Appendix F

Geotechnical Assessment

GHD Geotechnics

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Cardno Lawson Treloar

Report on Wollongong Coastal Study

Geotechnical Assessment

June 2010

GHD GEOTECHNICS

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30 June 2010

Cardno Lawson Treloar
Level 2, 910 Pacific Highway
GORDON NSW 2072

Our ref: 21/18903//BA041 Rev1.doc

Attn: Sean Garber

Dear Sean

Wollongong Coastal Study
Geotechnical Assessment

We present herein our Geotechnical Hazards Assessment that forms a part of the Wollongong Coastal Study to assist Wollongong City Council with future planning considerations in coastal areas. This assessment was undertaken by GHD Geotechnics under subcontract to Cardno Lawson Treloar Pty Ltd to supplement the broader coastal study.

GHD Geotechnics assessment of geotechnical hazards has included a review of existing data, most significantly including the University of Wollongong Landslide Inventory and Susceptibility Mapping. This aspect of the study was assisted by Dr Phil Flentje of the University of Wollongong.

Parameters defining the coastal effects, including consideration of climate change, were provided by Cardno Lawson Treloar for prediction at times of 2050 and 2100.

The Geotechnical Assessment of these coastal processes has culminated in the establishment of a Coastal Influenced Geotechnical Hazard Zone defined as including areas where coastal processes (including climate change) will directly influence geotechnical hazards for the defined study time period to 2100.

This Zone is proposed for Council's use in defining the need for geotechnical assessments for proposed or future development (in accordance with Wollongong City Council's Development Control Plan) to include specific assessment of coastal processes, including the potential for climate change influences.

Should you require any further assistance with geotechnical aspects of this coastal study, please do not hesitate to contact the undersigned.

Yours faithfully
GHD Geotechnics

Benjamin Rouvray
Principal Geotechnical Engineer

Peter Stone
Senior Principal Geotechnical Engineer

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1. Introduction

GHD Geotechnics was engaged by Cardno Lawson Treloar to undertake geotechnical assessment of the impact of coastal effects on geotechnical hazards within the Wollongong City Council Local Government Area as part of their Wollongong Coastal Study.

The project brief with respect to Geotechnical Hazards was in response to Council's identification of a number of areas being subject, or potentially subject, to geotechnical effects within the Coastal Study area. In particular, some of these areas will be potentially further exacerbated by ongoing interaction with Coastal Processes, in particular associated with climate change effects given predictions of sea level rise. The impact of coastal processes on these geotechnical hazards within the context of future Council planning is the subject of this report.

This report presents the findings of our geotechnical assessment including the development of a geotechnical assessment framework for the study incorporating Council's existing planning protocols.

2. Project Definition

GHD Geotechnics and our nominated subconsultant Dr Phil Flentje from the University of Wollongong have a long history of slope and cliff instability identification, assessment and management in the Wollongong Local Government area. As such we have been able to incorporate our knowledge of Council's existing records in the study and utilised in house information regarding the Council area. This information has been collated using a GIS database to enable the spatial location of all data sets and the generation of maps.

Given the magnitude and quantity of known geotechnical hazards, including slope and cliff instability, within the Wollongong Council Area, and Council's well established planning requirements for development specific Geotechnical Assessment, the prominent aspect of the study has been the establishment of a framework/criteria within which current, or potential future, geotechnical hazards are deemed to be influenced by Coastal processes for planning purposes.

In developing this framework/criteria, the impact of potential coastal effects on slope and cliff instability has been reviewed considering the existing conditions and 2050 and 2100 planning horizons. The determination of the coastal effects has included consideration of climate change over these planning horizon periods as defined by Cardno and provided to GHD Geotechnics. These coastal effects as provided to GHD Geotechnics include:

- Sea Level Predictions for 2050 (RL 0.4m) and 2100 (0.9m).
- Cliff Wave Run Up Modelling (2%exceedence, datum AHD) for return periods (ARI's) between 5 and 100-years for the present climate condition and also for a 2100 climate scenario with 0.9m of sea level rise. We understand that this incorporates bathymetry data and coastal topography. Nominally 56 cliff sites data points were provided.
- Wave Inundation has been undertaken for the existing and 2100 climate change scenarios. These identify the area subject to wave inundation from the 100yr ARI ocean storm. The scenarios assume an eroded beach, therefore wave inundation will extend from the relevant erosion hazard line.
- Erosion Hazard lines have been generated for existing conditions as well as 2050 and 2100 climate change conditions. There are 2 lines for each; the seaward line being the erosion hazard (storm bite) line and the landward line showing the zone of reduced soil capacity (i.e. between it and the erosion line).
- Rainfall Projections via the 90 day cumulative rainfall curve for selected locations in the Illawarra for particular climate change scenarios. It is understood that rainfall projections for climate change are widely varying with projections in the range of plus or minus 30% of existing rainfall. We understand that for the purpose of this study, Cardno's have considered the scenarios at 10% increase in intensity for 2050 and 20% increase in intensity for 2100.

Reference should be made to the Cardno reports for further details on the basis of these coastal effects. GHD has adopted this information in assessing the impact on geotechnical hazards.

It is valid to suggest that the entire Illawarra escarpment exists as a result of coastal effects over geological time. It is therefore critical to define the boundary of this study. Given the 100 year projection of effects being considered (ie to 2100), the coastal effects on geotechnical stability have only been considered where such effects directly impact upon the geotechnical stability. Secondary or regressive effects may be initiated but these have largely been excluded from this assessment, though should be considered in any site specific geotechnical assessment.

This geotechnical assessment does not include coastal geomorphological processes apart from where they influence slope and cliff instability mechanisms. That is, certain coastal geomorphological processes are not included herein and reference should be made to Cardno's report. We have summarized below coastal geomorphological processes that have been excluded form our geotechnical assessment:

- Dune migration
- Beach deposition/erosion
- Estuarine deposition/erosion (including creeks and drainage paths)
- Coastal inundation impacts on slopes surrounding estuarine areas (ie limited to slopes at the coast with exception of Lake Illawarra) as we understand that these hazards would require estuary specific assessment including review of flood impacts.

Thus, our geotechnical assessment is typically associated with slope and cliff instability occurring at headlands and coastal slopes. We also note that this assessment has not specifically assessed any existing man made structures

3. Geotechnical Assessment Framework

We summarise below the Geotechnical Assessment Framework and the steps involved in its development as follows:

3.1 Existing Data Review

This included review and interrogation of the existing data sources within the study area as defined by the Wollongong City Council Local Government Area (LGA). Figure 1 accompanying this report presents the study area with the northern extent being the southern boundary of the Royal National Park to the southern boundary of the Wollongong LGA at Lake Illawarra. The existing data sources included:

- Digital Elevation Model (DEM) of topography of Council LGA developed from Airborne Laser Scan (ALS) provided by Wollongong Council. University of Wollongong (UoW) has developed a 2m DEM based on this ALS data that has been utilized within this assessment.
- University of Wollongong (UoW) Landslide Inventory via ESRI ArcGIS software. We understand that the UoW Landslide Inventory has been previously provided by UoW direct to Wollongong Council. This includes existing datasets as developed by our subconsultant at the University of Wollongong including:
  - Landslide inventory – location and distribution of known landslides from over 120 years of records.
  - Slide category landslide susceptibility model – GIS interogation of topography, geology, vegetation, slope aspect, ground curvatures, surface water flow accumulation, wetness index to develop susceptibility maps for Wollongong Council Area. For more detailed discussion of the landslide susceptibility modeling reference should be made to the two papers by Flentje 2007. Copies of these papers are presented in Appendix A.
  - Geology as incorporated into inventory.
  - Current Coastal geometry – from review of RL0m AHD.
- Published Geology maps as provided by the Department of Primary Industries (now the Department of Industry and Investment).
- Limited review of existing geotechnical reports recovered from GHD Geotechnics archives.
- Published paper on Holocene Sea Level change in south east Australia (Refer Sloss 2007).
- Published papers by Flentje on Landslides in Wollongong area (Flentje 1998, 2005, 2007).

3.2 Establish Coastal Geotechnical Domains

From our historical knowledge of geotechnical hazards in the Wollongong Council Area and our understanding of the coastal geology, we have developed 5 Coastal Geotechnical Domains. Each domain defines an area characterized by geological units and their associated slopes. Discussion of each of the domains is provided at Section 6. The domain extents are presented on Figure 1 and are named as follows:

- Domain 1 “Narrabeen Group”

- Domain 2 “Faulted Transition from Illawarra to Narrabeen”
- Domain 3 “Illawarra Coal Measures”
- Domain 4 “Coastal Plains”
- Domain 5 “Lake Illawarra”

From interrogation of the existing data, generic characteristics have been generated for each of the domains that have been considered in assessing the impact of coastal processes.

3.3 Review Generic Hazards

The landslide inventory as maintained by the University of Wollongong (UoW) Landslide research team has been reviewed in the assessment of the impact of coastal effects on geotechnical hazards and in particular identifying generic hazards. This has included reviewing known geotechnical hazards from the landslide inventory in proximity to the coast and also interrogation of the landslide susceptibility mapping prepared by the University of Wollongong. Figure 4 graphically presents all landslides contained within the landslide inventory for the entire study area. Figure 5 presents the landslide susceptibility modeling for the study area.

Typical sections have also been developed of the Wollongong escarpment from the top of the escarpment to the Coastal Geotechnical Domains occurring near sea level. These generic sections are included as Figures 12 to 15 within the figures accompanying this report. Whilst the area of coastal impact is isolated to the profile in vicinity of the coast line, these sections present the relationship between the escarpment formation and the coast.

Typical sections Figure 12B to 15B include annotated presentation of geotechnical hazards that exist along the escarpment. The sections presented for Coledale and Austinmer, where geotechnical hazards are active at the coast line, specifically include the geotechnical hazards that are affected by coastal effects.

From these figures, we note the following generic geotechnical hazard types that are applicable to each domain, including a brief description of their interaction with coastal processes:

- Rock falls and/or cliff regression associated with jointed rock mass at cliffs and shoreline rock platforms. This is an ongoing effect but may be exacerbated by more frequent waves/spray occurring to higher points at the cliffs.
- Landslide features underlain by low strength claystones (eg Wombarra Claystone in north). These will be affected by increasing rainfall and also toe erosion that may occur due to cliff regression and/or wave erosion.
- Debris flows associated with landslides higher up the escarpment and/or direct result of coastal erosion acting on the basal slopes and cliffs. Ongoing erosion, or erosion to higher points on the cliffs, will affect this hazard.

3.4 Consider Coastal Effects including climate change impacts

Given the known history of geotechnical instability in the WCC area, this study does not propose to review the ongoing development of the Illawarra escarpment, but rather to specifically assess the following current and predicted coastal effects on geotechnical hazards in close proximity to the coast.

3.4.1 Sea Level Change

On the basis that the mean current sea level is RL0m AHD, Cardno have provided sea level change predictions for our use of RL0.4m AHD at 2050 and 0.9m AHD at 2100. Figures 6A to 6G present contours for 0m AHD and the 2100 prediction of 0.9m AHD. These contours are also shown at Figures 7 to 11 that present a series of more detailed maps of a typical area for each domain type.

From reference to (Sloss 2007) regarding sea level change in the geological Holocene period, these predictions would provide a sea level impact to the coast line that was inferred to have occurred for a period of around 5 thousand years within the past 10 thousand years (refer extract of abstract below)[1]. Thus, the predicted increase in sea level would invoke coastal processes within the study area that are inferred to have occurred for many thousands of years.

Whilst the rate of the individual coastal processes will impact upon the 100 year planning horizon being considered, the relatively recent occurrence of a similar sea level (ie in geological time) for an estimated period of more than five thousand years has demonstrated the range of geomorphological processes that can be expected to occur as per the current coastal landform.

3.4.2 Cliff Run Up

Cardno have undertaken cliff run up modeling for a number of nominated cliff locations within the study area. For details of this modeling, reference should be made to the Cardno report. The locations of the Cardno cliff run up locations are shown at Figures 7 to 11 within the typical map area selected for each domain type.

In assessing the geotechnical impact of these cliff wave run up, we have considered the range of levels to which the waves will run up for the range of analyses undertaken (ie ARI 5 to 100 years) for current conditions and the 2100 predictions. The range for these periods is:

- Current 3.2 to 8.9m AHD; and
- 2100 4.2 to 11.2m AHD

In order to assess the potential impact of these cliff run up predictions on existing slopes we have utilized the DEM and projected the RL9 and RL11m contours within the GIS model for the cliffs within the Council LGA Coastal Area. This has then been used to consider geomorphological processes that may be invoked from the wave run up to these predicted levels at the coastal cliffs to determining if this will impact on geotechnical hazards. For example, cliff regression due to wave related erosion, undercutting at the toe of an active or potential landslide zone, etc.

3.4.3 Wave Inundation

Cardno have predicted wave inundation for embayments and beaches as part of their coastal assessment. These inundation predictions typically occur in between the cliffs and headlands

[1] "*Results show that sea level during the Holocene marine transgression rose to between -15 and -11 m at 9400–9000 cal. yr BP. Sea level then rose to approximately -5 m by 8500 cal. yr BP and to approximately -3.5 m between 8300 and 8000 cal. yr BP inundating shallow incised valleys resulting in the deposition of shell-rich transgressive sandsheets within shallow incised bedrock valleys. Present sea level was attained between 7900 and 7700 cal. yr BP, approximately 700–900 years earlier than previously proposed. Sea level continued to rise to between +1 and +1.5 m between 7700 and 7400 cal. yr BP, followed by a sea-level highstand that lasted until about 2000 cal. yr BP followed by a gradual fall to present." (Sloss 2007)*

that are the subject of this geotechnical assessment. As such, the wave inundation has not specifically been considered in assessing geotechnical hazards.

It should be noted that the wave inundation does predict water levels higher than existing for the slopes within the embayment areas, but as noted previously, these slopes are excluded from this assessment as we understand that assessment of these embayments would require incorporation of a flood study that is beyond the scope of this coastal assessment.

Detailed assessment of the interaction of the wave inundation predictions with the geotechnical hazards at the intersection of beaches and embayments with coastal cliffs and headlands has not been undertaken within this report. Reference should be made to the Cardno report for further discussion of this interaction. For the purposes of planning, where development is proposed at these points of wave inundation and geotechnical hazard interaction, both mechanisms may require consideration.

3.4.4 Erosion Hazard

Similarly to the wave inundation modeling, the erosion hazard predictions by Cardno are specific to embayments and beaches as part of their coastal assessment. As such, the erosion hazard has not specifically been considered in assessing geotechnical hazards.

Detailed assessment of the interaction of the erosion hazard predictions with the geotechnical hazards at the intersection of beaches and embayments with coastal cliffs and headlands has not been undertaken within this report. Reference should be made to the Cardno report for further discussion of this interaction. For the purposes of planning, where development is proposed at these points of erosion and geotechnical hazard interaction, both mechanisms may require consideration.

