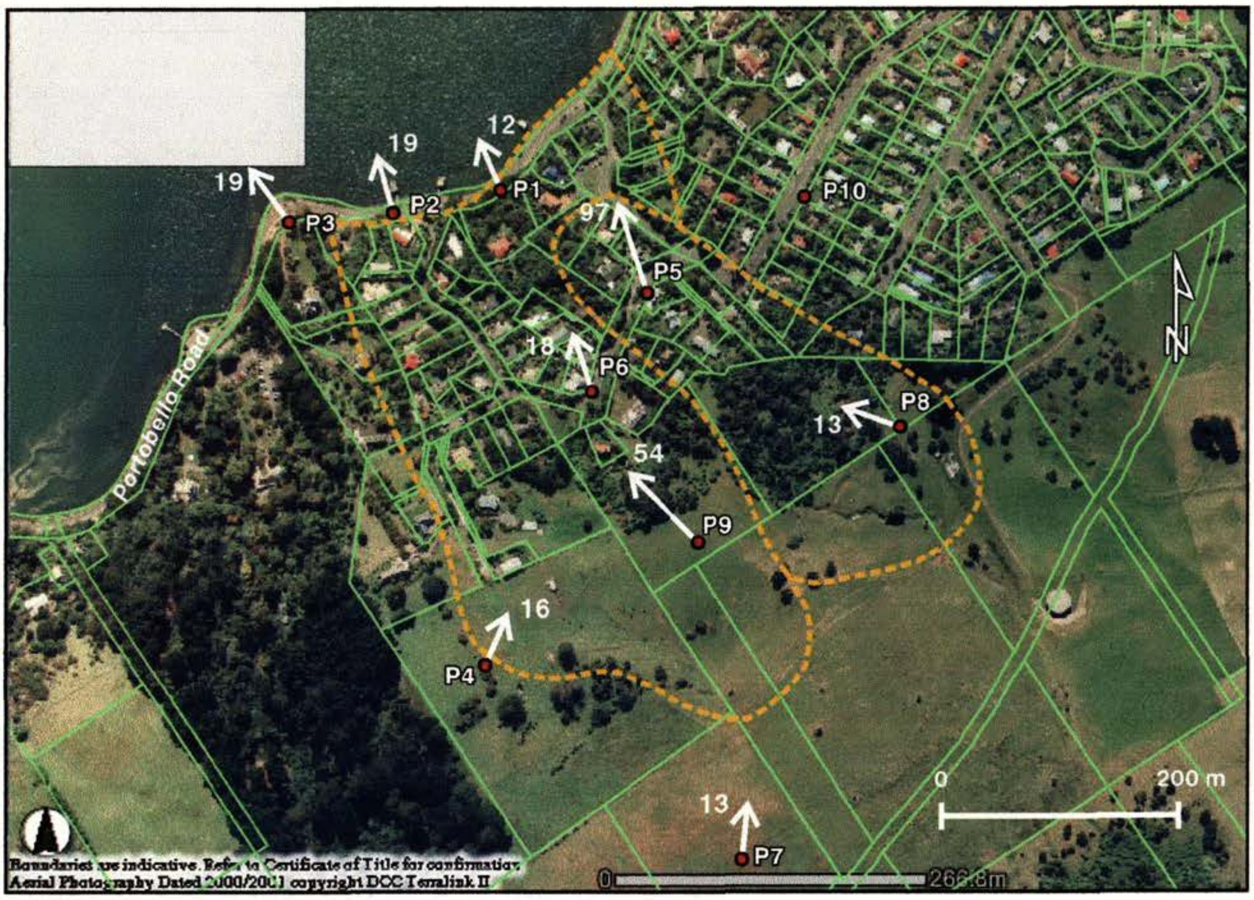
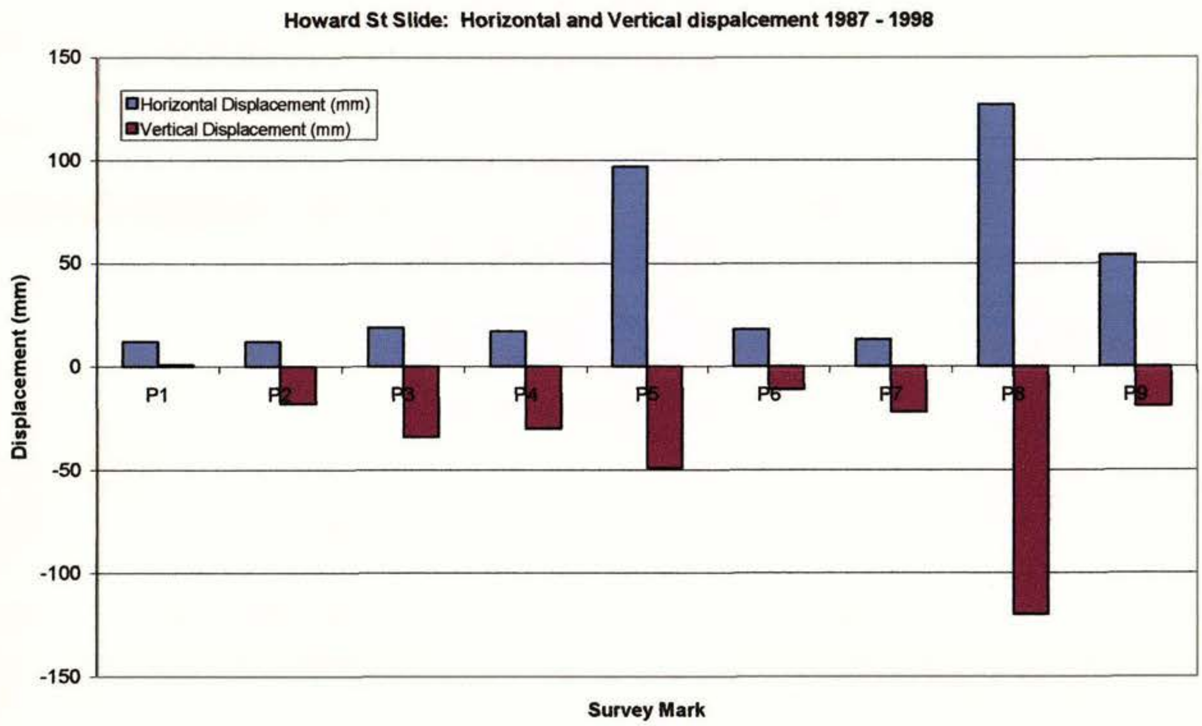


Figure 3.6: The Howard Street slide showing two lobes. The smaller eastern lobe is the more active. Total horizontal and vertical displacements measured at survey marks on the Howard Street slide 1987– 1998



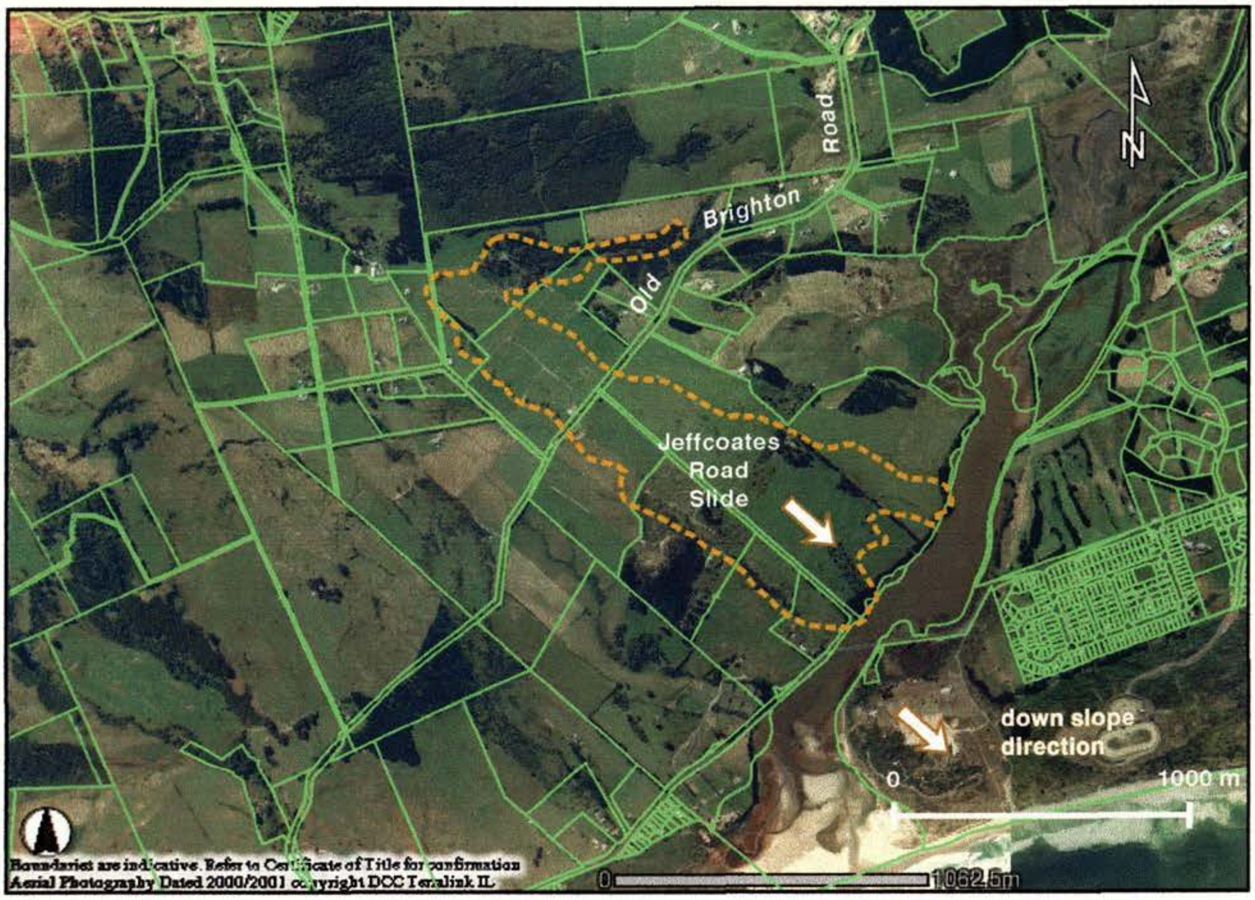
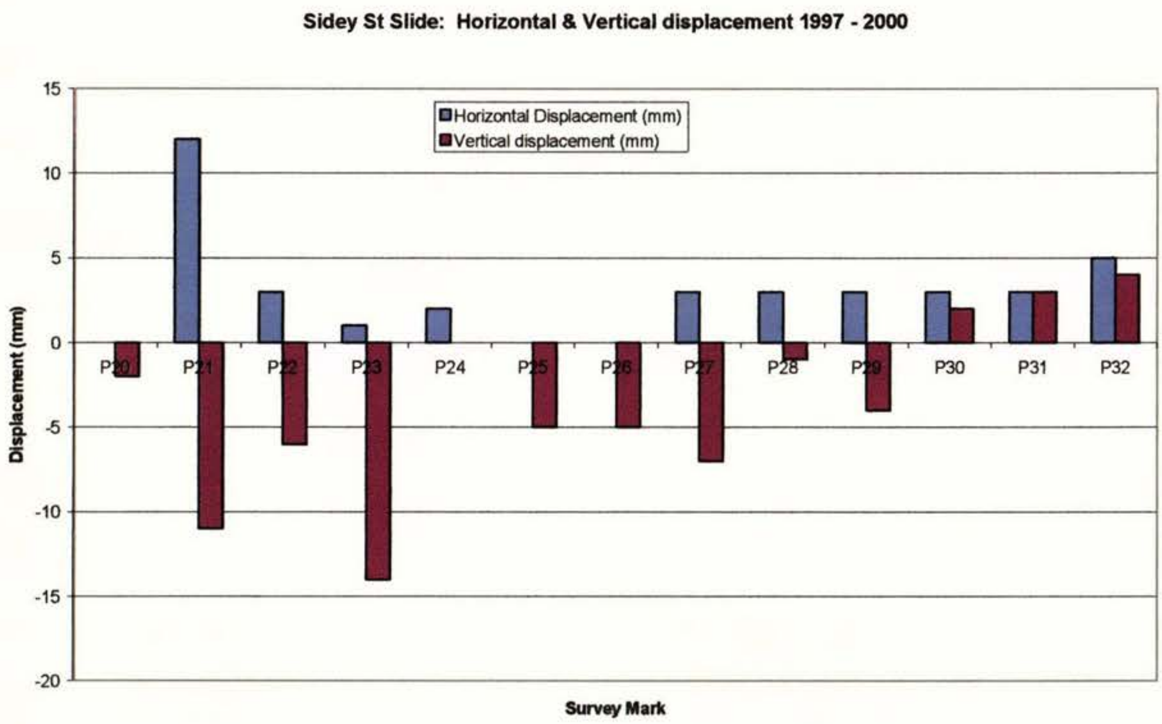


Figure 3.7: The extent of the Jeffcoates Road slide, a slow moving earth flow on the lower flanks of Saddle Hill. Spatial extent delinated by field evidence, such as displaced road markings, fence posts and hummocky terrain.

Figure 3.8: Approximate extent of the Sidey Street slide with the monitoring pins indicated. The vectors of horizontal movement are not shown as they were measured a donwslope (-) or upslope (+) movement from a baseline bearing. Total horizontal and vertical deformation (mm) of survey marks at the Sidey Street slide 1997 – 2000 are given on the graph below.



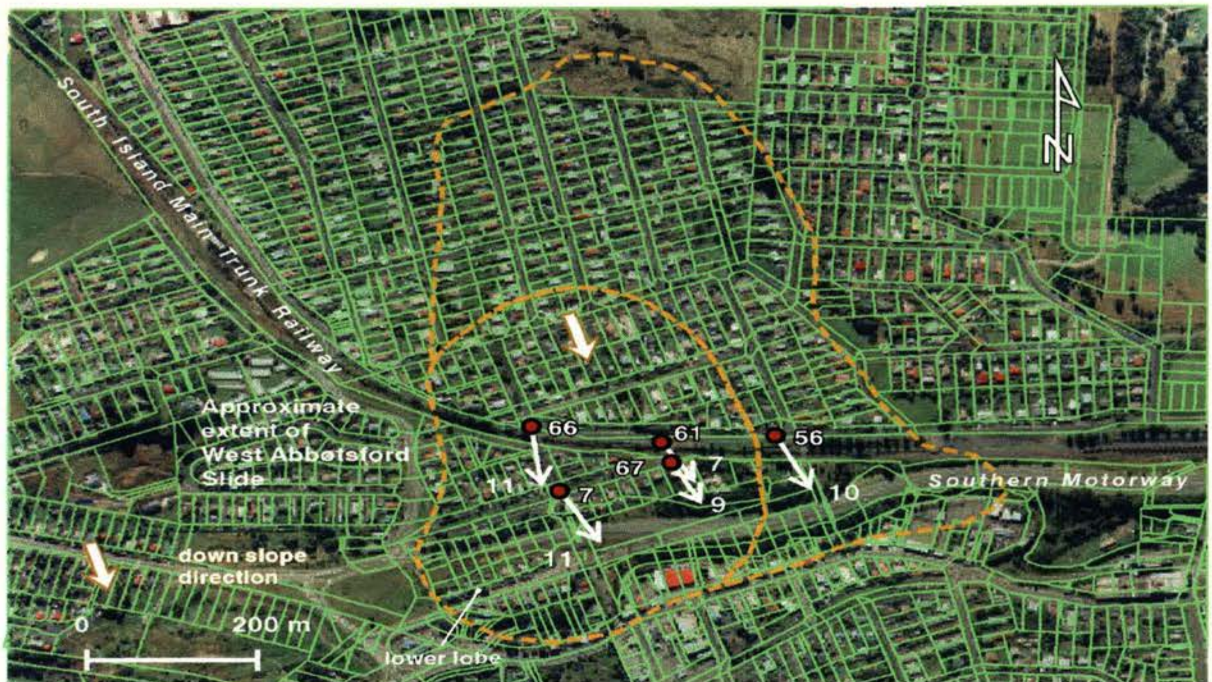
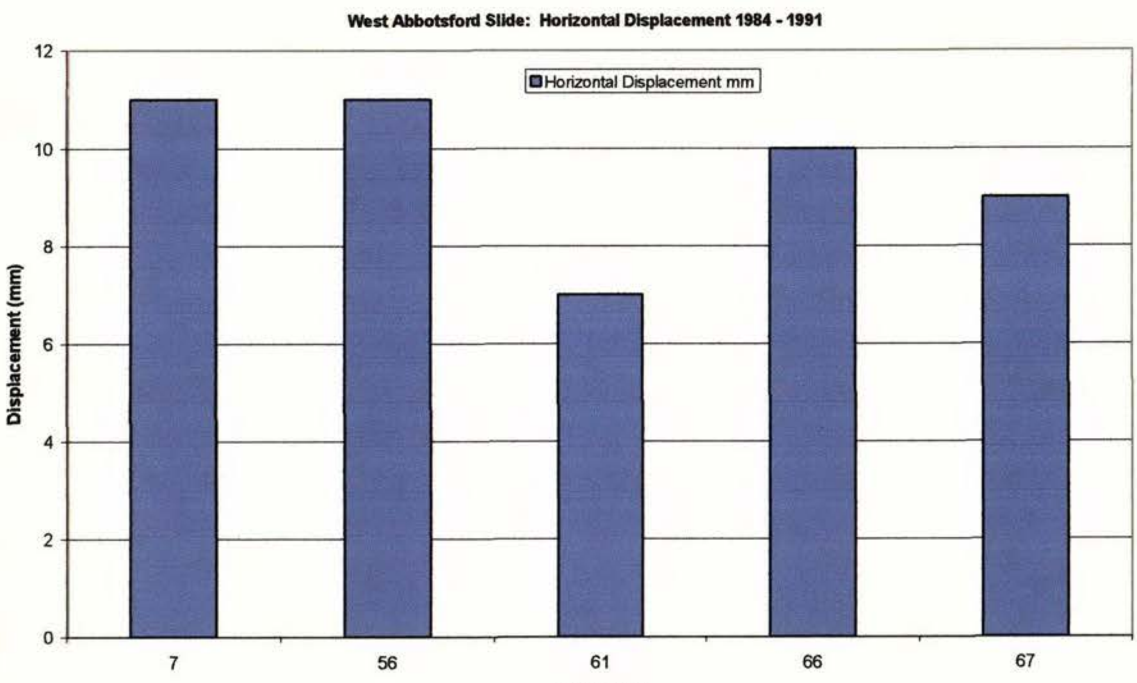


Figure 3.9: The approximate extent of the West Abbotsford slide and the more active lower lobe showing vectors of those survey marks that have recorded horizontal displacement (mm) 1984 – 1991. Total horizontal displacement measured at survey marks are given in the graph below



4.0 DIFFERENTIAL SYNTHETIC APERTURE RADAR INTERFEROMETRY (DINSAR)

Differential radar interferometry (DInSAR) is a well-established technique for the detection of small surface movements. It was originally developed in the late 1980s to early 1990s (Gabriel *et al.* 1989, Massonnet *et al.* 1993, Zebker *et al.* 1994a), and its capability is proven worldwide for diverse applications, and in particular, for detecting and measuring slope instability (Carnec *et al.* 1996, Rott *et al.* 1999, Tarchi *et al.* 2003).

DInSAR involves the measurement relative shifts in signal phase between pairs of remotely sensed synthetic aperture radar (SAR) images (Figure 4). SAR data are coherent in time – i.e. subsequent scenes, if acquired from exactly the same viewing position and if there are no surface changes, remain identical in both amplitude (strength of the returning signal) and phase (the point along the sinusoidal waveform which characterises electromagnetic energy at which the radar signal returns to the sensor). If there has been slight surface movement between acquisitions, the phase value shifts, and the magnitude of surface movement can be determined from the phase difference between SAR scenes. This is how line-of-sight (23° from vertical), centimetre-scale measurements of surface movement can be made from a sensor orbiting at an altitude of several hundred kilometres.

Further details are available from review papers, such as Bamler & Hartl (1998). For Dunedin, DInSAR is particularly advantageous because it potentially provides an overview of slope instability for the entire city and surrounds, with a high spatial density of measurements (a few tens of metres) with frequent re-measurements (every 35 days in the case of the ERS satellites) that are independent of solar illumination and cloud cover.