3.4.5 Rainfall Projections

There are a variety of geotechnical hazards in proximity to the coast that are affected by rainfall, these include:

- Landslides –are typically closely related to cumulative rainfall and associated increase/build up in pore water pressure.
- Debris flows – are typically related to shorter duration high intensity rainfall events.
- Rockfalls – can be related to rainfall due to erosion, pore pressure build up, etc, though do frequently occur outside of rainfall periods.

The correlation between rainfall and landslides/debris flows is via the impact of the rainfall on pore pressure within the slide/flow mass. As pore pressure is not readily able to be widely monitored this correlation cannot be readily quantified. Conversely, rainfall can be and is widely monitored (for example the Bureau of Meteorology) and hence rainfall data is internationally used in place of pore water pressure to correlate with triggers of landslides/debris flows. Review of international literature has shown landslide frequency is often related to rainfall frequency and in particular cumulative rainfall.

Importantly, we note that the site specific impact on geotechnical instability is also controlled by other parameters including surface drainage, concentration of surface flows, ground infiltration, subsurface drainage, etc.

For the purpose of this assessment of coastal effects, Cardno have advised a nominal 10% at 2050 and 20% at 2100 increase in 90day cumulative rainfall.

From our understanding of landslide frequency in the WCC area, disruptive landslides (ie of small magnitude (<50mm) to disrupt rail, road, residential land use) occur every few years. Thus, the current rainfall occurrence provides an environment of active landsliding for large areas of the WCC LGA.

For the increases in rainfall nominated above, there will likely be an increase in the frequency of occurrence and possibly the magnitude of landslide response. However, as rainfall affects geotechnical stability generally within the Illawarra escarpment it is not considered to be a determining factor related to coastal processes for the WCC LGA (ie it is an active contributor to geotechnical instability regardless of proximity to coast). Thus, for simplicity we have not specifically considered the impact of rainfall further in this assessment.

However, in assessing the impact of climate change on site specific geotechnical hazards, the predictions provided by Cardno (or others) may need to be considered. Importantly, any site specific geotechnical assessment for planning should consider rainfall and associated impacts (ie drainage, concentrated flows, infiltration, etc) irrespective of proximity to the coastal zone.

3.5 Existing Council Planning Requirements

The most significant aspect of the Geotechnical Assessment Framework is to provide an output to this geotechnical assessment that can be integrated within Council's existing planning protocols.

From reference to the Wollongong Council Development Control Plan 2009, Council has a well established framework for managing geotechnical hazards for proposed development. In particular, we note the following extract from Chapter E12 – Geotechnical Assessment that defines the objective of the control plan for Geotechnical Hazards:

> *The objectives of this Chapter are:*
>
> *a) To outline the procedure to be followed when Council is considering applications for the development of sites that may be subject to slope instability;*
>
> *b) To ensure geotechnical and related structural matters are appropriately investigated and documented by applicants prior to the lodgement of any Development Application to carry out development;*
>
> *c) To establish whether or not the proposed development is appropriate to be carried out, either conditionally or unconditionally, having regard to the results of those geotechnical and related structural investigations;*
>
> *d) To ensure all geotechnical and related structural engineering conditions, are identified by applicants of the Development Application including all appropriate constraints and remedial actions required prior to, during and after the carrying out of the development;*
>
> *e) To ensure the level of risk to property and/or life posed by slope instability on the site or related land is equal to or less than the level of acceptable risk as defined by the*

Australian Geomechanics Society's Practice Note Guidelines for Landslide Risk Management 2007.

As the Council Control Plan requires site specific geotechnical assessment for development, as per the objectives above, this report does not seek to define the risks associated with coastal effects on the hazard within the coastal study.

Rather, this report seeks to define where development specific assessment of geotechnical hazards, in accordance with the Development Control Plan, is required to consider coastal effects including consideration of climate change. Thus this report seeks to define a "Coastal Influenced Geotechnical Hazard Zone" as described in Section 7.

3.6 Site Inspection

Limited site inspection was undertaken by our Principal Geotechnical Engineer and subconsultant Engineering Geologist to observe typical slope and cliff instability areas within each of the geotechnical domains, described later within this report. This inspection enabled review of the potential interaction of the defined coastal processes to areas with known geotechnical instability hazards. These inspections also enabled interrogation of the project definition to refine the geotechnical assessment framework.

3.7 Review in Conjunction with Council

The final stage of our geotechnical assessment included presentation of the results to Council's Geotechnical Manager. This was undertaken to benefit from Council's in-house knowledge of the areas being assessed and to ensure there was some consistency with Council's current management of these areas.

4. Study Area Geology

4.1 Study Area Description

The city of Wollongong is nestled on a narrow coastal plain approximately 70km south of Sydney in the state of New South Wales (NSW), Australia. Over the last 150 years or so of modern settlement the population of the Wollongong area has increased to about 200,000 people. The coastal plain is triangular in shape with a coastal length of 45km (see Figure 1). The coastal plain is up to 17km wide in the south near Dapto and extends north to Thirroul. To the north of Thirroul, urban development exists on the lower slopes of the escarpment. The coastal plain is bounded to the north, west and south by an erosional escarpment (as discussed below), which ranges in height from 260m in the north and rising up to 620m in the south.

The main road link to Sydney is the F6 Freeway that traverses the escarpment via the Mount Ousley Road area. Several other roads link the coastal plain to the top of the escarpment such as at Bulli Pass and Lawrence Hargrave Drive. Lawrence Hargrave Drive to the north links the northern suburbs to the F6 freeway and Sydney via the spectacular near vertical 200m high cliffs near Clifton, and the recently completed Sea Cliff Bridge.

The South Coast railway line and the Unanderra to Moss Vale railway line also cross the escarpment slopes and coastal plain; both provide important freight and passenger services between Sydney, Wollongong and the surrounding areas.

4.2 Geological Setting of the Illawarra escarpment

The Illawarra escarpment consists of slopes with moderate to steep inclinations with several intermediate benches and cliff lines. The geological sequence encountered on the escarpment comprises an essentially flat-lying sequence of interlayered sandstone, mudstone and coal of the Illawarra Coal Measures (Late Permian age), overlain by interbedded sandstones and mudstones/claystones of the Narrabeen Group (Late Permian to early Triassic age). Spectacular cliffs of Hawkesbury Sandstone (of Middle Triassic age) cap the escarpment and there is dense vegetation over most of the escarpment below these cliffs. The Illawarra Coal Measures and the underlying Shoalhaven Group also incorporate a series of igneous basaltic Necks, Stocks, Sills and Flows that are generally considered to be of post-Mesozoic (less than 65 million years) or Cenozoic age.

The Illawarra Escarpment is an erosional escarpment that has evolved on a passive continental margin. This major tectonic plate margin feature developed following the onset of rifting and continental breakup between Australia and the Lord Howe Rise/Dampier Ridge approximately 80 million years ago (Brown et al, 2003). The escarpment is a variable geomorphological feature. In the southern half of the study area it is a relatively mature feature with a wide coastal plain with well developed and incised drainage lines. North of the suburb of Thirroul, to Clifton the escarpment coastline comprises a series of small bays and headlands which merge to the north into a coastal cliff line up to 100m in height separated from the main upper escarpment slopes by a gentle narrow sloping terrace. This 10km section of escarpment is currently being undercut at or near sea level by marine erosion and is relatively over steepened when compared to the escarpment further to the south. It is not surprising then to note that it contains a significantly larger density of landslides.

To demonstrate the escarpment geometry and interaction with the geological sequence, four representative cross sections of the escarpment have been included within the figures accompanying this report. The location of these representative sections is shown on the map sheet presented as Figure 1. These figures also include annotations of active geomorphological processes at the escarpment.

4.3 Geology data of the study area

A generalised stratigraphic column outlining the geology of the Wollongong region is shown below as Plate 1 adapted from Bowman (1974).

The Illawarra escarpment geology has been mapped within the 188 km^2 Study Area by our subconsultant Dr Phil Flentje over a period of several years between 1993 and 1996 as part of his doctoral research (Flentje, 1998)[2]. Outside of this area, the Department of Primary Industries (DPI) 1:100,000, 1985 Wollongong geological map data has been used.

The Flentje geological mapping was completed using several techniques including large scale geological field mapping (1:4000) where conditions permitted, including inference between known areas of outcrop and also computer modelling in some areas. The field mapping was often undertaken with the aid of a comprehensive borehole database compiled specifically for the project (comprises 845 boreholes to date). The boreholes were sourced from a wide variety of locations, including the Wollongong City Council, coal exploration companies (BHP Billiton, Shell etc), the Bureau of Mineral Resources, the Geological Society of NSW, the NSW Rail Corporation, the Roads and Traffic Authority of NSW and numerous local geotechnical consulting firms. In areas where no field mapping and/or no borehole data was available, the positions of geological boundaries have been inferred on the basis of previous mapping by other workers (published and non published) and on the basis of topography.

We have presented within the figures attached to this report the geology of the study area as per the Department of Primary Industries maps (refer Figure 2) and the geology based on the Flentje 1998 thesis (refer Figure 3). For the domain specific typical mapped areas we have presented the Flentje 1998 geology with the exception of Domain 5 that has presented the DPI geology given the limited mapping in this area.

The Permian to Triassic aged sedimentary sequence of the Sydney Basin is generally regarded as being an essentially undisturbed, near horizontally bedded sequence, particularly within the Illawarra region. However, the Illawarra region is located on the southeastern margin of the Sydney Basin geological complex, and as such the entire regions bedrock exhibits a generally northwest dip of approximately 3-5^{o} and it also contains a range of structural features, such as fold axes and discontinuities including dykes, sills and faults with throws of up to 40m or so.

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[2] The geology of the region (after Bowman 1974) is discussed comprehensively in Chapter 3 of the Flentje thesis (Flentje 1998), which is available for download at:

http://www.uow.edu.au/eng/research/landslide/flentjephdthesis/index.htm.

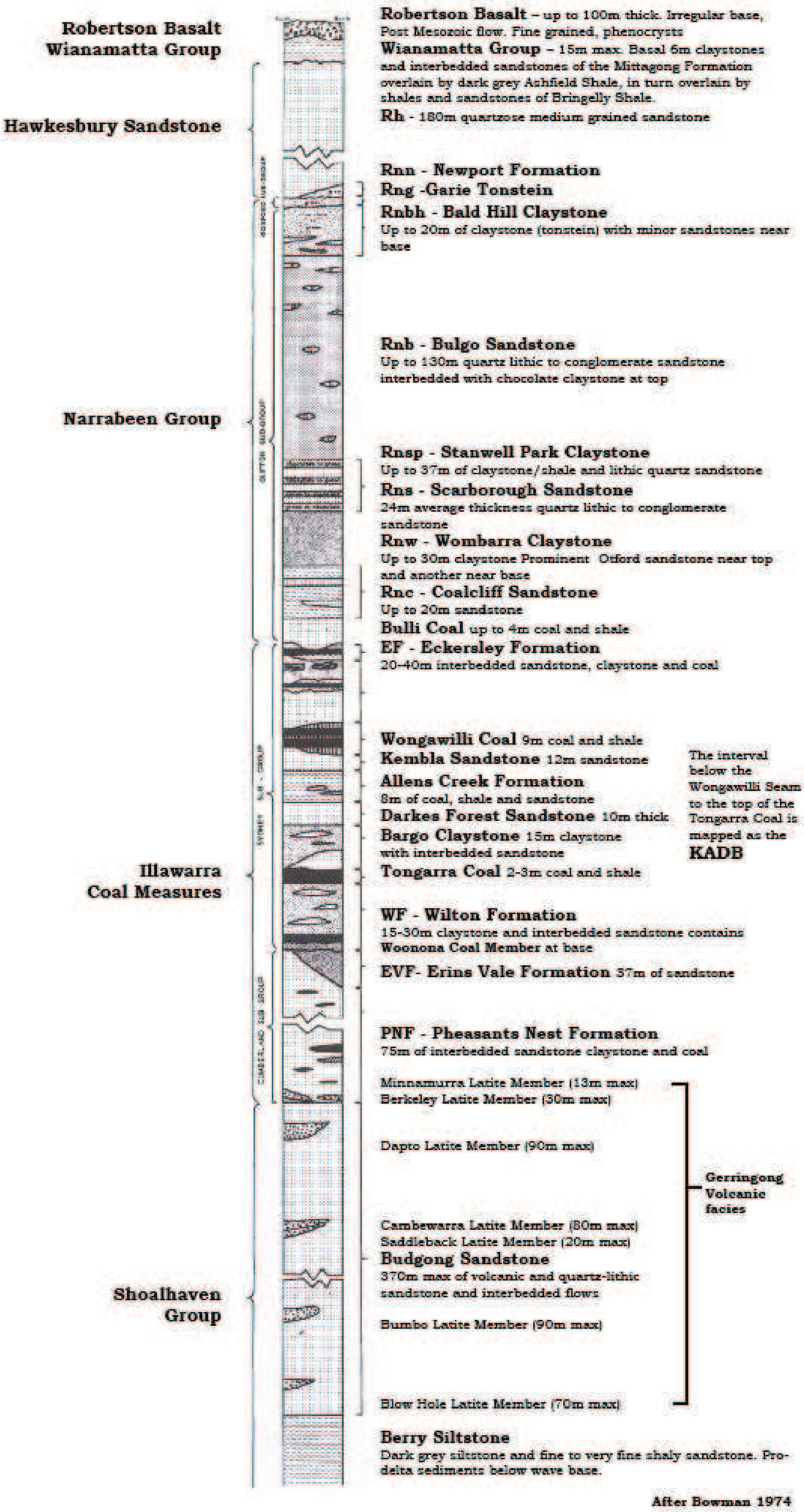

Plate 1 Generalised Stratigraphic Column of the Illawarra region.

5. Wollongong LGA Geotechnical History

5.1 Wollongong Regional Landslide Inventory

The Flentje Wollongong Regional Landslide Inventory, developed over the last fifteen years, comprises a relational MS Access and ESRI ArcGIS™ Geodatabase with over 70 fields of information for each landslide site (Chowdhury and Flentje 1998, Flentje and Chowdhury 2005). Field mapping and desktop compilation work have been carried out on field maps and using GIS software at 1:4000 or larger scales. The landslide inventory is presented for the entire study area on Figure 4 and for the typical area presented for each domain on Figures 7C to 11C.

Each landslide within the inventory is referenced by the key Site Reference Code (SRC). The Landslide Inventory for the Wollongong Council Area currently contains 553 landslide locations with significantly higher number of landslide events for these sites (ie including first time occurrences and multiple recurrences at some sites). The 553 landslides comprise the following slide categories according to the Cruden and Varnes 1996 classification:

- 454 Slides;
- 48 Flows;
- 40 Falls;
- 1 Avalanche;
- 3 Scour; and
- 7 Unknown.

Of the 454 Slide category landslides located within the 188 km^2 Wollongong landslide inventory, landslide volumes have been determined for 378 sites. The volumes range from <1m^3 up to 720,000m^3, with an average volume of 21,800m^3. A GIS-based analysis of the landslide inventory reveals that 2.37% of the 188 km^2 Study Area is affected by landslides.

As discussed previously, this inventory has been utilised to develop landslide susceptibility mapping and the University of Wollongong Landslide Research team are undertaking ongoing research in this area.

GHD Geotechnics has been involved in the emergency call-out, investigation, analysis, remedial design and ongoing monitoring of geotechnical hazards within the Wollongong LGA for approximately 30 years. This has included assessments undertaken for Wollongong City Council, the Roads and traffic Authority, Railcorp and some private land owners.

As demonstrated above, the landslide history of the Wollongong LGA is well documented and acknowledged by Council and other authorities active in the area.

5.2 Wollongong City Council Development Control Plan

As noted at Section 3, Wollongong City Council has an existing protocol for geotechnical assessment of developments within the Local Government Area. This is contained within the Development Control Plan at Part E – General Controls – Environmental Controls: Chapter E12: Geotechnical Assessment. Reference should be made to this section of the development control plan for details on how geotechnical assessment is currently required for proposed development.

The existence of this control plan highlights the current level of awareness and understanding of geotechnical stability issues within the Wollongong LGA. This report does not attempt to revisit these existing protocols but rather propose a framework whereby these existing controls can incorporate consideration of coastal effects including changes to these effects due to climate change.

6. Coastal Geotechnical Domains

The following section presents a description of the five geotechnical domains generated as a result of our Geotechnical Assessment. The purpose of the domains is to identify areas with common topography, geology and geotechnical hazards. This has enabled domain specific assessment of the impact of coastal effects. The domain boundaries for the entire Wollongong LGA are shown at Figure 1.

To assist in the presentation of the domain specific generic conditions, a typical area has been selected for each domain with presentation of the data sets considered in assessing the impact of coastal effects. The following typical areas have been selected for each domain:

- Figures 7A to 7D – Domain 1 "Narrabeen Group" – typical area Stanwell Park and Coalcliff.
- Figures 8A to 8D – Domain 2 "Faulted Transition from Illawarra to Narrabeen" – typical area Scarborough and Clifton.
- Figures 9A to 9D - Domain 3 "Illawarra Coal Measures" – typical area Austinmer and Thirroul.
- Figures 10A to 10D – Domain 4 "Coastal Plains" – typical area Bulli.
- Figures 11A to 11D – Domain 5 "Lake Illawarra" – typical area Lake heights and Berkeley.

We have also presented at Figures 12 to 15 four typical sections of the Illawarra escarpment to demonstrate the active geotechnical processes within each domain from the coast to the crest of the escarpment. We note that Figure 12B located at Coalcliff provides the greatest level of detail of active coastal processes and their interaction with geotechnical hazards as this is the area where these processes are most active along the Illawarra escarpment.

6.1 Domain 1 "Narrabeen Group"

This domain generally presents as prominent sea side cliffs with some localised embayments and beaches.

6.1.1 Location:

Extends from Garie Beach in the north, at the northern extent of the Wollongong Council Local Government Area, to the Clifton Fault south of Coalcliff Beach.

6.1.2 Topography:

The Illawarra Escarpment is generally within 1km of the coast line within this domain. This domain includes steep cliffs and slopes with significant vertical relief from the escarpment to the coast with the exception of some local embayment/beaches that have associated creeks and flatter topography.

6.1.3 Geology:

This area is characterised by the Narrabeen Group and its associated sandstone and claystone units. Of particular note is the presence of the Stanwell Park and Wombarra Claystone that are associated with numerous landslide areas within this domain.

Domain 1 has the lower Narrabeen Group sequences outcropping at sea level. South of the Royal National Park the Scarborough Sandstone forms prominent 15m to 20m high vertical coastal cliffs behind Stanwell Park beach. Whilst normally covered by the beach sand deposits, after storm wave erosion, the Wombarra Claystone can be seen near sea level along the beach. This sequence continues south to the north end of Coalcliff Beach although here the base of the Scarborough Sandstone is a few metres higher. The Scarborough Sandstone is a very strong to moderately strong quartz lithic to conglomeratic thickly bedded sandstone with sub-vertical typically widely spaced jointing. Hazards associated with this interval include occasional rockfalls.

The village of Coalcliff is located on notably gentler slopes that have developed on the relatively weaker Wombarra Claystone. With extremely low strength parameters, (residual friction angles nominally 15°) the Wombarra Claystone is recognized as being closely associated with the occurrence of both deep and shallow seated 'slide' type landsliding. Over 10% of the subcrop area of this sequence is affected by known 'slide' category landslides. Hence in Coalcliff, colluvium covered slopes extend downslope to the zone of wave influence, typically several meters above the coastal rock platforms if present, or the back of the beach sands.

The coastal rock platform on the south side of Coalcliff Beach is comprised of the Coalcliff Sandstone, the basal formation of the Narrabeen Group. Near the southern end of the Seacliff Bridge, a small normal fault known as the Jetty Fault (downthrown to the north several meters) represents the southern most extent of the Narrabeen Group at sea level, as south of this fault the Bulli Seam occurs at sea level, with the Coalcliff Sandstone standing in vertical cliffs several metres above sea level. The coastal rock platform below the southern end of the Seacliff Bridge is comprised of the Upper Eckersley Formation. At Clifton, the lower coastal cliff and sea level geology is changed substantially by vertical normal faulting along the Clifton Fault. This fault is downthrown to the north, at sea level by approximately 45m and hence at this location we have defined a boundary between Domain 1 and Domain 2.

6.1.4 Prominent Geotechnical Features:

- The Illawarra Escarpment within this zone is oversteepened, and the lower slopes have been truncated by coastal erosion during Quaternary period high sea level stands (such as at present).

6.1.5 Generic Coastal Related Geotechnical Hazard Types:

- Rock falls and/or cliff regression associated with jointed rock mass at cliffs and shoreline rock platforms.
- Landslide features underlain by low strength claystones (eg Wombarra Claystone) affected by toe erosion.
- Debris flows associated with landslides higher up the escarpment and or direct result of coastal erosion acting on the basal slopes and cliffs.

6.1.6 Excluded Areas:

- We understand that planning within the Royal National Park is not governed by Wollongong Council. Thus, we have excluded the area north of Undola Beach (ie east of Otford) from this geotechnical domain.
- We also note that the geomorphological and coastal processes of embayment/estuarine/ alluvial areas is not solely "geotechnical" in nature and is understood to be part of Cardno's coastal assessment (for example Stanwell Park beach).
- Man made structures have been excluded given the need to assess structure specific effects. All existing man made structures in vicinity of the coast would require specific assessments and ongoing management.

6.2 Domain 2 "Faulted Transition from Illawarra to Narrabeen"

Generally includes Narrabeen Group rock at the coast, though does include the upper units from the Illawarra Coal Measures at sea level.

6.2.1 Location:

Commences at Clifton Fault south of Coalcliff Beach extending south to the North Scarborough Fault at the northern end of Scarborough beach.

6.2.2 Topography:

The Illawarra Escarpment is generally within 1.5km of the coast line within this domain. This domain includes steep cliffs and slopes with significant vertical relief from the escarpment to the coast with the exception of some local embayment/beaches that have associated creeks and flatter topography. This domain is characterised by the presence of rock shelves at sea level.

6.2.3 Geology:

This area is characterised by the Narrabeen Group, and its associated sandstone and claystone units, being underlain by the upper most Illawarra Coal Measures at sea level. Thus, there is a prominence of rock shelves at sea level with upslope areas commensurate with Domain 1. As per Domain 1, the presence of the Wombarra Claystone is prominent within this domain.

South of the Clifton Fault, the lower coastal cliffs are comprised of the Eckersley Formation. This domain has essentially no urban development at the coast, except at the very southern end, above the north end of Wombarra Beach. This Coastal Domain comprises the Eckersley formation at sea level which rises in very steep cliffs (slopes of between 30° and 50°) up to approximately 45m – 60m whereby the ~2m thick Bulli Seam is overlain by the 10m to 15m thick Coalcliff Sandstone. There is some coastal sand and beach development along this coastal Domain, but generally the coastal zone is rocky with near vertical cliffs immediately adjoining the rocky shoreline. The Eckersley Formation comprises repeated cycles of sandstone fining up into siltstone and coal and this sequence includes the Balgownie Coal member and includes the Bulli Coal at the top.

The southern end of this domain includes the slopes that contain the Wilson Street landslide and the Scarborough Fault zone (note the location of this fault is not well defined). In the gully to the north of the Scarborough Sports Field, the Wongawilli Coal Seam is exposed at up to 15m above sea level. The Scarborough Fault is a normal fault, which is downthrown to the north approximately 35m at sea level. This marks the southern extent of this Domain.

Generally the Coastal Zone in this Domain extends to upslope of the Coalcliff Sandstone cliffline, with a variable setback from the cliff edge. The cliff top is included as any loss of support below, due to coastal erosion and or landsliding could involve failure of the cliff edge and a portion of the upslope terrace area. Generally this is in the range of 10m to 20m although based on local knowledge of the cliff setting this has been relaxed in a few locations to less than 10m. These steep slopes exhibit all categories of landslide hazard including rockfalls, debris flows and slides.

6.2.4 Prominent Geotechnical Features:

- Oversteepened escarpment and truncated lower slopes as for Domain 1.
- Extensive landslides and debris flows above sea cliffs with underlying rock shelves.
- Moderate to steep slopes with prominent groundwater associated with the overlying escarpment and associated landslide instability.

6.2.5 Generic Coastal Related Geotechnical Hazard Types:

- Rock falls and/or cliff regression associated with jointed rock mass at cliffs and shoreline rock platforms.
- Landslide features underlain by low strength claystones (eg Wombarra Claystone) affected by toe erosion.
- Debris flows associated with landslides higher up the escarpment and the steep slopes immediately adjacent to the costline.

6.2.6 Excluded Areas:

- Geomorphological and coastal processes of embayment/estuarine/alluvial areas are understood to be part of Cardno's coastal assessment (for example Coalcliff Beach).
- Man made structures have been excluded given the need to assess structure specific effects. All existing man made structures in vicinity of the coast would require ongoing management. In particular we have excluded the Ocean outfall of the Scarborough Drainage Tunnel that would require a site specific assessment.

6.3 Domain 3 "Illawarra Coal Measures"

Within the defined coastal zone includes the Illawarra Coal Measures.

6.3.1 Location:

Commences at North Scarborough Fault at the northern end of Scarborough beach and extends south to Thirroul ending at the northern end of Thirroul Beach.

6.3.2 Topography:

The Illawarra Escarpment is generally beyond 1.5km of the coast line within this domain. This domain includes localised coastal cliffs with moderate slopes. It includes more regular local embayment/beaches that have associated creeks and flatter topography particularly south o Austinmer.

6.3.3 Geology:

This area is characterised by the Illawarra Coal Measures and includes more prominent beaches than Domains 1 and 2 in combination with similar coastal cliffs albeit formed in varying geological units. The Austinmer geological section presented at Figures 13A and 13B presents the interaction of the geomorphological processes within this domain.

The geological unit exposed at sea level is typically the Wilton Formation with the overlying Kembla Sandstone to Bargo claystone exposed at the cliffs and slopes along the coast in Domain 3.

The majority of coastal geotechnical hazards within Domain 3 are associated with steep coastal cliffs. The majority of the landslide inventory sites within this domain are located upslope of the coastal zone (ie west of Lawrence Hargrave drive) within the overlying Eckersley formation and Wombarra Claystone.

6.3.4 Prominent Geotechnical Features:

- Oversteepened escarpment and truncated lower slopes as for Domain 1 and 2. The southern extent of this domian is defined by the northern extent of the coastal plain.
- Moderate slopes with prominent groundwater associated with the overlying escarpment and associated landslide instability.
- Localised coastal cliffs (<20m).
- Localised embayment/estuarine/alluvial zones becoming more prominent to the south of domain.

6.3.5 Generic Coastal Related Geotechnical Hazard Types:

- Rock falls and/or cliff regression associated with jointed rock mass at cliffs and shoreline rock platforms.
- Landslide features underlain affected by toe erosion.
- Debris flows associated with landslides higher up the escarpment and the steep slopes immediately adjacent to the costline.

6.3.6 Excluded Areas:

- Geomorphological and coastal processes of embayment/estuarine/alluvial areas are understood to be part of Cardno's coastal assessment (for example beach areas at Scarborough, Coledale, Austinmer and both north and south Thirroul).

- Man made structures have been excluded given the need to assess structure specific effects. All existing man made structures in vicinity of the coast would require ongoing management.

6.4 Domain 4 "Coastal Plains"

Prominence of coastal plains and associated estuarine, alluvial and dunal environments. Localised headlands and sea cliffs associated with the Illawarra Coal Measures.

6.4.1 Location:

Commences at the northern end of Thirroul Beach, extending south to the entrance to Lake Illawarra.

6.4.2 Topography:

The Illawarra Escarpment is generally within 3km to 15km of the coast line within this domain. This domain includes coastal plains with localised moderate slopes and headlands generally <25m, although the unique Hill 60 region reaches up to 50m.

6.4.3 Geology:

This localised headlands and cliffs are characterised by the Illawarra Coal Measures. Coastal plains include estuarine, alluvial and/or dunal environments. The Wollongong City headlands, coastal cliffs and those at Hill 60, Port Kembla are formed from the Bulgo Sandstone. The Dapto Latite member of the Gerringong Volcanic facies also occurs within Port Kembla.

6.4.4 Prominent Geotechnical Features:

- Generally flat slopes with localised headlands and moderate slopes with some localised landslide instability.
- Localised coastal cliffs (generally less than <10m, but the cliffs in the vicinity of Wollongong Harbour and the North Beach reach 20m and the slopes and cliffs at Hill 60 and the cliffs to the south reach up to 45m in height).
- Prominent embayment/estuarine/alluvial zones.

6.4.5 Generic Coastal Related Geotechnical Hazard Types:

- Rock falls and/or cliff regression associated with jointed rock mass at cliffs and shoreline rock platforms.
- Localised landslide features underlain affected by toe erosion.

6.4.6 Excluded Areas:

- The majority of the Domain 4 Coastal Plains is subject to coastal processes rather than distinctly geotechnical impacts. Thus, with the exception of headlands, this domain is predominately subject to assessment of coastal processes by Cardno. This includes Port Kembla.

- Man made structures have been excluded given the need to assess structure specific effects. All existing man made structures in vicinity of the coast would require ongoing management.

6.5 Domain 5 “Lake Illawarra”

This is the southern extent of the Wollongong Council local government area including consideration of the slopes that are adjacent to Lake Illawarra.

6.5.1 Location:

Commences at the entrance to Lake Illawarra and follows the lake frontage to the southern extent of the Wollongong Council LGA at Haywards Bay.

6.5.2 Topography:

The Illawarra Escarpment is generally in excess of 12km of the coast line within this domain. The slopes in vicinity of the lake vary from flat to moderate with localised steep areas.

6.5.3 Geology:

This area is underlain by the Shoalhaven Group with the intrusive Broughton formation including the Dapto Latite member and prominent alluvial and estuarine deposits associated with the various creeks that enter the lake including Budjong Creek, Hooka Creek, Mullet Creek, Yallah Creek, Duck Creek and Macquarie Rivulet. There has also been some land reclamation on the western banks of Lake Illawarra.