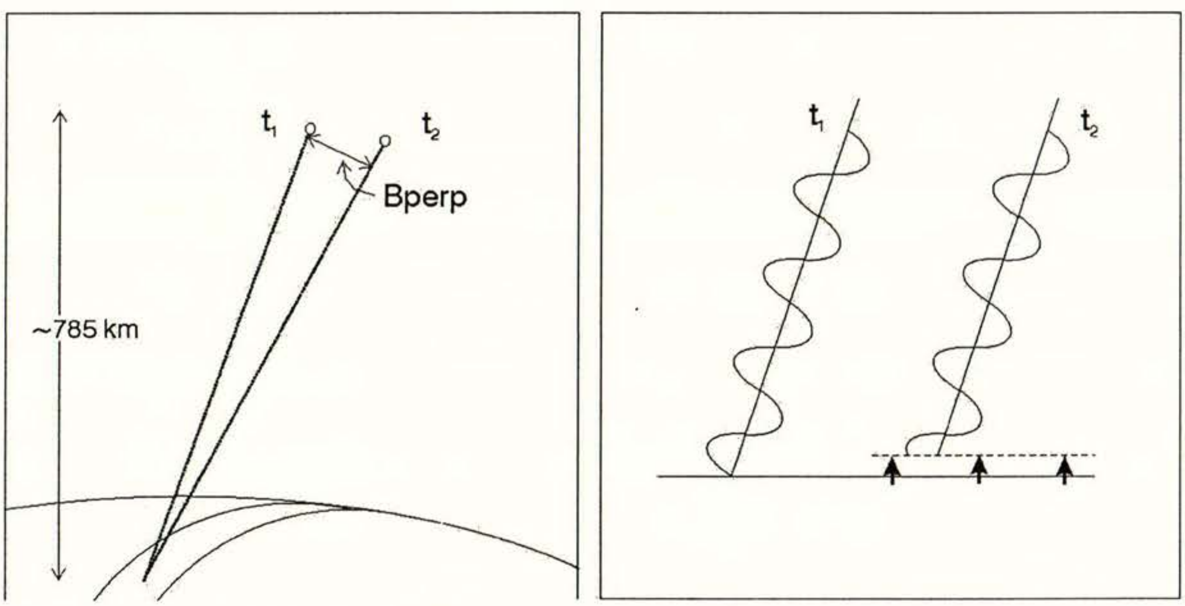


Figure 4 (left) Orbital radar interferometry imaging geometry: radar acquisitions are obtained by the sensor from an altitude of ~785 km at two separate times, t1 and t2. (right) small surface movements are derived from the measurement of the resulting change in phase in the coherent SAR signal.

5.0 DATA ACQUISITION

5.1 Satellite radar instrument availability

A number of orbiting radars suitable for DInSAR were launched successfully during the 1990s, and these acquire radar data at 2 different bandwidths – C-band (5.6 cm wavelength in the case of the ERS satellites) and L-band (25 cm wavelength in the case of the J-ERS-1 satellite). C- and L-band data have different advantages and disadvantages: C-band data are ~4 times more sensitive and can measure smaller (to cm level) movements, whereas L-band is less susceptible to temporal decorrelation and atmospheric noise (e.g. Strozzi *et al.* 2003), both of which are a potential problem when using DInSAR in a New Zealand context, as we will show later.

In the planning stages of this project, both C- and L-band data were considered: C-band from sensors onboard the ERS, Envisat and RADARSAT satellites, which are orbiting at the time of writing, and L-band from the J-ERS-1 satellite. The use of J-ERS-1 L-band data was discounted because J-ERS-1 stopped acquiring data in 1998. Besides this, the J-ERS-1 envelope of orbits and orbital positioning information are not well-constrained (Strozzi *et al.* 2003), so a low proportion of image pairs are suitable for DInSAR processing, and only limited archived J-ERS-1 data are available of Dunedin anyway.

Of the C-band instruments, RADARSAT is a semi-commercial enterprise, so data costs are high. The orbits were not planned specifically for interferometric imaging purposes until recently. Envisat was launched in late 2002, and although data acquisition began in mid-2003, it was too late to process and include results from Envisat during this study. On the other hand, the ERS satellites are the most commonly-used worldwide for interferometric applications, and ERS C-band data with an orbital geometry suitable for interferometry are readily available from 1995 to the present.

Although the ERS-1 satellite was launched in 1991, it has no on-board data storage, and SAR acquisitions must be transferred immediately to the nearest ground receiving station. New Zealand's nearest ground receiving station is in Hobart, Australia, but this was not operational for ERS reception until mid-1995. Hence no ERS data for New Zealand exist prior to this. The available ERS scenes are listed in Table 2, and their location displayed in Figure 5-1.

Table 2 – Archived ERS SAR data availability for Dunedin (figure 5-1)

Track 444 Frame 4527-4545

Satellite	Orbit	Date	Comments
E1	21975	27/09/1995	
E1	22977	6/12/1995	
E1	23478	10/01/1996	Not available on ordering
E1	25482	29/05/1996	
E2	3304	7/12/1995	Not available on ordering
E2	3805	11/01/1996	Not available on ordering
E2	20338	11/03/1999	
E2	20839	15/04/1999	
E2	23344	7/10/1999	
E2	23845	11/11/1999	
E2	24346	16/12/1999	
E2	24847	20/01/2000	
E2	25348	24/02/2000	
E2	25849	30/03/2000	
E2	39877*	5/12/2002	Unsuitable Doppler Centroid value
E2	40378*	9/01/2003	
E2	40879*	13/02/2003	Unsuitable Doppler Centroid value
E2	41380*	20/03/2003	Not available before project end
E2	41881*	24/04/2003	Not available before project end

* commissioned from ESA during this project

Track 172 frame 4527-4545

Satellite	Orbit	Date	
E1	22705	17/11/1995	Inadequate time-span to detect surface motion in Dunedin
E1	23206	22/12/1995	
E1	25210	10/05/1996	
E2	3032	18/11/1995	
E2	3533	23/12/1995	
E2	5537	11/05/1996	

Track 137 Frame 6255

Satellite	Orbit	Date	
E1	22670	15/11/1995	Inadequate time-span to detect surface motion in Dunedin
E1	23171	20/12/1995	
E2	3498	21/12/1995	

Track 409 Frame 6255

Satellite	Orbit	Date	
E1	22942	4/12/1995	Inadequate time-span to detect surface motion in Dunedin
E1	23443	8/01/1996	
E2	3269	5/12/1995	
E2	3770	9/01/1996	

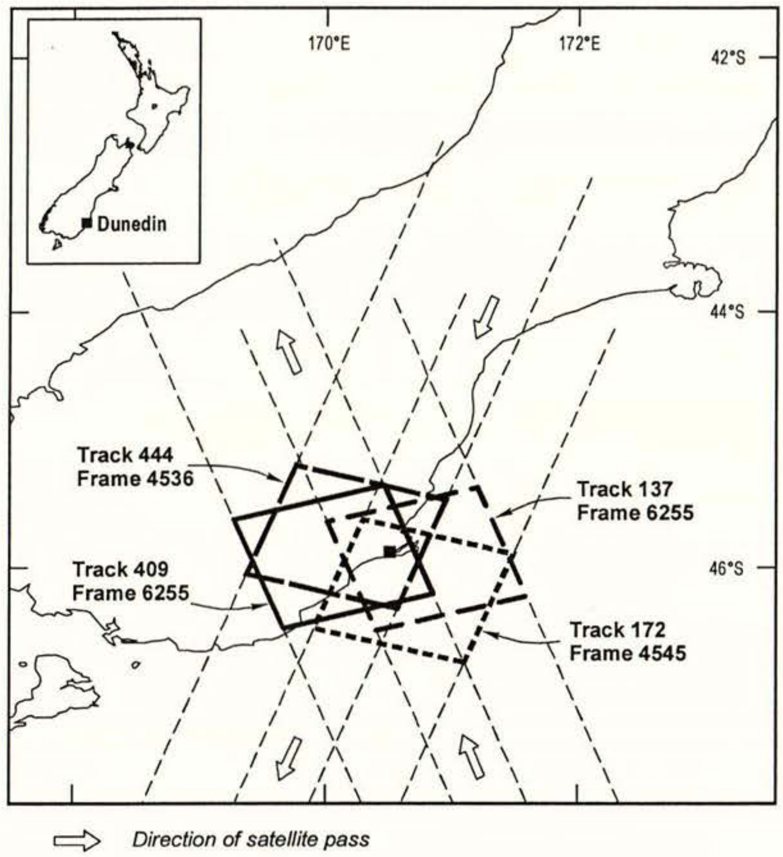


Figure 5-1 Location of ERS radar tracks and scenes over Dunedin. Tracks 172 and 444 are obtained on descending (northeast to southwest) passes; tracks 137 and 409 are obtained on ascending passes (southeast to northwest). The data for this study was acquired along track 444. An inadequate number of scenes was acquired over time along the other tracks – this is most likely because nobody ordered them in advance.

5.2 ERS data availability

ERS SAR data of Dunedin along tracks 172, 137 and 409 (Figure 5-1) were acquired from late 1995 to mid 1996 only (Table 2), and we chose not to process these because they do not span enough time for significant, detectable surface movement to occur, given the rates of motion already measured in the field at most of the known Dunedin slides (section 3). The lack of data along these tracks demonstrates one of the problems with orbital DInSAR: advanced planning is often needed. Although the ERS satellites nominally have a repeat visit interval of 35 days, unless scenes are actively ordered, with funds available to pay for them, then there is a risk that they will not be acquired, as is evident here. Inadequate data acquisition for DInSAR for a particular region is a common problem globally, when data are not ordered in advance (Stevens & Wadge 2003).

We were fortunate that there are plentiful data for Track 444 acquired and archived over 5 years from 1995 onwards. We commissioned additional scenes for 2002-2003 to supplement the existing archived data (Table 2). These data were provided at a vastly discounted rate (<10% of full cost) by the European Space Agency, following the success of Category-1 research proposal (AO-1145), under which we were assigned 70 ERS SAR scenes, as well as Envisat ASAR data.

On ordering the 1995-2000 data, three scenes from the archives were not available due to excessive missing data within the frame (Table 2, orbits 23478, 3304 and 3805). We commissioned another 6 scenes during 2002 and 2003, four of which were delivered to us successfully within the time frame of this study. The delivery rate (gap between data acquisition and deliver to the user) was in the order of months, and this highlights one of the present obstacles to implementing this type of monitoring on a near real-time, semi-operational basis, as is already discussed in Stevens & Wadge (2003).

5.3 Data processing

The interferogram, or image of the phase shift between SAR acquisitions, is calculated by aligning the SAR acquisitions exactly on a pixel by pixel basis (termed coregistration), and multiplying the complex value of each pixel in the first (master) image, by the complex conjugate value of the second (slave) image. The phase shift is measured in the range modulo zero to π, or half of the radar wavelength, which in the case of the ERS satellites is 28.33 mm. To measure the total deformation over several adjacent cycles (termed fringes in the interferogram), an integer number is added to each cycle (a process termed phase unwrapping).

The phase shift between SAR scenes is made up of several components: these include (a) the surface deformation, (b) a stereo effect due to topography when the satellite is not in exactly the same imaging position in subsequent orbits, and (c) noise from the atmosphere and instrumentation (Tararye & Massonnet 1996). The topographic component is removed via a separate source of data. In this case we used a high resolution digital elevation model (DEM) provided by the Dunedin City Council (DCC). Atmospheric noise can be eliminated by the processing, and inter-comparison of, as many SAR pairs as possible. Instrumentation noise accounts for the threshold of measurement of ~1 cm in the line of sight of the instrument.