6.5.4 Prominent Geotechnical Features:

- Requires Further Data (If available) - This area has not been as well studied as the northern areas of Wollongong. There are currently no landslides within the landslide inventory retained by Flentje along the lake shores. Thus the assessment of this domain should be considered to be of a lower confidence than for the northern domains 1 to 4.

6.5.5 Generic Coastal Related Geotechnical Hazard Types:

- The lake region has differing coastal effects than for the northern domains. Given the lake inlet will control ocean waves, the impact on the fringe of the lake will be predominately from inundation. Thus, the hazards in this area will be similar to that in the northern region (albiet differing geology) though with lesser coastal effects.
- Given the existing landslide inventory does not extend to the Lake Illawarra domain, the hazards are not as well defined.
- There was limited data provided regarding the application of the Wollongong City Council development Control Plan in relation to geotechnical matters within this domain. Thus, the baseline understanding of geotechnical hazards is limited but should consider the Wollongong City Council Development Control Plan for Geotechnical Assessment, as appropriate.

6.5.6 Excluded Areas:

- The areas subject to coastal processes (alluvial/estuarine), rather than distinctly geotechnical impacts are assumed to be assessed by Cardno. Thus, the geotechnical areas to be considered are typically the side slopes abutting the lake.
- Man made structures have been excluded given the need to assess structure specific effects. All existing man made structures in vicinity of the coast would require ongoing management.

7. Coastal Influenced Geotechnical Hazard Zone

This Geotechnical Assessment of Coastal Effects has culminated in the establishment of a Coastal Influenced Geotechnical Hazard Zone (the Zone) defined as follows.

> ***The Coastal Influenced Geotechnical Hazard Zone includes areas where coastal processes (including climate change) could directly influence geotechnical hazards for the defined study time period to 2100. Geotechnical assessments of proposed or future development in accordance with Wollongong City Council's Development Control Plan requirements should include specific assessment of coastal processes if located within this Zone.***

This Coastal Influenced Geotechnical Hazard Zone has been developed considering potential for future coastal effects, as determined by Cardno Lawson Treloar, on the existing landform using a judgemental approach. This judgemental approach has incorporated:

- Coastal geology;
- Topography;
- Drainage features;
- Existing historical geotechnical hazard data;
- The knowledge of the authors incorporating Council's geotechnical representative's historical knowledge;
- A nominal minimum 10m "buffer zone".

It is expected that site specific implications of the identified Coastal Influenced Geotechnical Hazard Zone will be considered within the existing Wollongong City Council planning requirements.

The Coastal Influenced Geotechnical Hazard Zone is presented on Figures 6A to 6G accompanying this report as a red line (typically) paralleling the coast. Areas on the coast side of the line are deemed to be within the defined Zone. The red line defining the Zone is discontinuous at areas where coastal geomorphological effects will govern as this will be defined by Cardno's study.

7.1 Assumptions and Considerations

In developing this Coastal Influenced Geotechnical Hazard Zone, we note the following assumptions and considerations:

- It is acknowledged that the Illawarra escarpment has developed as a result of coastal processes and associated geomorphological and climatic conditions. This has occurred over millions of years and is continuing to occur.

- This study is constrained to a 100 year forecast period. Thus the influence of coastal processes has considered geotechnical hazards that are currently active or could reasonably be assumed to become active in this period.
- In attempting to define this zone, we acknowledge that given the scale of the Illawarra escarpment, this zone could be argued to extend significantly further inland. The line presented is based on the combined knowledge of the authors of this report including interrogation of existing data. It has been developed, and is presented, for consideration of future Council planning use in accordance with the project brief.
- Many areas located within the Zone have previously had coastal effects considered in assessing land use (eg RTA and selected Council sites). Thus, this is not necessarily a new requirement, but rather confirms that coastal effects may influence development in these areas.
- It should be noted that sites located within the Zone have not been specifically determined to contain geotechnical hazards. Rather, future assessment of planning and development in this zone (and associated geotechnical assessments) should consider potential impacts of coastal processes. Subject to Council's policy in this regard this may require consideration of climate change and associated sea level change.
- As rainfall influence is not only applicable solely to the coastal zone, it requires consideration for all geotechnical development across the Council area. That is, rainfall and its frequency is relevant to geotechnical hazards across the Illawarra Escarpment and is thus not a coastal specific determining influence for the purpose of this study. This does not down play its importance for assessment of planning and required geotechnical assessments.

- This zone has been developed for coastal slopes and cliffs and should be considered in conjunction with Cardno's assessment of coastal plains and beaches. Areas of interaction between the slopes/cliffs and plains/beaches that may require consideration of both impacts include:
  - Headland contacts with beaches and dune areas
  - Beaches at toe of coastal cliffs
  - Estuaries junction with coastal slopes (note this study excludes slopes surrounding estuarine areas)
  - Rear dune areas
  - Lake Illawarra

8. Conclusion

- GHD Geotechnics have undertaken an assessment of geotechnical hazards within the Wollongong City Council Local Government Area. This has included review of existing data most significantly including the University of Wollongong Landslide Inventory and Susceptibility Mapping.
- Cardno have provided defined parameters for the study to quantify the coastal effects including consideration of climate change for prediction at times of 2050 and 2100.
- The Geotechnical Assessment of these coastal processes has culminated in the establishment of a Coastal Influenced Geotechnical Hazard Zone defined as including areas where coastal processes (including climate change) will directly influence geotechnical hazards for the defined study time period to 2100.
- Geotechnical assessments of proposed or future development in accordance with Wollongong City Council's Development Control Plan requirements should include specific assessment of coastal processes if located within this defined Zone.

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The University Of Wollongong, New South Wales, Australia; Department Of Civil, Mining And Environmental Engineering; 1998

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Standard Sheets

General Notes

GENERAL NOTES

The report contains the results of a geotechnical investigation conducted for a specific purpose and client. The results should not be used by other parties, or for other purposes, as they may contain neither adequate nor appropriate information. In particular, the investigation does not cover contamination issues unless specifically required to do so by the client.

TEST HOLE LOGGING

The information on the test hole logs (boreholes, test pits, exposures etc.) is based on a visual and tactile assessment, except at the discrete locations where test information is available (field and/or laboratory results). The test hole logs include both factual data and inferred information. Moreover, the location of test holes should be considered approximate, unless noted otherwise (refer report). Reference should also be made to the relevant standard sheets for the explanation of logging procedures (Soil and Rock Descriptions, Core Log Sheet Notes etc.).

GROUNDWATER

Unless otherwise indicated, the water levels presented on the test hole logs are the levels of free water or seepage in the test hole recorded at the given time of measuring. The actual groundwater level may differ from this recorded level depending on material permeabilities (i.e. depending on response time of the measuring instrument). Further, variations of this level could occur with time due to such effects as seasonal, environmental and tidal fluctuations or construction activities. Confirmation of groundwater levels, phreatic surfaces or piezometric pressures can only be made by appropriate instrumentation techniques and monitoring programmes.

INTERPRETATION OF RESULTS

The discussion or recommendations contained within this report normally are based on a site evaluation from discrete test hole data, often with only approximate locations (e.g. GPS). Generalised, idealised or inferred subsurface conditions (including any geotechnical cross-sections) have been assumed or prepared by interpolation and/or extrapolation of these data. As such these conditions are an interpretation and must be considered as a guide only.

CHANGE IN CONDITIONS

Local variations or anomalies in the generalised ground conditions do occur in the natural environment, particularly between discrete test hole locations. Additionally, certain design or construction procedures may have been assumed in assessing the soil-structure interaction behaviour of the site. Furthermore, conditions may change at the site from those encountered at the time of the geotechnical investigation through construction activities and constantly changing natural forces.

Any change in design, in construction methods, or in ground conditions as noted during construction, from those assumed or reported should be referred to this firm for appropriate assessment and comment.

GEOTECHNICAL VERIFICATION

Verification of the geotechnical assumptions and/or model is an integral part of the design process - investigation, construction verification, and performance monitoring. Variability is a feature of the natural environment and, in many instances, verification of soil or rock quality, or foundation levels, is required. There may be a requirement to extend foundation depths, to modify a foundation system and/or to conduct monitoring as a result of this natural variability. Allowance for verification by appropriate geotechnical personnel must be recognised and programmed for construction.

FOUNDATIONS

Where referred to in the report, the soil or rock quality, or the recommended depth of any foundation (piles, caissons, footings etc.) is an engineering estimate. The estimate is influenced, and perhaps limited, by the fieldwork method and testing carried out in connection with the site investigation, and other pertinent information as has been made available. The material quality and/or foundation depth remains, however, an estimate and therefore liable to variation. Foundation drawings, designs and specifications should provide for variations in the final depth, depending upon the ground conditions at each point of support, and allow for geotechnical verification.

CLIMATE CHANGE

GHD Geotechnics acknowledges the occurrence of ongoing climate change. Cognisance is given to climate change issues as may be applicable to specific geotechnical investigations and assessments.

REPRODUCTION OF REPORTS

Where it is desired to reproduce the information contained in our geotechnical report, or other technical information, for the inclusion in contract documents or engineering specification of the subject development, such reproductions must include at least all of the relevant test hole and test data, together with the appropriate Standard Description sheets and remarks made in the written report of a factual or descriptive nature.