The suitability of an individual SAR pair for interferometric processing and interpretation is determined by the orbital geometry, or more specifically the perpendicular baseline (Bperp), or distance between imaging positions perpendicular to the Earth's surface (Figure 4). The smaller the Bperp, the smaller the stereo effect on the data, and the less susceptible the pair to errors contained in the DEM used to remove the topographic stereo effect in the data. Removal of the topographic effect is a process called phase flattening. The DCC DEM has a spatial resolution of 5 m and a sub-metre vertical accuracy, and was derived from aerial stereo photogrammetry. Taking into account the spatial resolution and vertical accuracy of the DEM, it is reasonable to assume that we can remove the topographic component accurately from ERS SAR pairs with a baseline of 500 metres or less (Stevens 1999).

Table 3 shows that the ERS pairs with <500 m Bperp fall into three groups: those pairs with acquisitions separated by <1 year, those separated by 3-4 years, and those with >7 years separation. The number of pairs allowed us to identify interferograms that contained obvious atmospheric anomalies, and provided a means to confirm that observed deformation was real, and not noise, by comparing interferograms spanning similar periods with one another, to ascertain that they contain the same signal.

The ERS SAR data were delivered in RAW format, and were first processed to single look complex (SLC) format using the Atlantis Earth View APP software, a necessary processing step. A georeferenced ERS SAR amplitude image of Dunedin, derived from the SLC product, is displayed in Figure 5-2. Interferometric processing of the SLC images, to measure phase shifts and to derive surface deformation, was then performed using the Atlantis EV-InSAR software. The orbital geometry of the SAR data was refined using the published University of Delft orbital vectors (Scharroo & Visser 1998), which removes potential errors introduced from poorly constrained orbital geometry. Processing the ERS pairs was reasonably time-consuming (~12-24 hours for each pair), partly because of the large data file sizes involved, and partly because of low data coherence levels, apart from in urban areas (see next section), which meant much manual interaction was needed during processing. Each SAR pair was co-registered with manually selected tie-points, and each processing run was checked to ensure that the DCC DEM was aligned exactly with the SAR pair for topographic phase removal. Each of the resulting interferograms was then georeferenced to the Universal Transverse Mercator (UTM) coordinate system, and was exported from the Atlantis EV-InSAR software in a GeoTIFF format.

Of the 41 interferograms produced (Table 3), those involving the scenes acquired in February 2000 (orbit 25348) and December 2002 (orbit 39877) failed to produce meaningful results in any pairing combination. This is probably due to a large Doppler centroid value of these acquisitions, which is an issue affecting some ERS scenes acquired after technical difficulties in the instrumentation pointing gyros arose in late 1999. Some scenes were found to contain obvious atmospheric noise, in terms of broad-scale spurious fringes generally covering the whole scene. Atmosphere-affected interferograms were not discarded entirely because some useful observations were possible from the data, as atmospheric anomalies tend to have a large spatial extent, whereas landslides are localised and generally distinguishable from the atmospheric noise.

Table 3 ERS SAR pairs suitable for interferometric processing with the DCC DEM (Bperp < ~500 m) in order of temporal separation between acquisitions. All scenes acquired along track 444, frames 4527-4545. Pairs in italics contained significant atmospheric noise.

Master SAR Orbit	Slave SAR Orbit	| ~ Bperp (m) |	Temporal Separation
20338 – Mar 1999	20839 – Apr 1999	51	1 mo
23344 – Oct 1999	23845 – Nov 1999	68	1 mo
24847 – Jan 2000	*25348 – Feb 2000*	*264*	*1 mo*
25348 – Feb 2000	25849 – Mar 2000	217	1 mo
39877 – Dec 2002	40378 - Jan 2003	137	1 mo
21975 – Sept 1995	*22977 – Dec 1995*	*271*	*2 mo*
23845 – Nov 1999	*24847 – Jan 2000*	*98*	*2 mo*
23845 – Nov 1999	25348 – Feb 2000	166	3 mo
23344 – Oct 1999	*24847 – Jan 2000*	*30*	*3 mo*
23344 – Oct 1999	25348 – Feb 2000	234	4 mo
23845 – Nov 1999	25849 – Mar 2000	383	4 mo
23344 – Oct 1999	25849 – Mar 2000	250	5 mo
21975 – Sept 1995	25482 – May 1996	505	8 mo
20839 – Apr 1999	24346 – Dec 1999	302	8 mo
20338 – Mar 1999	24346 – Dec 1999	353	9 mo
23344 – Oct 1999	39877 – Dec 2002	379	3 yr 2 mo
22977 – Dec 1995	*20338 – Mar 1999*	*202*	*3 yr 3 mo*
22977 – Dec 1995	*20839 – Apr 1999*	*253*	*3 yr 4 mo*
25482 – May 1996	23344 – Oct 1999	333	3 yr 5 mo
21975 – Sept 1995	20338 – Mar 1999	473	3 yr 6 mo
25482 – May 1996	23845 – Nov 1999	265	3 yr 6 mo
25482 – May 1996	*24847 – Jan 2000*	*363*	*3 yr 8 mo*
20839 – Apr 1999	39877 – Dec 2002	317	3 yr 8 mo
25482 – May 1996	25348 – Feb 2000	99	3 yr 9 mo
20338 – Mar 1999	39877 – Dec 2002	266	3 yr 9 mo
20839 – Apr 1999	40378 - Jan 2003	180	3 yr 9 mo
21975 – Sept 1995	23344 – Oct 1999	172	3 yr 10 mo
20338 – Mar 1999	40378 - Jan 2003	129	3 yr 10 mo
22977 – Dec 1995	*23344 – Oct 1999*	*443*	*3 yr 10 mo*
25482 – May 1996	25849 – Mar 2000	118	3 yr 10 mo
21975 – Sept 1995	23845 – Nov 1999	240	3 yr 11 mo
24847 – Jan 2000	39877 – Dec 2002	349	3 yr 11 mo
22977 – Dec 1995	*24847 – Jan 2000*	*413*	*4 yr 1 mo*
21975 – Sept 1995	*24847 – Jan 2000*	*142*	*4 yr 4 mo*
21975 – Sept 1995	25348 – Feb 2000	406	4 yr 5 mo
21975 – Sept 1995	25849 – Mar 2000	262	4 yr 6 mo
22977 – Dec 1995	39877 – Dec 2002	64	7 yr
22977 – Dec 1995	*40378 - Jan 2003*	*73*	*7 yr 1 mo*
21975 – Sept 1995	39877 – Dec 2002	207	7 yr 2 mo
21975 – Sept 1995	40378 - Jan 2003	344	7 yr 3 mo
21975 – Sept 1995	40879 – Feb 2003	525	7 yr 4 mo

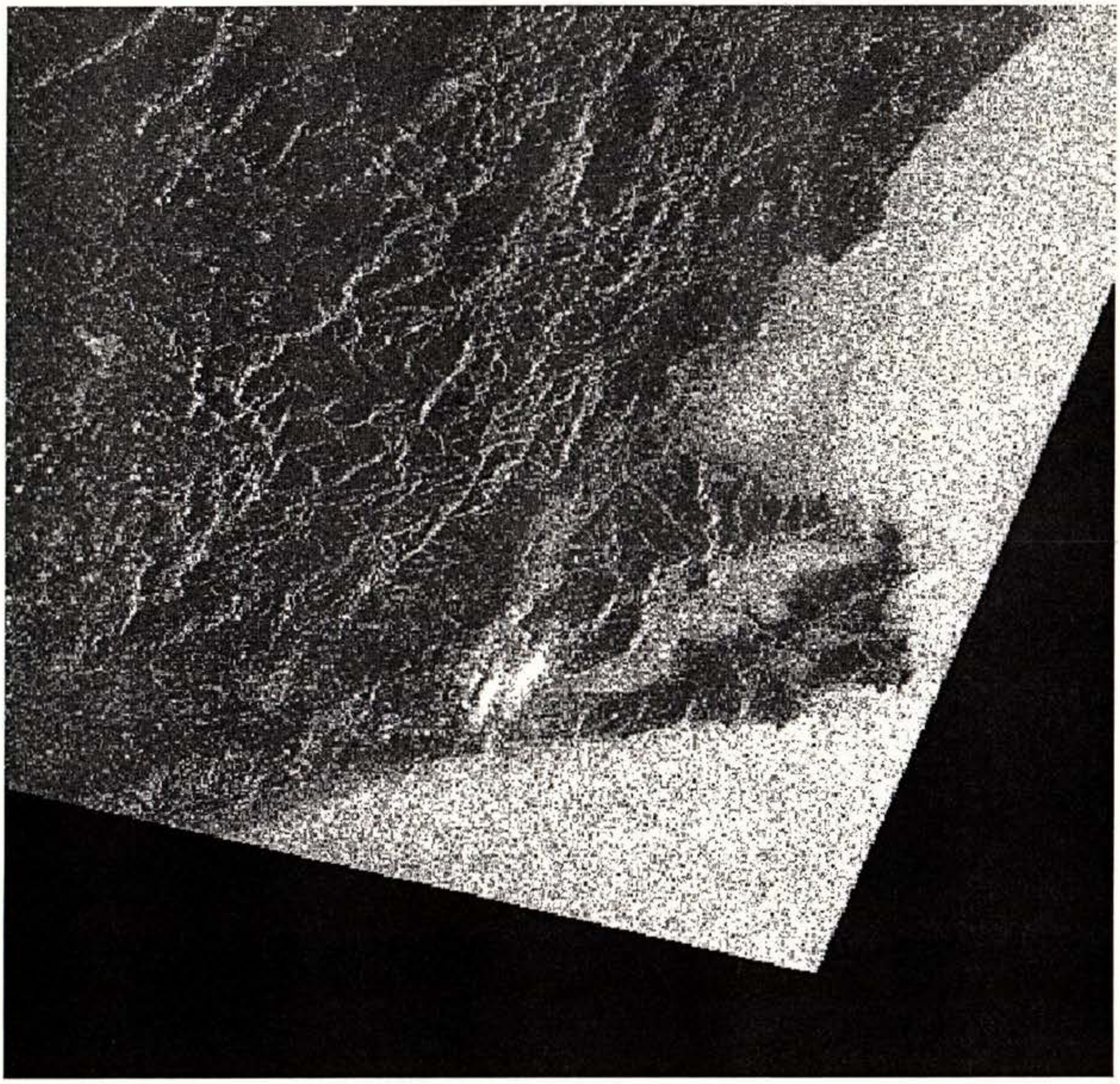


Figure 5-2 ERS SAR scene of Dunedin, acquired on November 11th 1999 on track 444, and chosen to be representative of all data acquired for this study. Dark areas represent a weak radar return from the surface of the Earth, bright areas represent a strong return. Note the strong return from eastward-facing slopes (facing the satellite) and from urban areas. Note also the geometric distortion – this is a function of layover and a full description is given in the text.

6.0 FEASIBILITY OF USING ERS DINSAR IN DUNEDIN

The success of DInSAR relies on large areas of the data containing a coherent signal that can be compared between different acquisitions over time. However, the ability to measure coherent radar returns from the Earth's surface decreases with time, and is dependent on the local conditions and land cover type (Zebker & Villasenor 1992). A coherent return relies on the relative stability of the objects on the surface (the scatterers) which reflect the broadcasted SAR signal back to the sensor. If these move or change significantly between data acquisitions, the data become decorrelated. DInSAR works best in arid, flat and unvegetated environments. Temporal decorrelation is a limiting factor when using DInSAR in the New Zealand environment. It is particularly caused by the following: vegetation growth, movement (e.g. in wind) and senescence, by moisture variations, snowfall, and extreme surface alteration, such as building construction.

A second limiting factor is the magnitude and spatial extent of surface deformation. Surface instability in the coherent areas of Dunedin should be detectable in the ERS data, providing the area is greater than a few pixels across, and providing the gradient of slip across the area of deformation does not cause an interferometric fringe cycling rate exceeding half a fringe per pixel, so centimetres of deformation relative to the sensor, spread over several hundreds of metres are well within the measuring capability using ERS SAR data.

Another factor which affects signal coherence is that of orbital geometry. Layover in near-range radar imagery is a common effect (e.g. Lillesand & Kiefer 1994), and occurs when slopes facing the sensor are steeper than the incidence angle of the incoming radar energy (~23° for ERS SAR data). Areas of layover are apparent in the ERS SAR data of Dunedin (Figure 5-2), where the slopes facing the satellite appear foreshortened, and data are lost. No useable interferometric information can be retrieved from these areas.

Lastly, the Bperp (Figure 4) should be less than several hundred metres in the case of ERS DInSAR. The likelihood of the satellite returning to exactly the same viewing position in subsequent orbits is low, and in the case of the ERS satellites, the orbital "envelope" of repeat passes is kept to within a couple of kilometres by the European Space Agency. In general, we have found that at least 25% or more of the available pairings within an archive of ERS SAR data have suitable Bperp, and in the case of the Dunedin track 444 data, 50% of the pairs had a suitable Bperp for differential interferometric processing. As the relative viewing positions increase to more than several hundred metres, the ERS data will become spatially decorrelated (Zebker *et al.* 1994b).

In this section, we investigate the feasibility of using ERS SAR in Dunedin, by using the DCC DEM as well as land surface cover maps to delineate theoretically the areas in Dunedin where we expect the technique to work successfully. We examine actual coherence levels in ERS SAR pairs with various temporal separations.

6.1 Layover

Layover in the ERS SAR data of Dunedin is an issue, because the terrain is steep in many places. Layover represents a compression or loss of data coinciding with these steep slopes. This is evident in the track 444 descending-pass ERS scene in Figure 5-2, where the mountainous areas are distorted towards the sensor, which is a typical sign of layover. To investigate the susceptibility of the ERS SAR data to layover in the data, we used the DCC DEM to delineate slopes likely to be affected by layover, by identifying all slopes with gradients larger than the radar incidence angle facing towards the sensor (Figure 6-1, shown in white). Only one of the known urban landslides in this study is near an area of layover in either ascending- or descending-pass data (the Sidey Street slide), even though large areas of the scenes are affected.

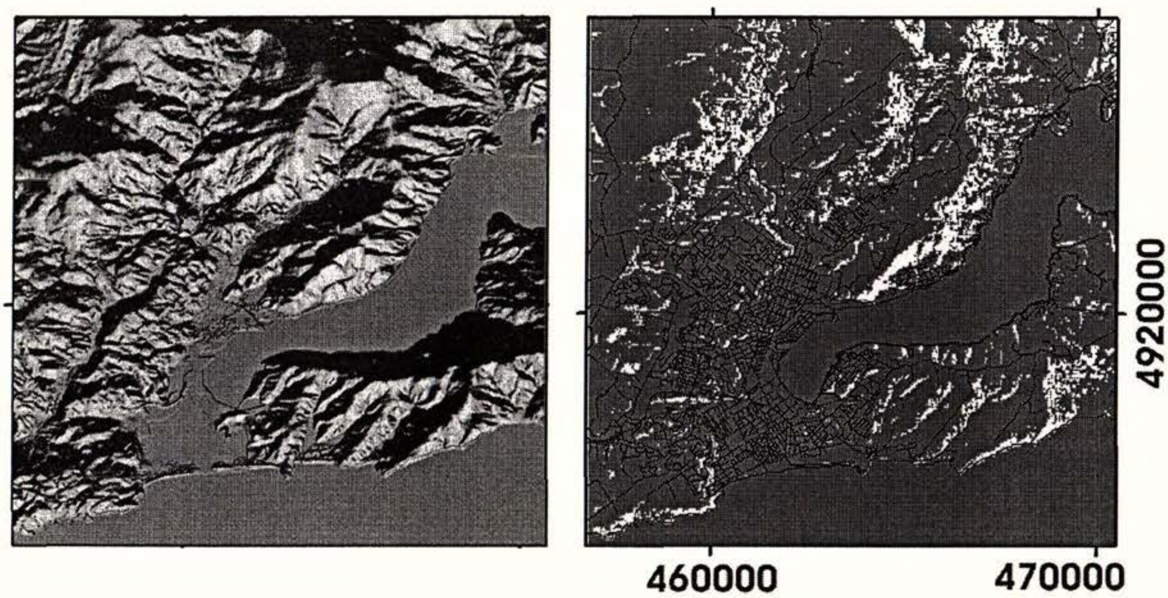


Figure 6-1 On left, a shaded relief image of Dunedin, on right, the DCC DEM was used to calculate areas of the Track 444 ERS SAR data that will be affected by radar layover due to excessively steep slopes. All known slides except the Sidey Street are located in areas unaffected by layover.

6.2 Land surface cover and temporal decorrelation

The Dunedin climate is temperate with large fluctuations in atmospheric and surface moisture throughout the year. Land surface cover in the Dunedin region is delineated broadly into urban and vegetated categories, and these are displayed in Figure 6-2 (a). It would be expected from previous studies (e.g. Zebker & Villasenor 1992) that the forested areas are likely to be decorrelated. Results for coherence in pasture and urban areas around the world have been varied, as individual responses for particular regions depend directly on the number of stable scatterers within a pixel and on the environmental conditions. We therefore processed a number of ERS pairs to examine decorrelation particularly for the Dunedin area.

The coherence images shown in Figure 6-2 were chosen to be representative of typical coherence levels in each of the three data groups demarcated on basis of temporal separation in Table 3. All of the ERS SAR pairs contain large areas of decorrelation, shown in white (Figure 6-2), regardless of the temporal separation, which correspond to vegetated areas and steep slopes where layover occurs. The areas corresponding to suburbs, and the dense inner-city built environment, contain coherent pixels (shown in red), although in most interferograms urban areas contain a mix of high and low coherence pixels. This probably reflects the low spatial density of buildings generally found within New Zealand cities, which tend to contain a large percentage of areas covered by vegetation, in parks and gardens. As would be expected, the density of coherent pixels drops in pairs with temporal separations longer than 7 years (Figure 6-2 c & d). Unfortunately, many of the known slides in Dunedin have a high proportion of vegetation cover (see section 3), and vegetated areas are unlikely to return a coherent signal in ERS SAR data for DInSAR purposes. This will be discussed in more detail in the next section.

We also considered using permanent scatterer (PS) processing techniques, which is a proven effective method to retrieve data in low coherence interferograms from a network of pixels which always remain stable and coherent within the low coherence areas (e.g. Ferretti *et al.* 2001). Sub-millimetric detection of surface motion is possible via this technique. However, PS processing requires a stack of at least ~20-25 SAR scenes of the same track and frame (Colesanti *et al.* 2003 a & b), and even the track 444 acquisitions of Dunedin do not contain enough acquisitions (Table 1). Detecting motion of Dunedin landslides via PS processing also relies on the presence of one or more stable scatterers within an active slide, so is more likely to be feasible for slides containing buildings or roads.

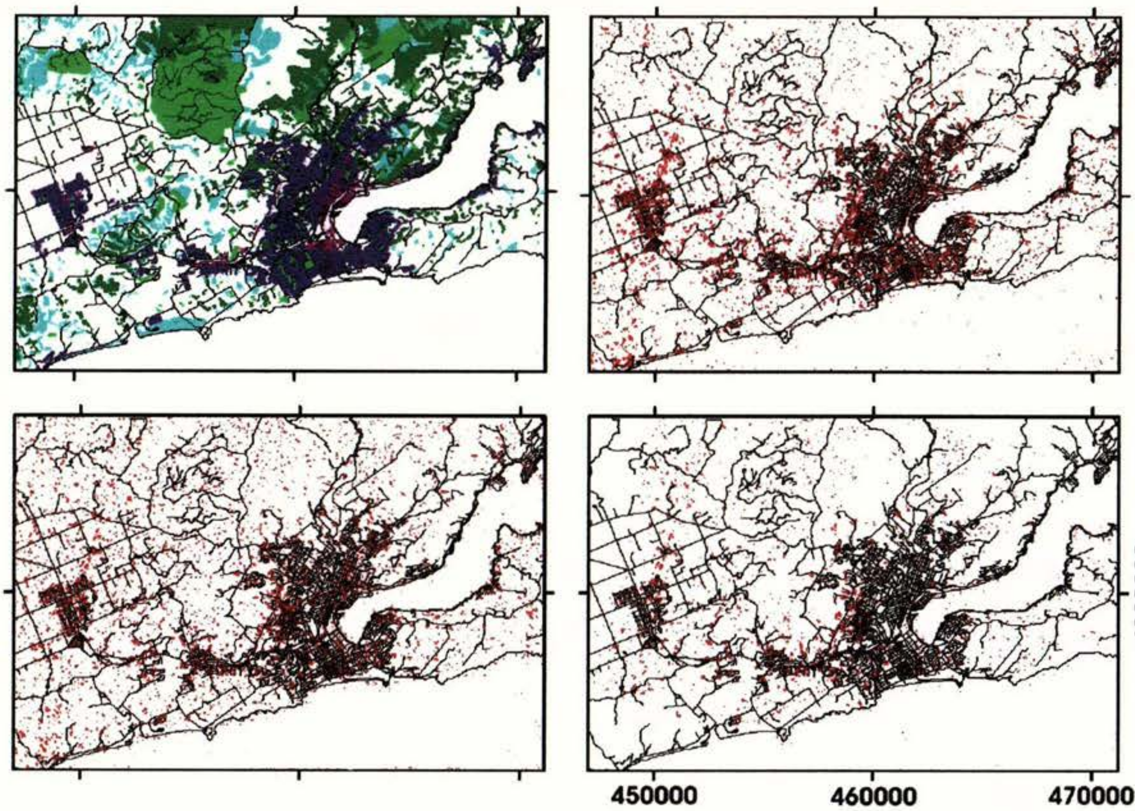


Figure 6.2 (a) Land surface cover of the Dunedin area. Urban areas are delineated by blue and purple shades; vegetated areas are shown in green. Farmland pasture is white. (b), (c) and (d) show typical coherence levels in the ERS SAR interferograms from the three groups observed in Table 2. Coherence is a measure of data quality, and highly coherent data are displayed in red. Note: the coherent data correspond to unvegetated surfaces in the urban areas. (b) coherence image derived from March 1999 – December 1999 ERS pair, of 9 months duration (c) coherence image from September 1995 - November 1999 ERS pair, nearly 4 years duration, (d) coherence image from September 1995 – January 2003, of 7.25 years duration. Note the coherence levels decrease with increasing time between ERS SAR acquisitions.