Ref: DS5.5.1 Issue 1.6 Date: 28/07/2009

Figures

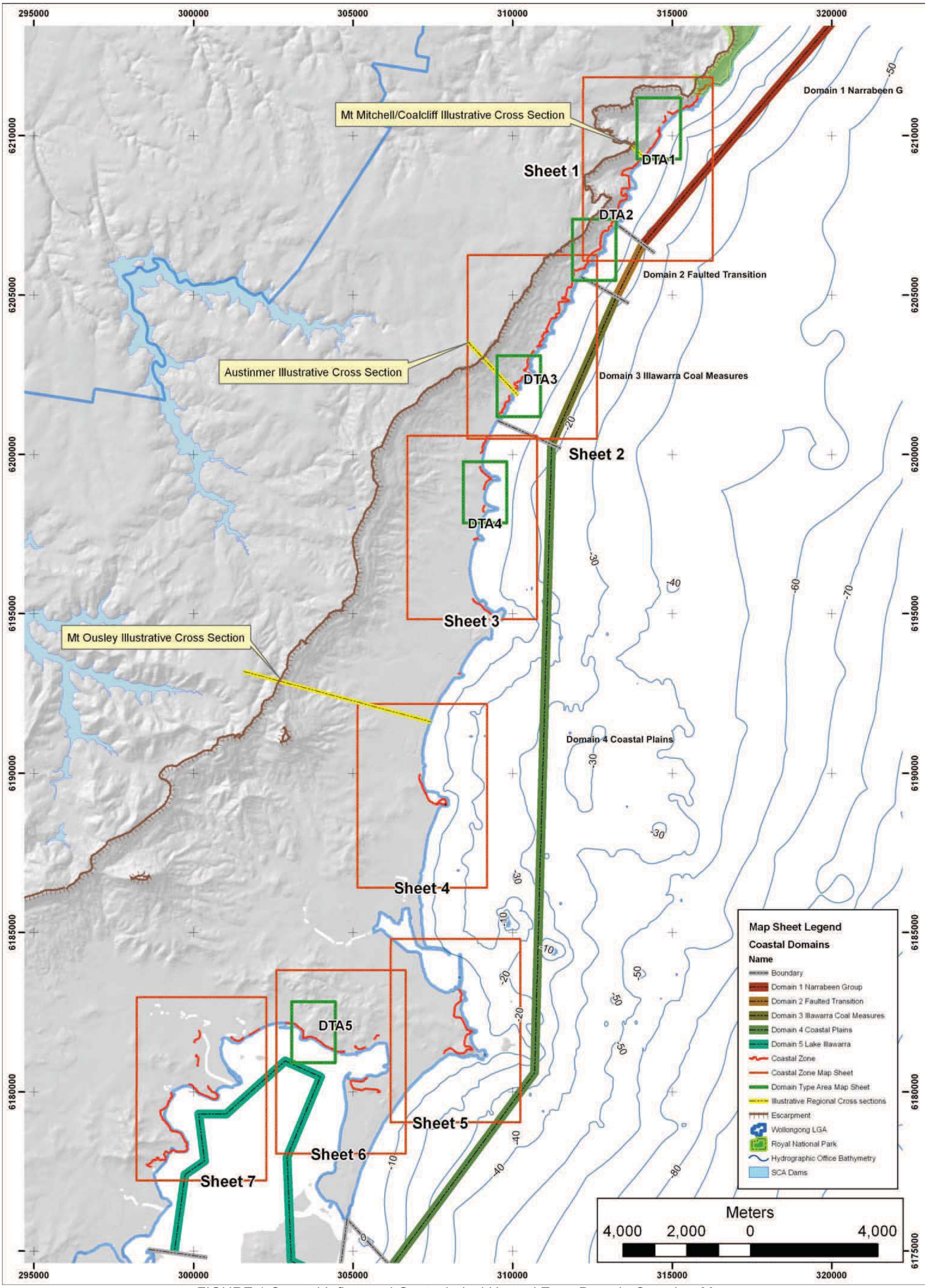

FIGURE 1 Coastal Influenced Geotechnical Hazard Zone Domain Overview Map

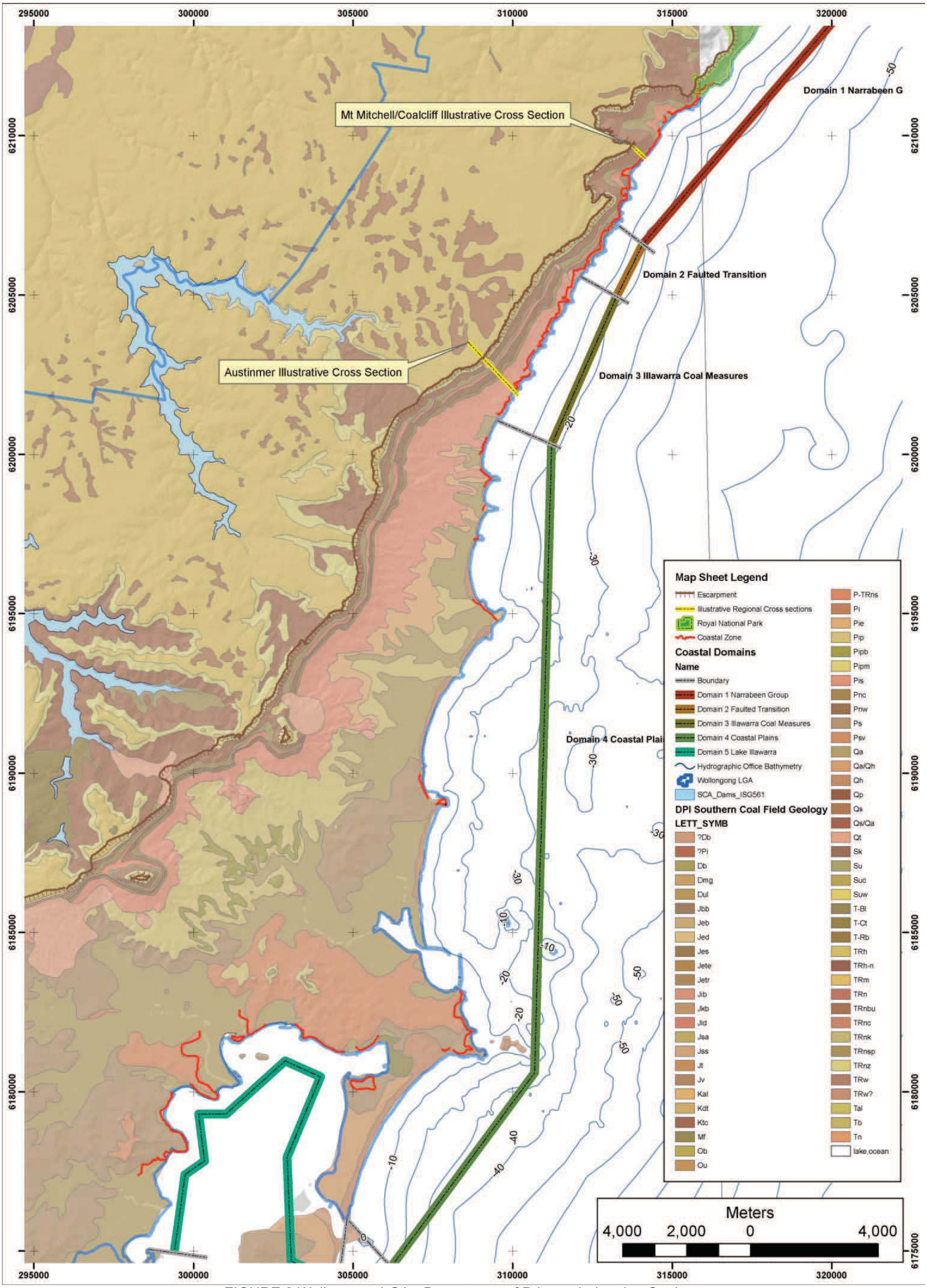

FIGURE 2 Wollongong LGA - Department of Primary Industries Geology

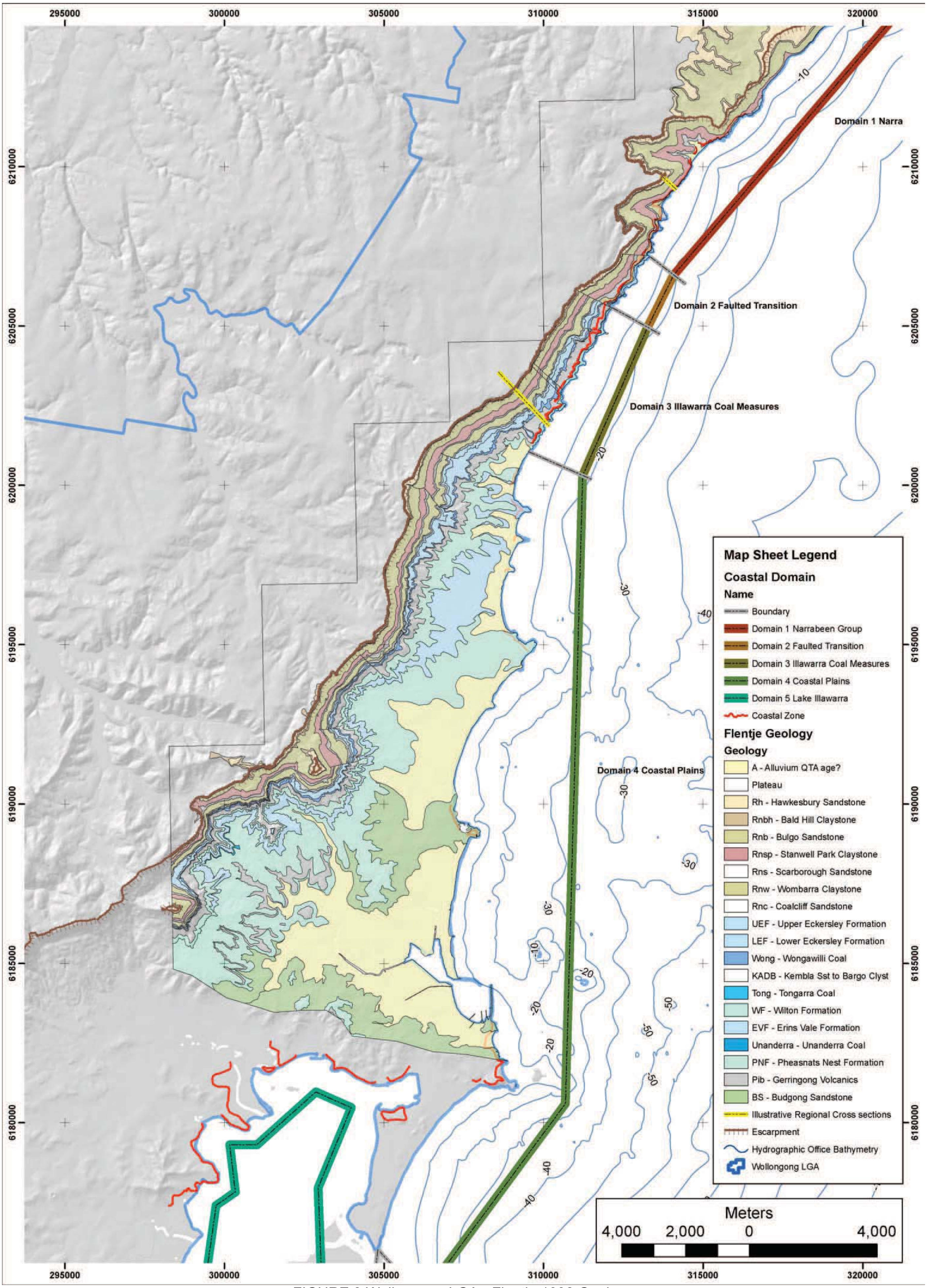

FIGURE 3 Wollongong LGA - Flentje 1998 Geology

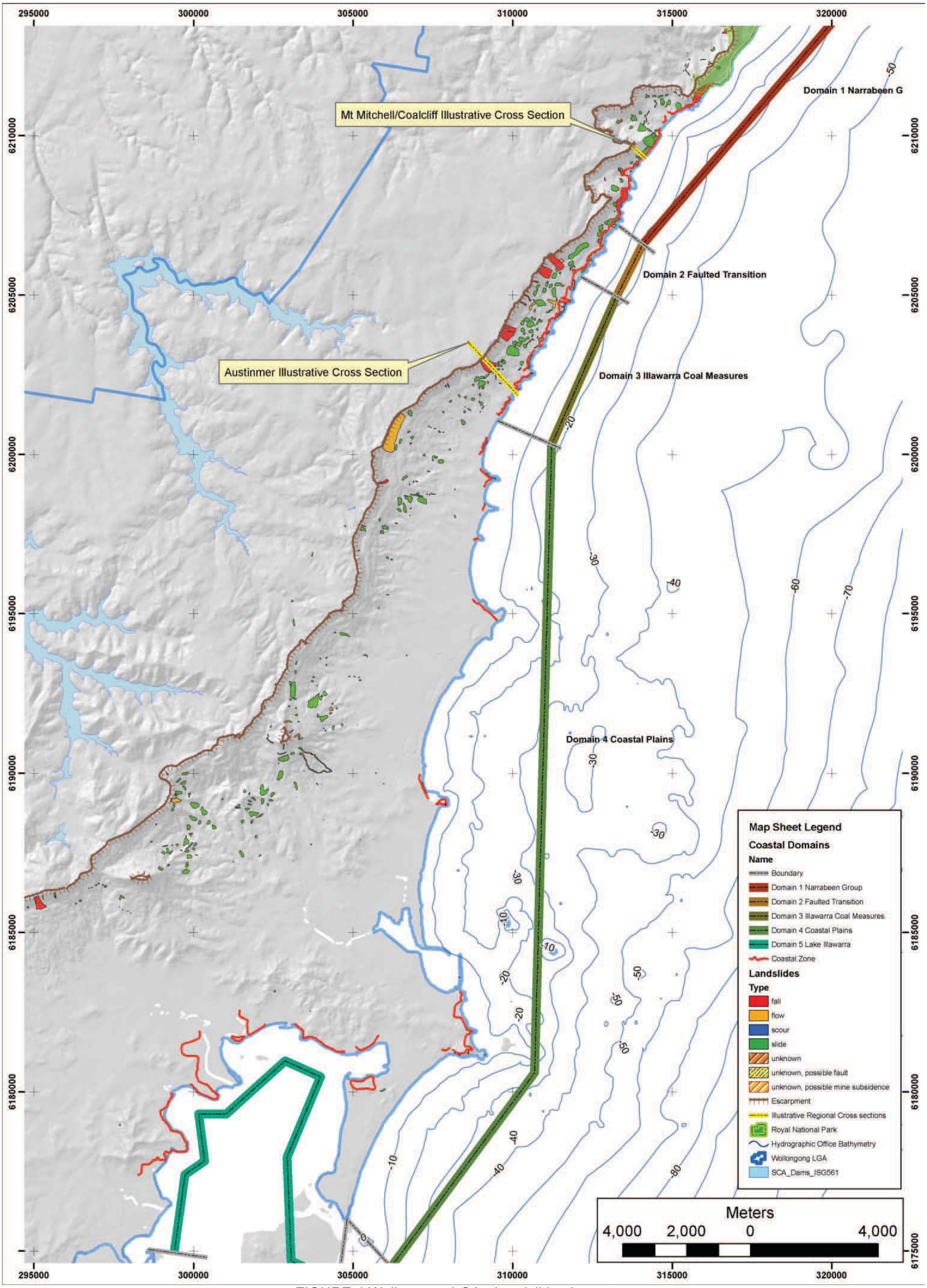

FIGURE 4 Wollongong LGA - Landslides Inventory

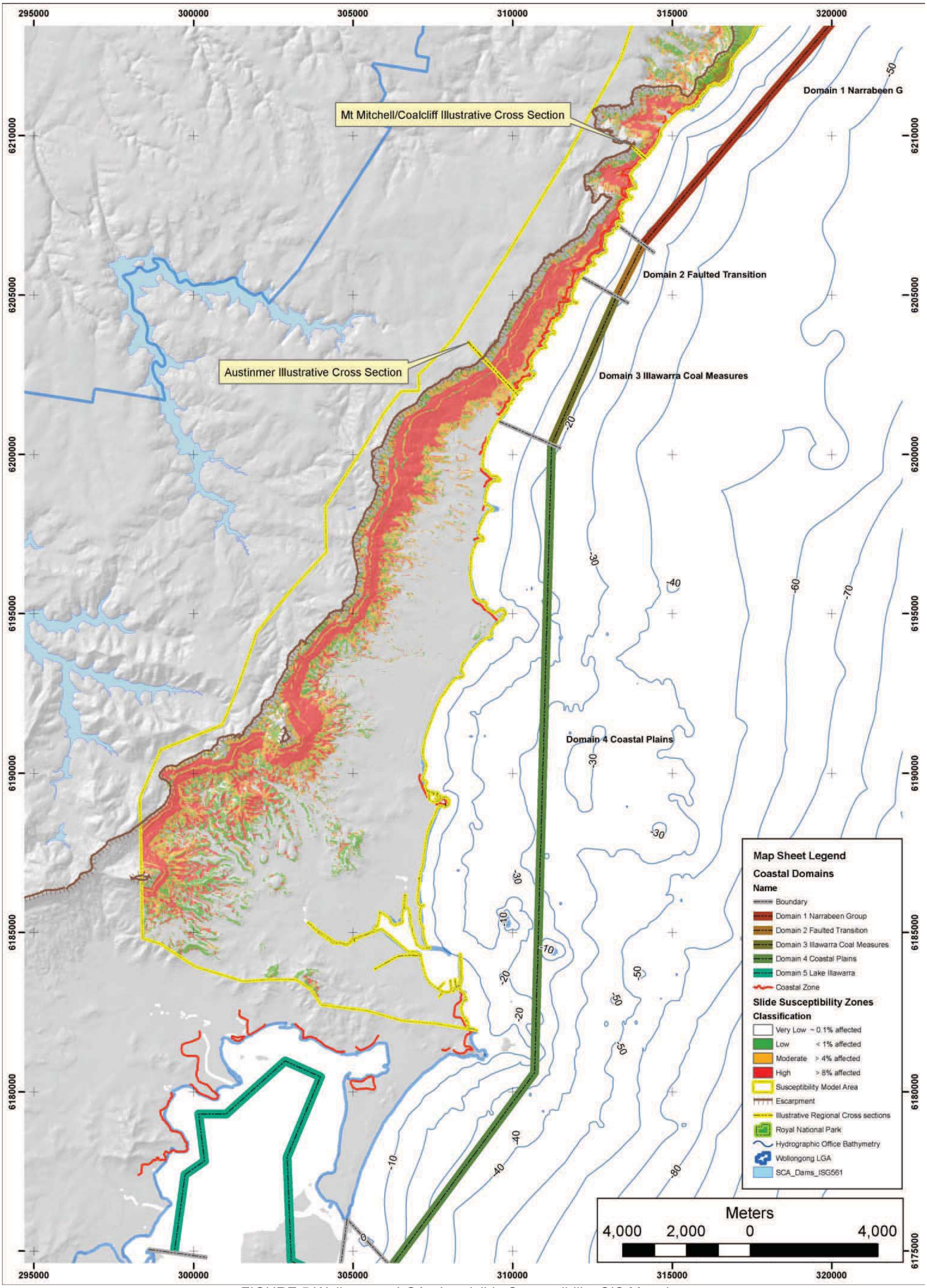

FIGURE 5 Wollongong LGA - Landslide Susceptibility GIS Mapping

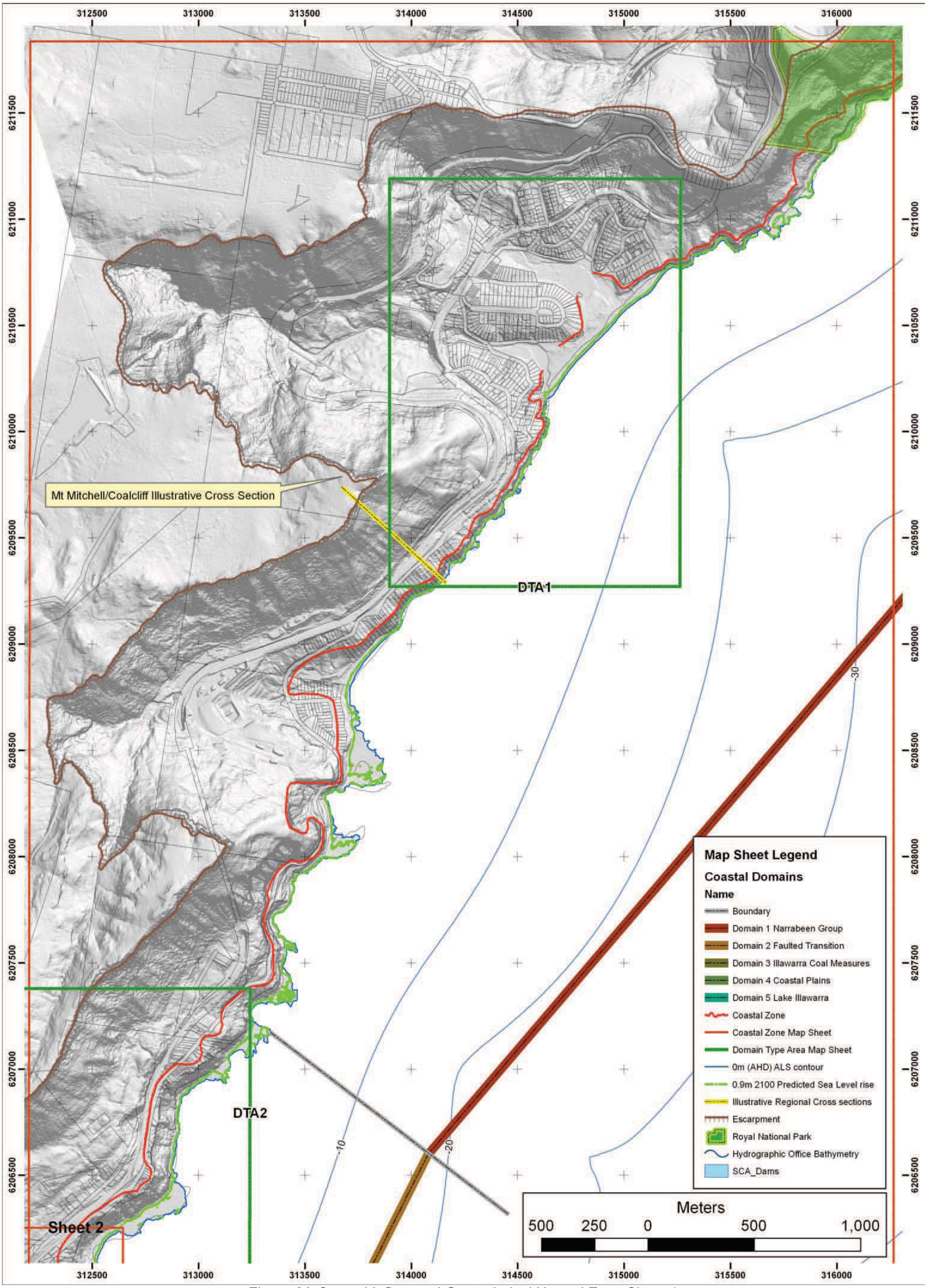

Figure 6A Coastal Influenced Geotechnical Hazard Zone Sheet 1

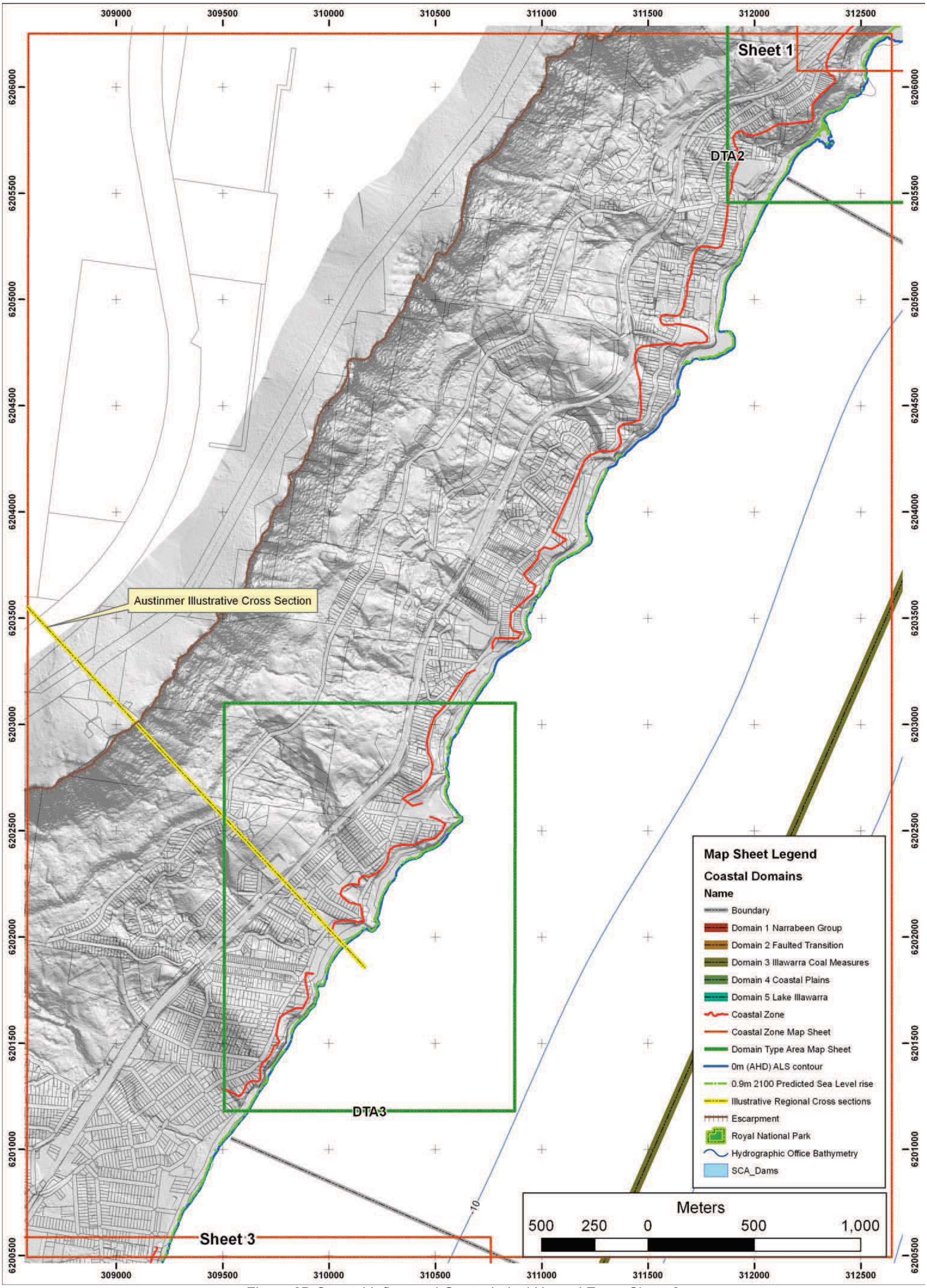

Figure 6B Coastal Influenced Geotechnical Hazard Zone Sheet 2

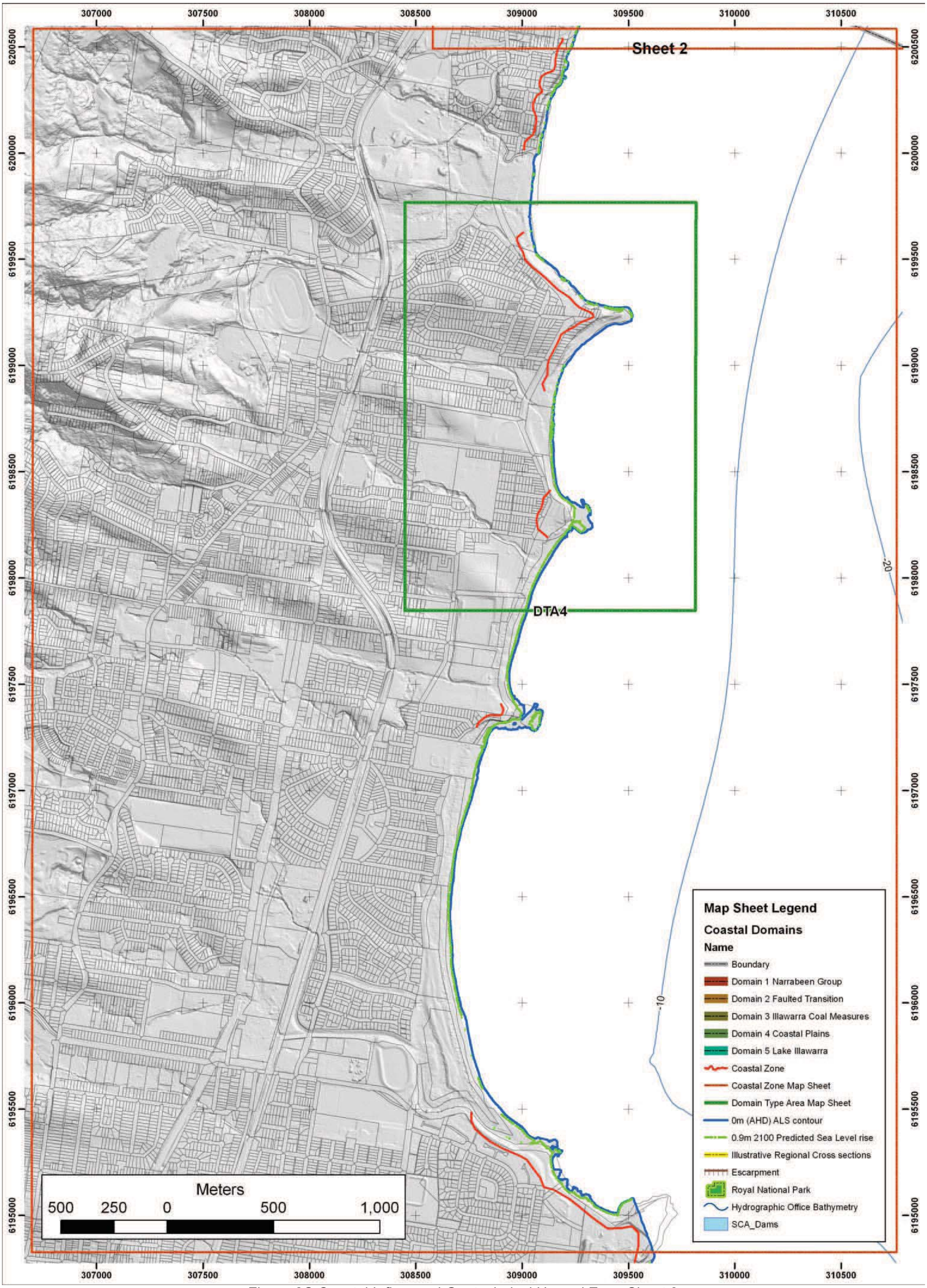

Figure 6C Coastal Influenced Geotechnical Hazard Zone Sheet 3