7.0 RESULTS

The UTM-georeferenced interferograms were imported into the Erdas Imagine image processing and GIS software package for inter-comparison, and were draped with GIS layers of Dunedin: coastline, roads and the extent of the known landslides. Areas of low quality data in the interferograms were masked out using the coherence levels.

At this stage, the interferograms were still "wrapped" – i.e. the pixel values of the interferogram, representing the phase difference, are given in the range zero to 2π, which represents a single fringe. Generally when interferograms are converted into deformation maps, an integer value is assigned to each fringe, and is increased by one with each increasing cycle. However, in the case of the Dunedin interferograms, the coherent pixels are relatively low, which makes phase unwrapping difficult, so we chose to work directly with the wrapped interferograms. We considered interferogram filtering as a solution to refine the noisy interferograms for unwrapping, but rejected this because the degree of filtering needed would have obscured any subtle or localised signals from landslides.

Our reasoning was as follows: in each flattened, wrapped interferogram, areas which have not moved will have approximately the same value, and this accounts for the majority of the coherent pixels in all of the Dunedin interferograms. Pixels with values different from this background value are either those affected by atmospheric anomalies, or represent surface motion. Distinguishing ground motion from atmospheric noise was then a process of elimination: if an anomalous phase value persists in all independent pairs spanning a similar period, it is likely to be surface deformation. If it appears in a few interferograms only, it is most likely to be due to atmospheric (or other) noise.

7.1 DInSAR investigation of known Dunedin slides

We have already discussed the sensitivity of ERS C-band radar coherence to land surface cover. Figure 7-1 shows recent oblique photographs (February 2001) depicting the typical cover types for some of the known slides during the study period. So given the surface cover, and the already recorded rates of motion, can we expect to be able to detect this motion using ERS DInSAR?

To begin with the worst-case scenarios in terms of surface cover: the Jeffcoates and Church Hill Road slides are mainly covered in pasture and forest (Figures 3-4 & 7-1 a & b), and these slides were totally decorrelated (low coherence) in all of the ERS data processed, even in SAR pairs separated by a few to several months, and regardless of season. Some individual coherent pixels were observed on the Jeffcoates slide, but these did not provide any meaningful results.

The West Abbotsford and District Road slides are covered by a mixture of scrub and medium density residential housing with moderate-sized gardens (Figures 3-4, 3-9 & 7-1 c). Surprisingly, although both slides are covered by a reasonable percentage of housing and roads, the District Road slide contains few coherent pixels, as does the active western (motorway) lobe of the West Abbotsford slide (Figure 7-2). However, the DCC field survey measurements show that both slides are moving at rates well below the detection threshold of ERS DInSAR, and this is confirmed by the pixel values of the individual coherent points across these slides, which remain similar to the values of the background areas that are not sliding.

The DCC field survey measurements of the Cargill Street, Albany Street and Evans Street slides indicate that their past rates of movement would be detectable by ERS DInSAR if sustained into the late 1990s and early 2000s. However, these areas were all decorrelated in all of the interferograms. Both the Cargill Street and Albany Street slides are covered in dense urban/residential buildings (Figures 3-1, 3-3 and 7-1 e) and we cannot attribute a single reason for the extensive decorrelation. However, as the Cargill Street slide only appears to affect 8 residential properties (Macfarlane 1990, Glassey 1995), it is possible that its spatial extent is too small to be detectable in the ERS interferograms. The extent of the Evans Street slide is also extremely small, and was only covered by 6 pixels in the interferograms. No meaningful result was found for this slide. The spatial extent of the Albany Street slide is also small, and at the most recent rates of 2-3 mm of motion per year following successful engineering works to control the slip (Glassey 1991), it is not currently sliding fast enough to be apparent in the interferometric data. The measured rates of motion at Sidey Street are also below the measurement threshold of ERS DInSAR, and on inspection of the data, it was found that areas near this slide are affected by radar layover because of the slopes facing the satellite exceed 23° (Figure 6-1).

The most active part of the Howard Street slide is largely covered by dense native vegetation at the head of the slide, and low density housing on the lower half of the slide, with a large percentage of land cover comprising well-established gardens (Figure 7-1 d). The residential area of the slide remains coherent over 3-4 years (Figure 7-3), but ERS data are completely decorrelated after several years. The interferograms of the Howard Street slide show no evidence of distal surface motion during the late 1990s, and this is perhaps attributable to the successful engineering remediation that has taken place there. The apparent phase shift to the west of the slide in Figure 7-3 (b) is most likely an atmospheric anomaly, as the same phase shift does not appear in interferograms spanning the same period (e.g. Figure 7-3 c).

Lastly, the Brighton Road slide is the fastest moving of the surveyed slides in Dunedin. At rates of 100mm per year horizontally, and 30 cm vertically, it would be expected that the slide would be decorrelated in all but the short-term (several months) ERS pairs (Table 2). Examination of the data shows that the active part of the slide is not only decorrelated in the long-term pairs (Table 2), but unexpectedly also in pairs separated by one to several months

(Figure 7-4). This may be attributed to the pasture cover over the head of the slide (Figure 3-2), but the reason for the decorrelation in the built areas remains unknown. Examination of the coherent data in other areas of Brighton shows that no significant motion occurred in the coherent areas over that time interval (Figure 7-4).

7.2 Analysis of coherent ERS DInSAR data of Dunedin

The areas of the ERS interferograms of Dunedin that contain coherent data were examined for evidence of previously unsurveyed surface instability. As the data contained pixels with coherence levels that were low to marginal in all of the interferograms, even in urban areas, great care was taken during the data interpretation stage of the project. The low coherence pixels in each of the interferograms were masked out to leave the reliable interferometric data, and these were examined carefully. As we have already mentioned, because the coherent data were located in small pockets or patches, phase unwrapping was problematic. The wrapped phase data were examined, and in particular, areas containing a small spatial extent of phase shift relative to large uniform areas of homogeneous phase values were identified as possibilities (e.g. Figure 7-5). As before, extreme care was taken in interpreting the cause of these small extent phase shifts, as they can be caused by: (a) surface deformation, (b) phase flattening errors, and (c) atmospheric noise. Atmospheric noise was identified by inter-comparison of all of the interferograms. Examination of all of the interferograms enabled us to detect areas which were not previously thought to be unstable. These were noted and given a weighting according to local coherence and the number of interferograms in which they appeared.

All of the interferograms were compared, and phase shifts occurring persistently in many interferograms were noted. On further examination, several phase shifts were discarded because they were found to coincide with one SAR image only, and were therefore atmospheric noise. Several were discarded because they coincided with areas affected by layover (Figure 6-1).

Figure 7-5 shows interferograms of central Dunedin, including the South Dunedin, St Kilda and Andersons Bay areas. The interferograms have been coloured so that stable, unmoving areas are displayed in yellow-green-blue. Pixels deviating from this background state are coloured in red. These correspond to areas of phase change due to surface motion or atmospheric noise. Figure 7-5 (b) contains the most atmospheric noise – this is evident from examination of the whole interferogram, and is confirmed by Meteorological Office records showing that heavy rain storms covered the city during both acquisitions that produced this interferogram. Areas of consistent phase difference, which are most likely due to surface deformation, are indicated (Figure 7-5, bottom left). The western-most marked area of deformation is especially interesting. This corresponds to an area of reclaimed land that was built during the 1960s, and its southern-most edge follows the old 1850s coastline (Figure 2). The apparent deformation observed is ~10 mm subsidence over 4 years along the satellite line-of-sight. This area was surveyed for deformation in the past, but these data were not available to us at the time of writing. Although it is possible for this area of reclaimed land to be moving ~40 years after being built (R. Macleod, pers. communication, 2003), further field investigations will be needed to confirm this. The other areas identified in the interferograms as potential slips in Figure 7-5 and elsewhere were investigated in the field, but no field evidence could be found to indicate surface motion, and further field surveys would be required to confirm whether these are active slips.