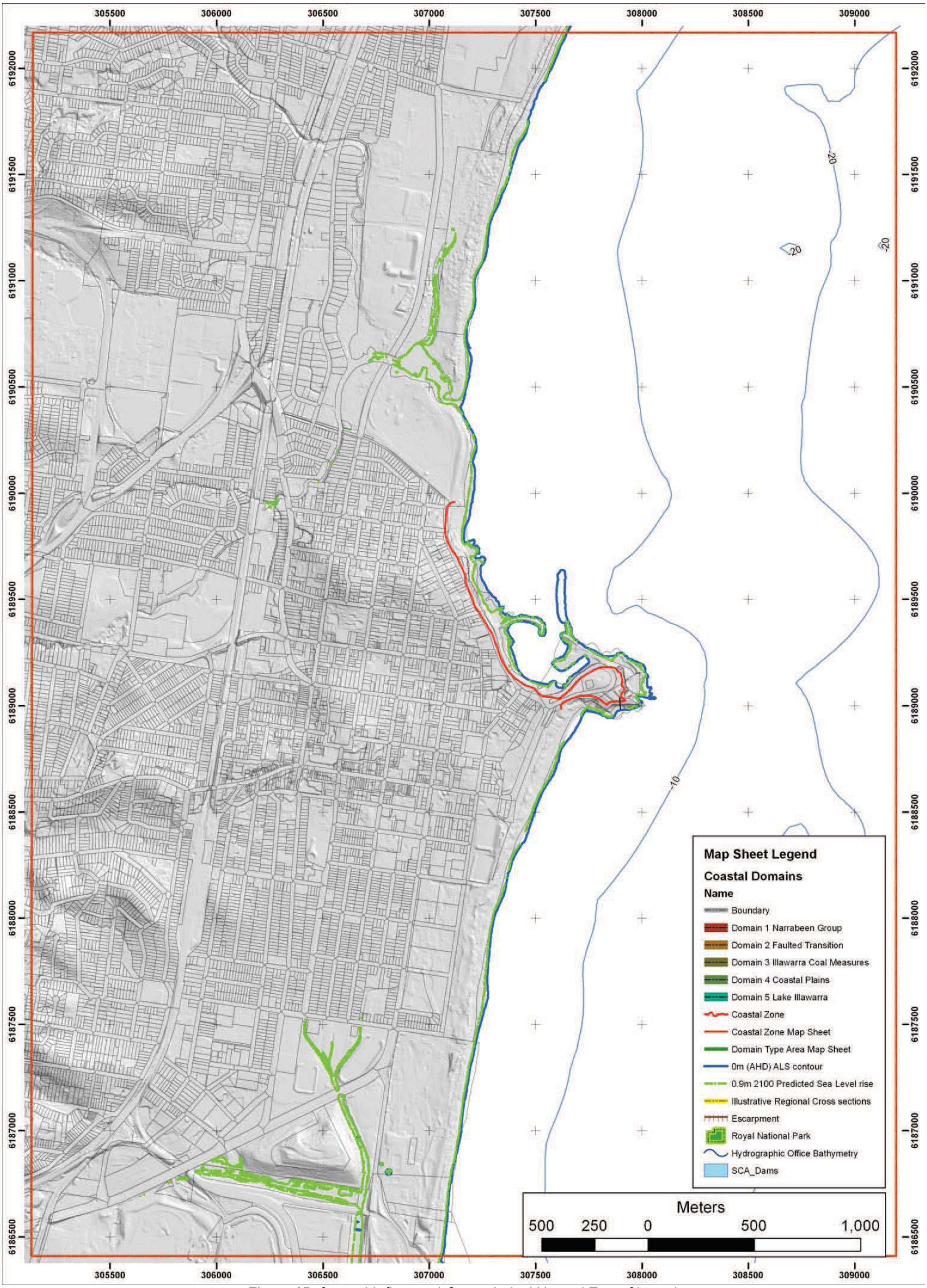

Figure 6D Coastal Influenced Geotechnical Hazard Zone Sheet 4

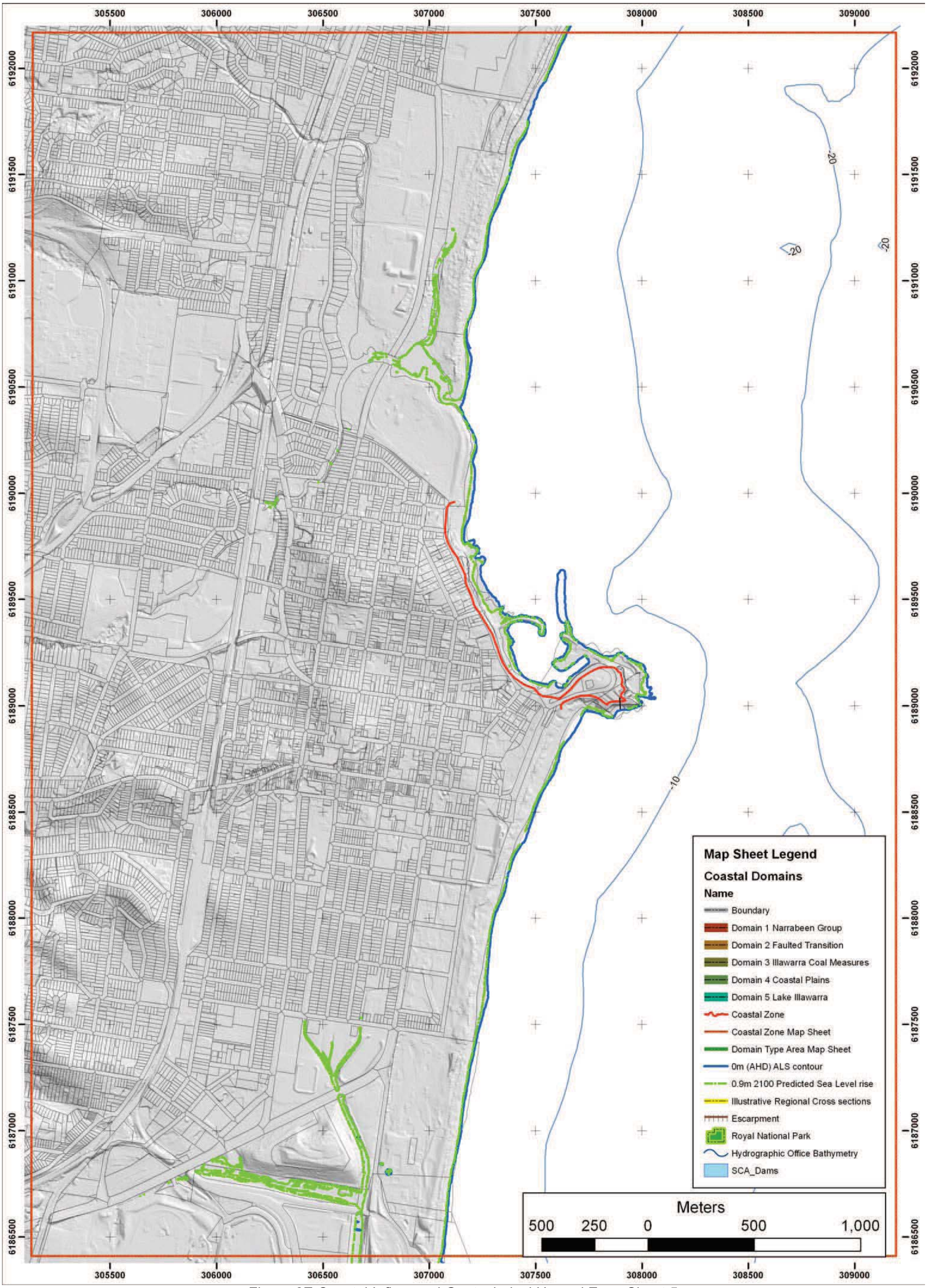

Figure 6E Coastal Influenced Geotechnical Hazard Zone Sheet 5

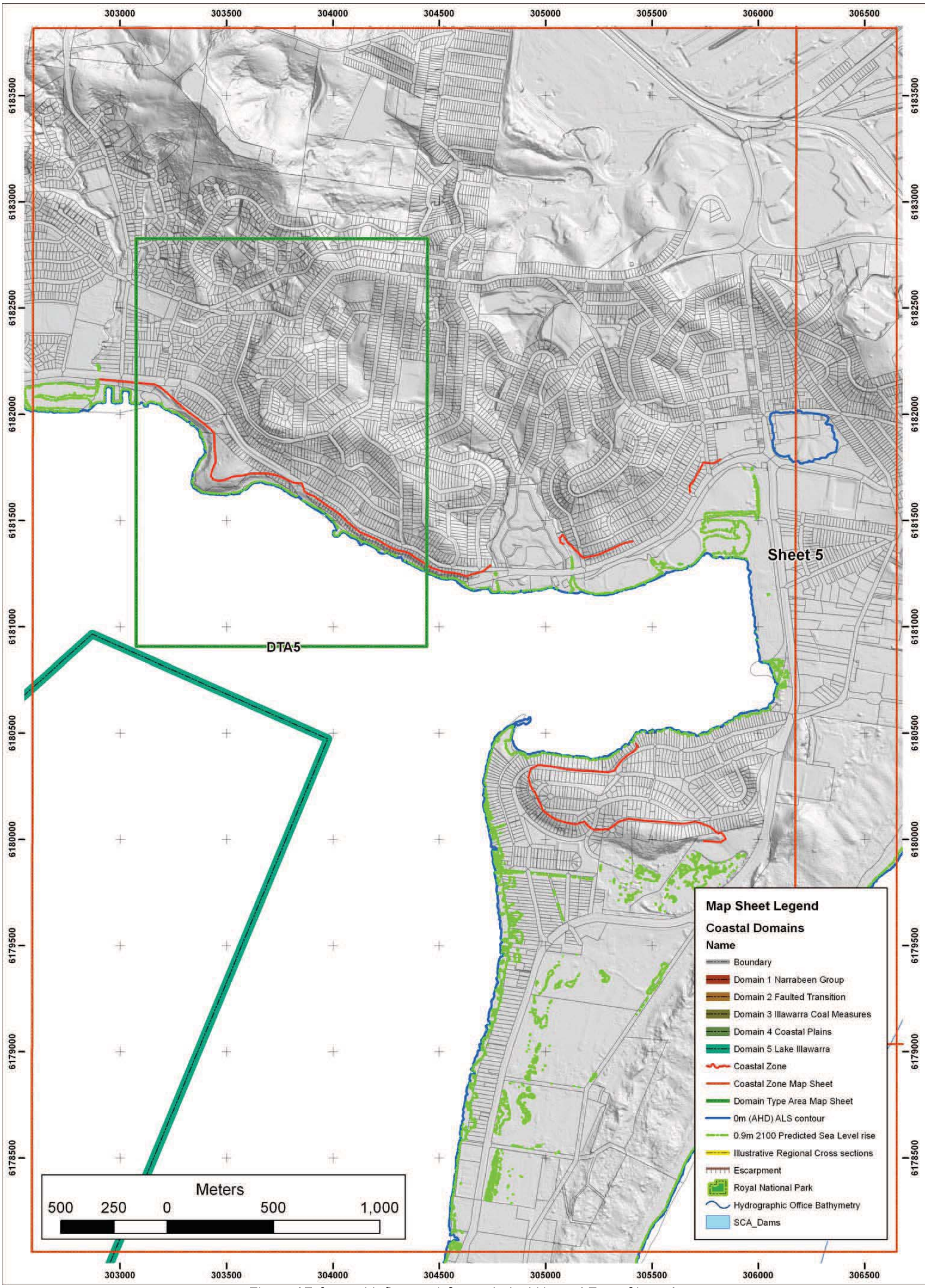

Figure 6F Coastal Influenced Geotechnical Hazard Zone Sheet 6

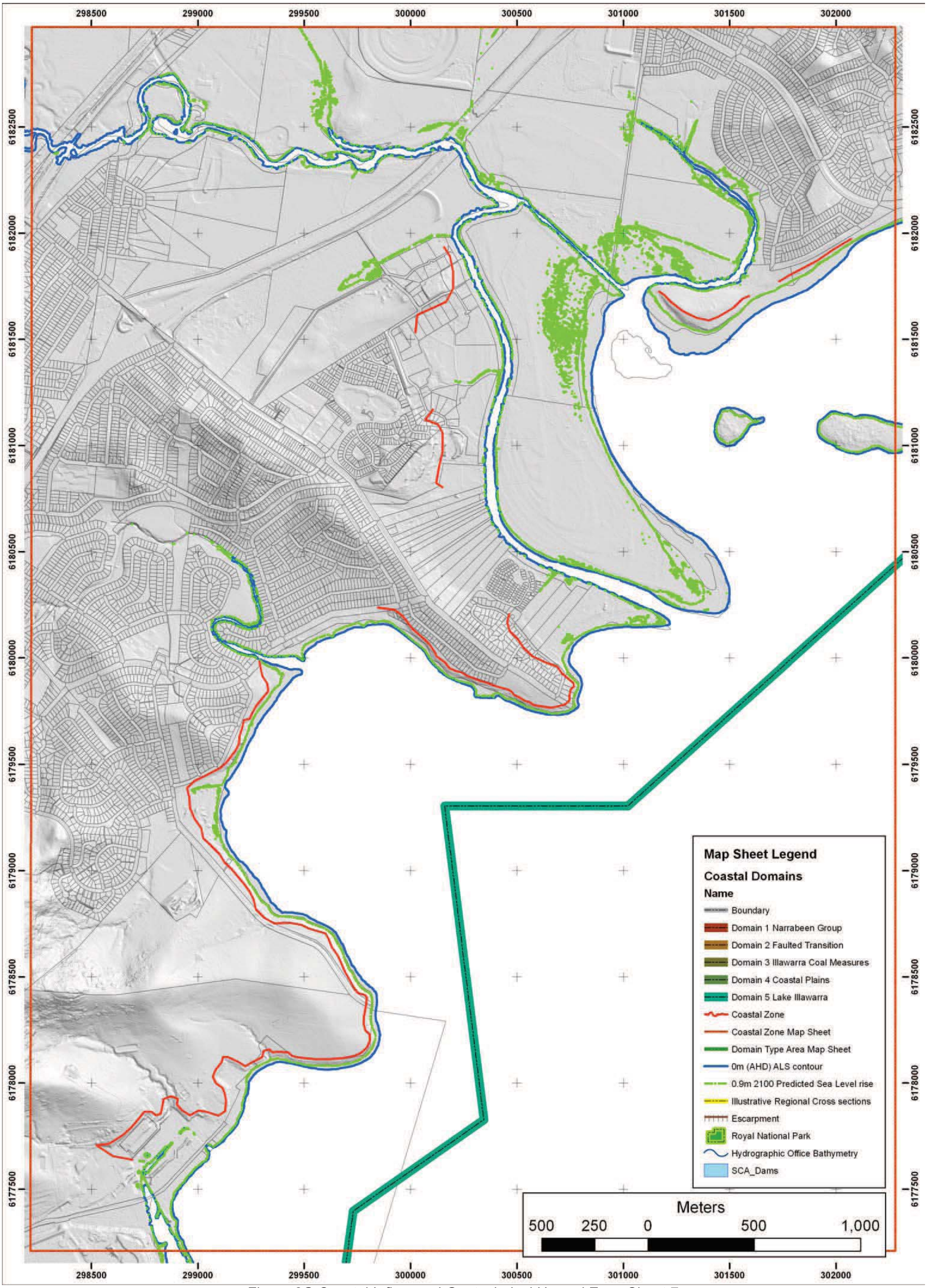

Figure 6G Coastal Influenced Geotechnical Hazard Zone Sheet 7

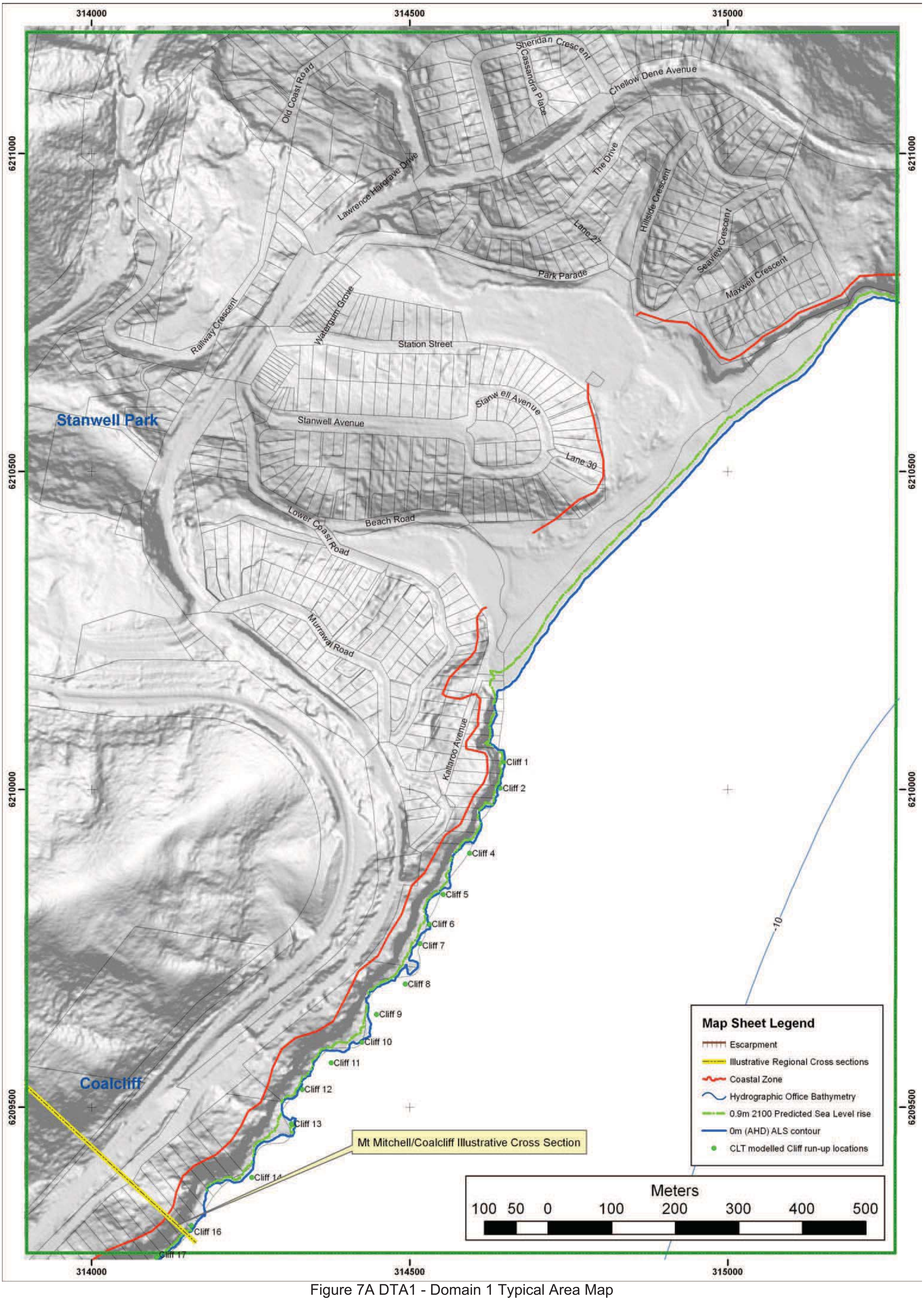