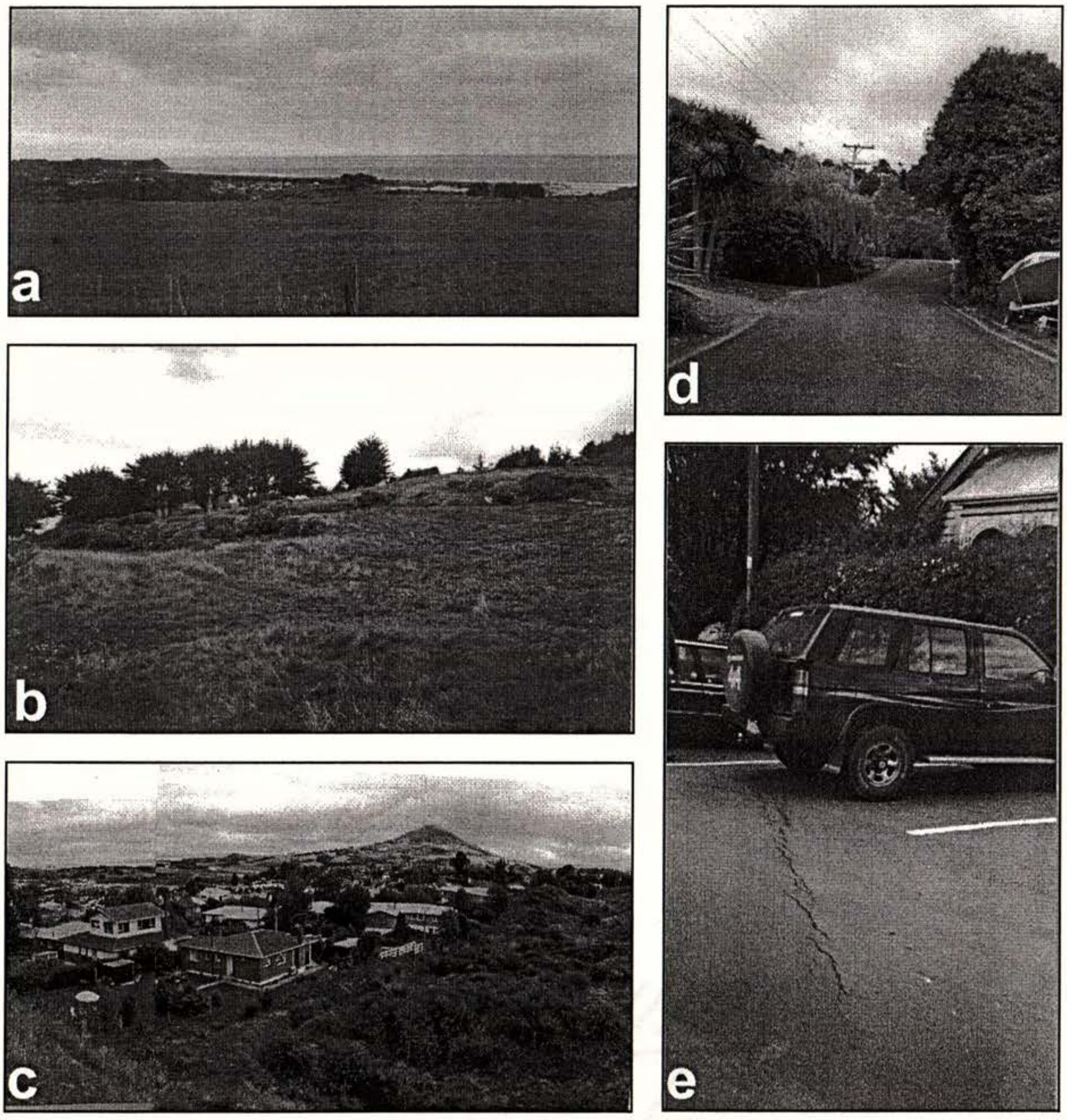


Figure 7-1 Field photographs of surface cover on selected known landslides: (a) Jettcoates (b) District Road, (c) West Abbotsford, (d) Howard Street, and (e) motion induced crack in road at head of Albany Street slide

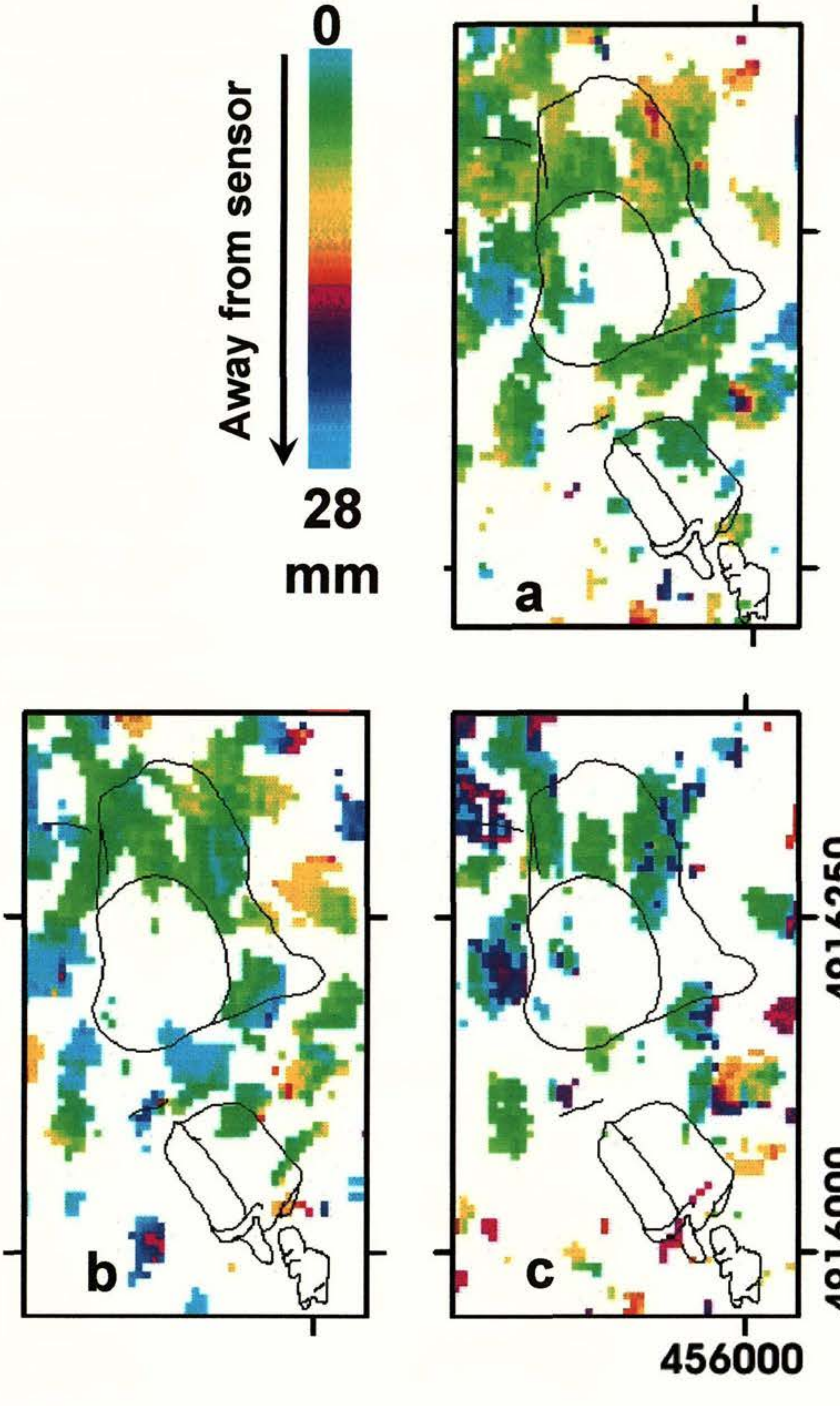


Figure 7-2 ERS SAR interferograms of West Abbotsford, Church Hill Road and District Road slides. Full explanation is given in the text. Interferograms are derived from the following pairs of scenes: (a) March 1999 – December 1999, (b) December 1995 – April 1999, (c) September 1995 – January 2003. Map coordinates are given in UTM, WGS84.

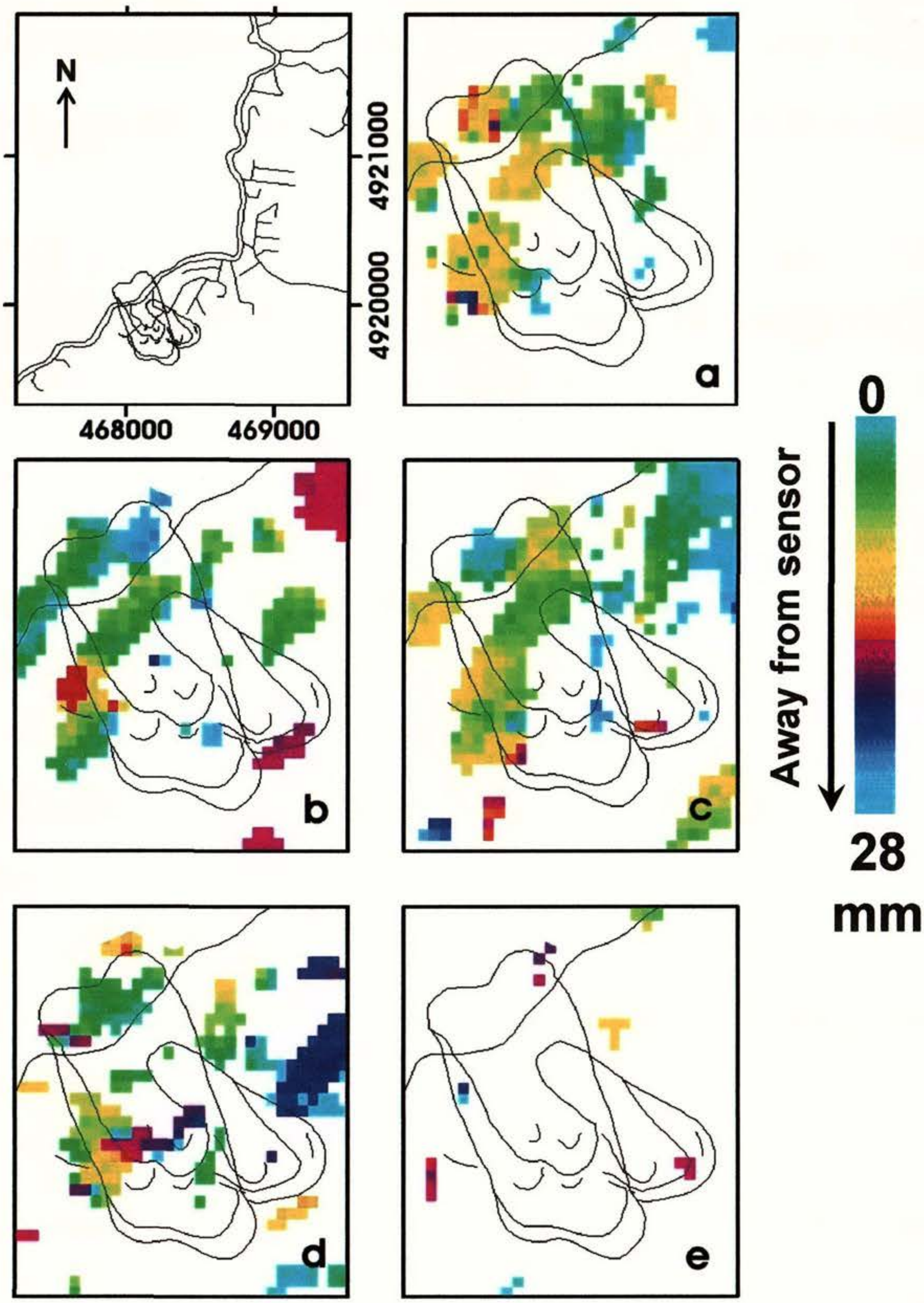


Figure 7-3 ERS SAR interferograms of the Howard Street slide. Full explanation is provided in the text. Interferograms are derived from: (a) March 1999 – December 1999, (b) December 1995 – March 1999, (c) Sept 1995 – January 2000, (d) March 1999 – January 2003, (e) September 1995 – January 2003. Map coordinates are given in UTM, WGS84.

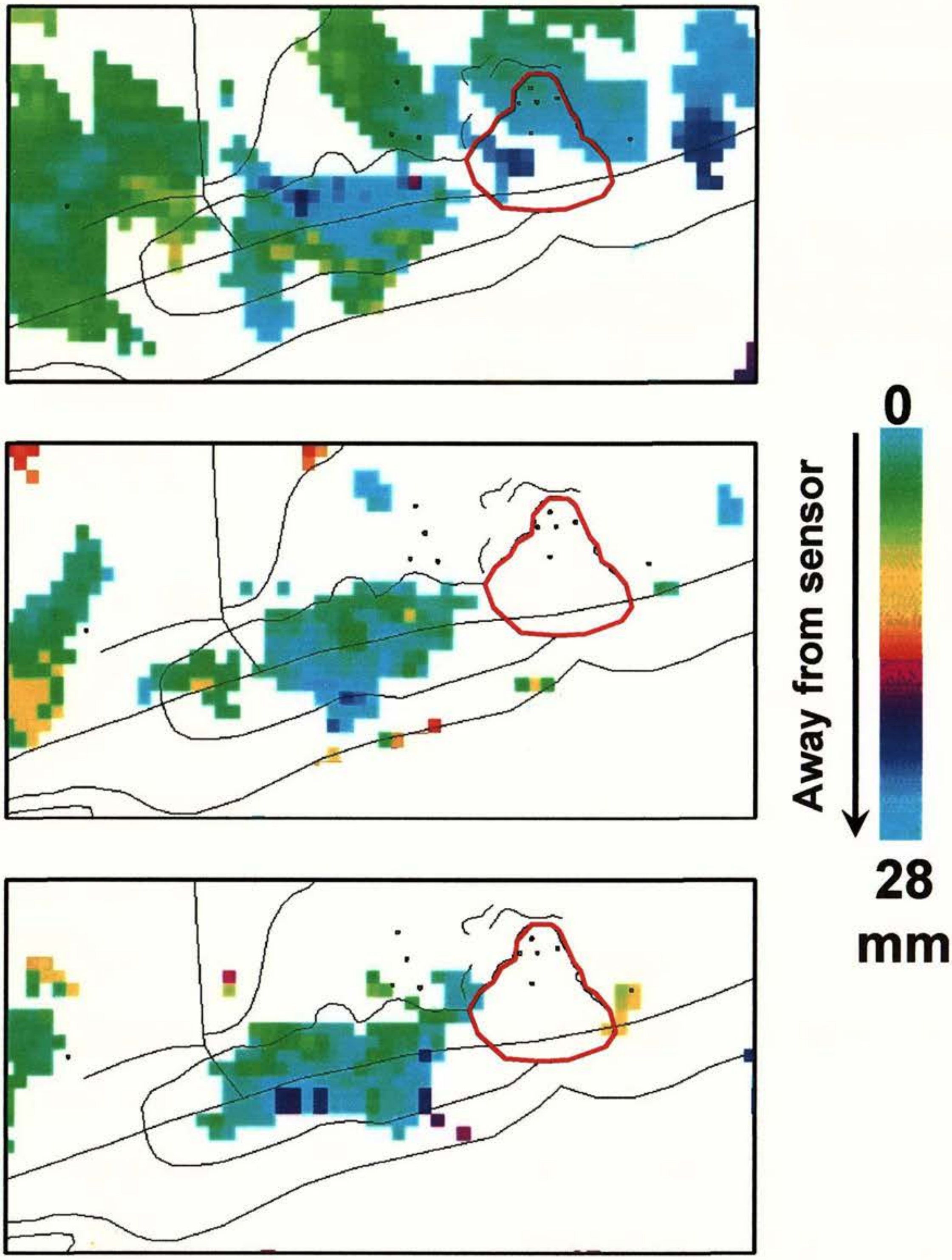


Figure 7-4 ERS interferograms of Brighton Road slide (outlined in red) and surrounds, which are explained in the main text. Interferograms are derived from: (a) October 1999 – November 1999, (b) February 2000 – March 2000, (c) November 1999 – January 2000.

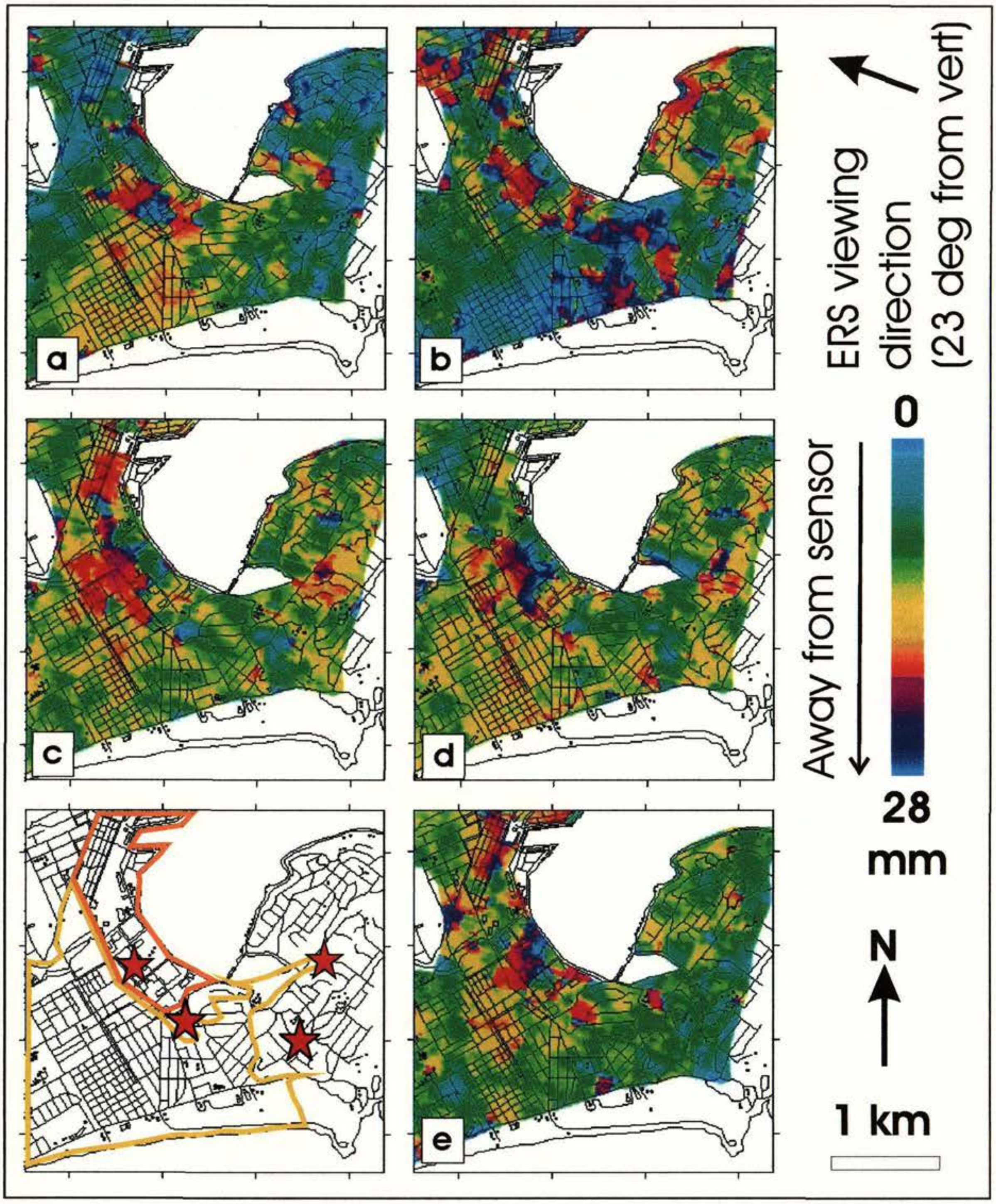


Figure 7-5 ERS interferograms of the central Dunedin area (a) December 1995 – March 1999, (b) December 1995 – Jan 2000, (c) September 1995 – October 2000, (d) September 1995 – November 1999, (e) January 2000 – December 2002. Areas of reclaimed land are indicated in bottom left plot, as are areas of newly-discovered surface deformation (red stars).

8.0 DISCUSSION AND RECOMMENDATIONS

We have collated the survey data made available to us by the Dunedin City Council and present comprehensive documentation of landslide motion in the Dunedin urban area. In this report we have provided a detailed review of orbital differential SAR interferometry, and have investigated its applicability for measuring slope instability in Dunedin.

In general, we found that the technique works well over the urban, built-up areas of Dunedin, but not in significantly vegetated areas. Although ERS DInSAR did not yield as many positive results as we had hoped, this study enabled us to make several interesting observations, and these results will be invaluable to other groups considering similar studies to this in similar environments and scenarios. Our study is unique, because thus far, as only successful studies applying ERS SAR to landslides have been published to date (e.g. Carnec *et al.* 1996, Rott *et al.* 1999), and this study injects some realism into the difficulties of using the technique in areas with moist, variable climates. We have also detected previously unrecorded deformation, namely the on-going subsidence of the reclaimed land in the industrial docks area of Dunedin.

Orbital L-band radar would resolve some of the decorrelation issues we have encountered during this study, but L-band data are less sensitive to surface motion because the radar wavelength is much longer. Typical rates of Dunedin slides would be unlikely to be detected using orbital L-band data. In the event that more than 25 radar scenes of Dunedin are acquired by a single sensor in future, the permanent scatterer processing technique developed by Ferretti *et al.* (2000, 2001) should be successful, and past studies have captured progressive and seasonal motion using this technique in urban areas (Colesanti *et al.* 2003 a & b).

The fact remains that traditional point-measuring survey techniques are time-consuming and relatively expensive to implement, especially as these slides move sporadically. Although we have shown that using orbital radar interferometry is extremely difficult in this environment, the newly-developed technique of ground-based radar interferometry might be a strong future possibility (Tarchi *et al.* 2003), especially because the surface relief of Dunedin would allow remote monitoring of slopes from adjacent hillsides.

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ACRONYMS

APP	Auxiliary Parameter Processor software – processes SAR RAW format to SLC format
DCC	Dunedin City Council
DEM	digital elevation model
DInSAR	differential synthetic aperture radar interferometry
ERS	Earth remote sensing satellites, operated by the European Space Agency, of which there are two: ERS-1 operated from 1991-1999, ERS-2 operated from 1995 - present
ESA	European Space Agency
EV-InSAR	Earth View Interferometric processing software
SAR	synthetic aperture radar
SLC	single look complex

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