Figure 7A DTA1 - Domain 1 Typical Area Map

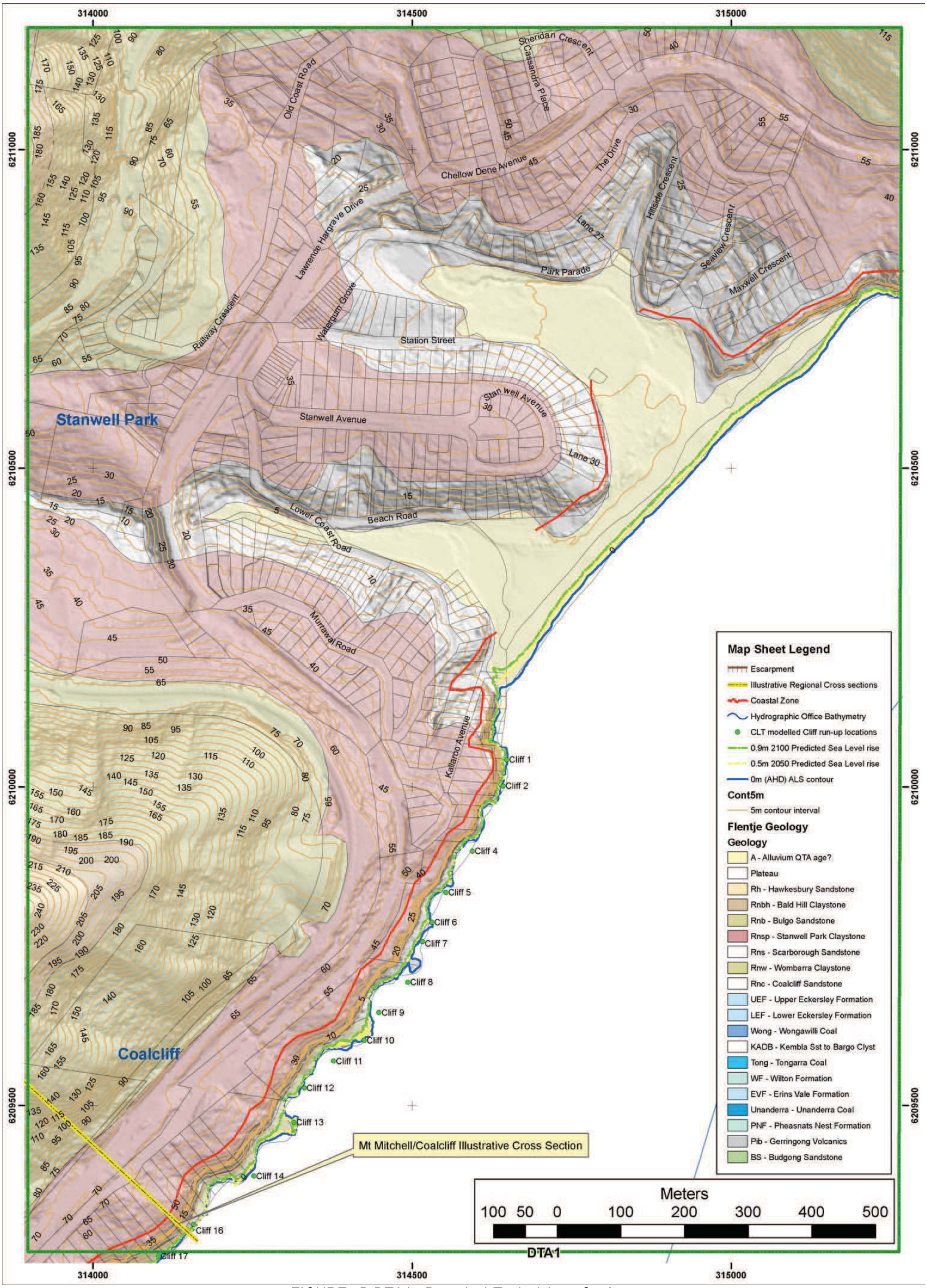

FIGURE 7B DTA1 - Domain 1 Typical Area Geology

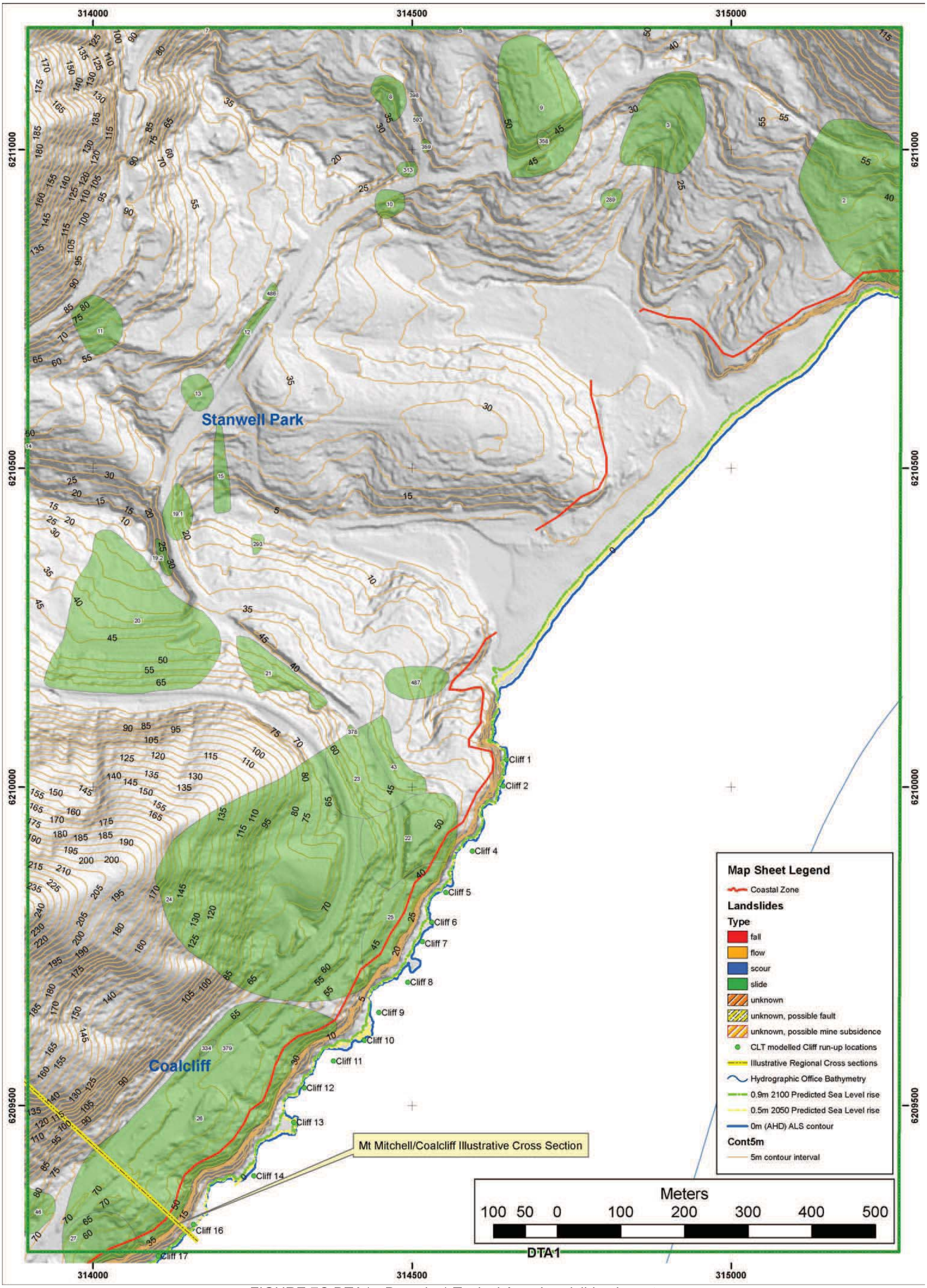

FIGURE 7C DTA1 - Domain 1 Typical Area Landslides Inventory

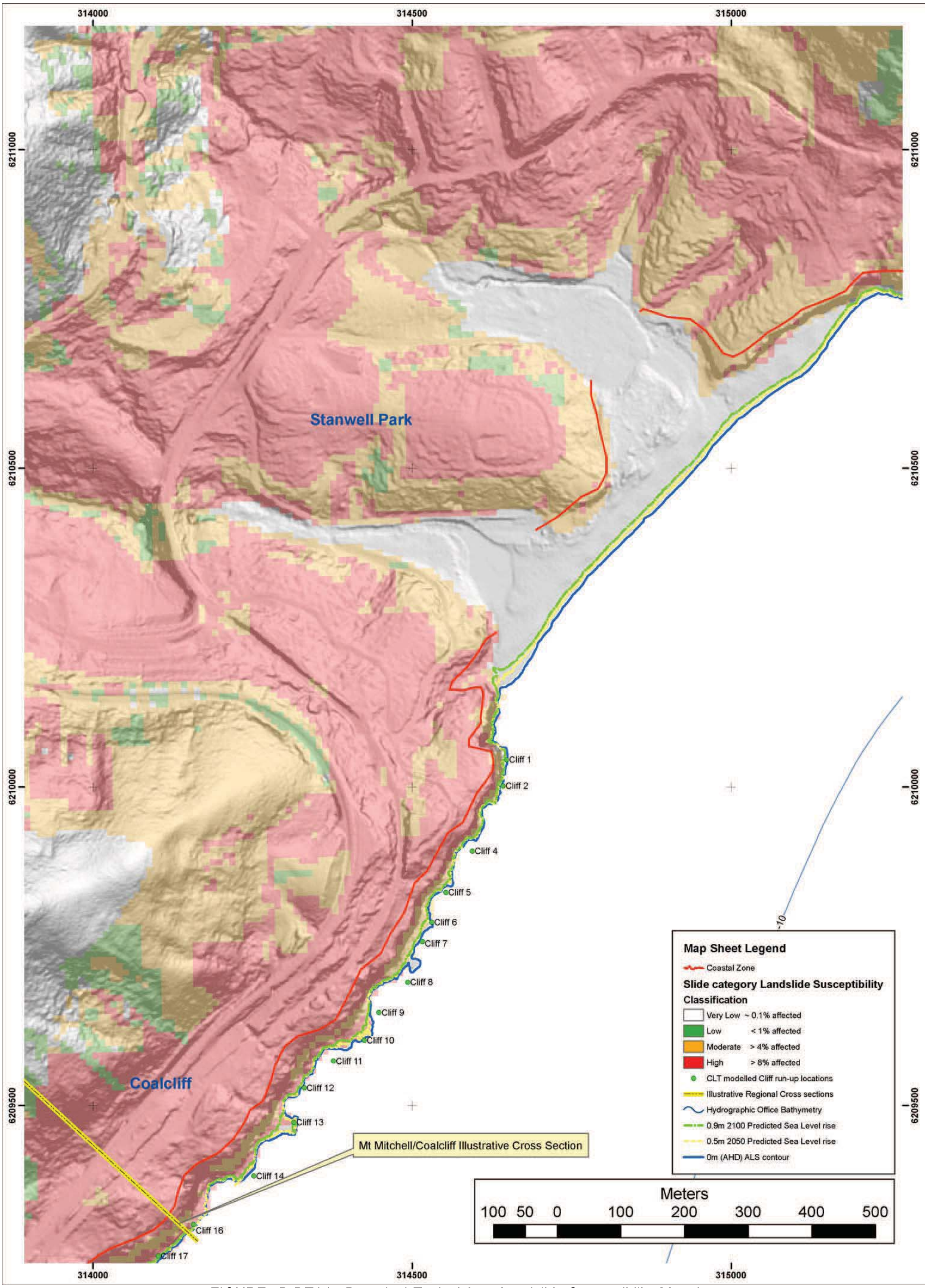

FIGURE 7D DTA1 - Domain 1 Typical Area Landslide Susceptibility Mapping

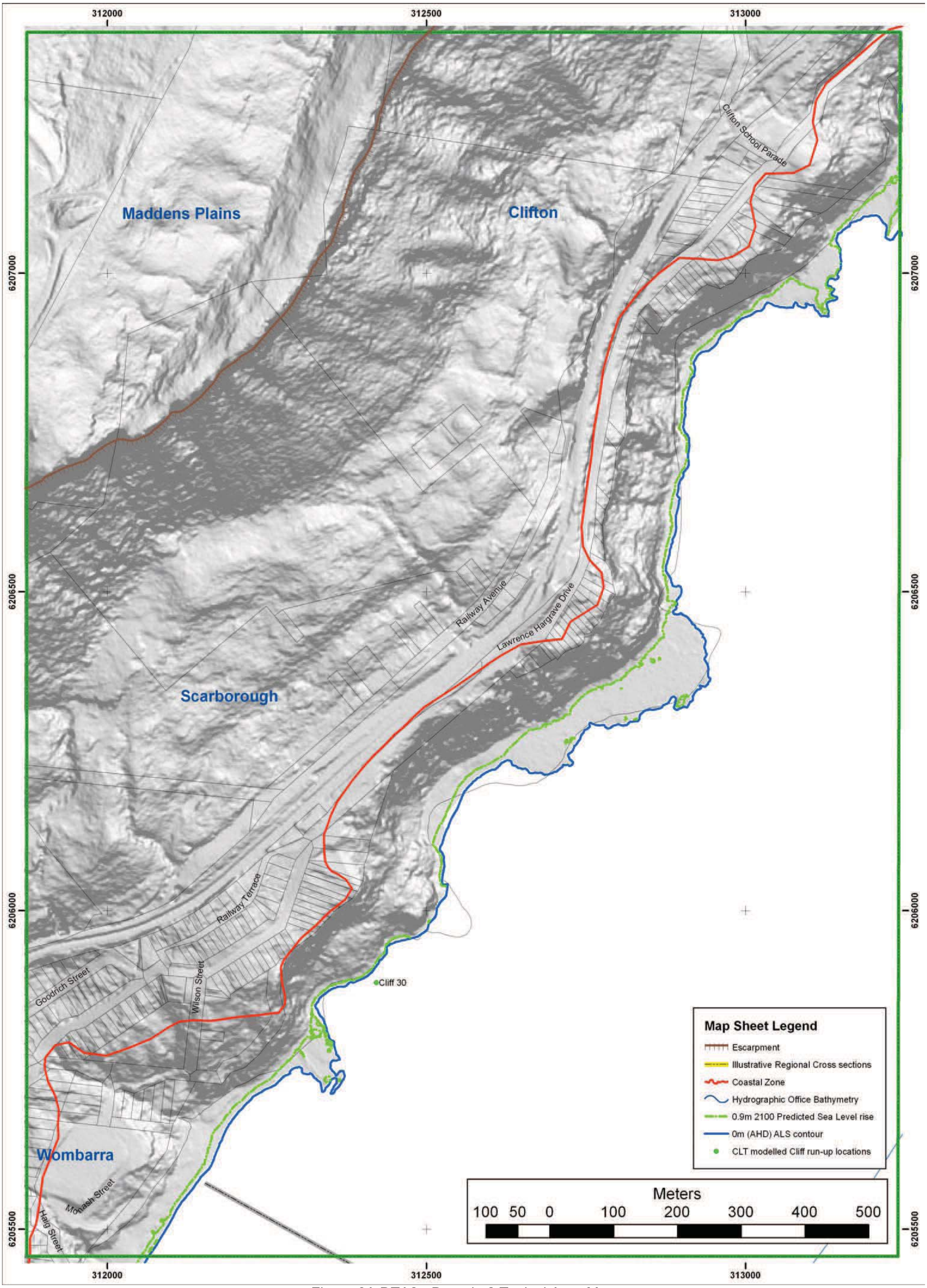

Figure 8A DTA2 - Domain 2 Typical Area Map

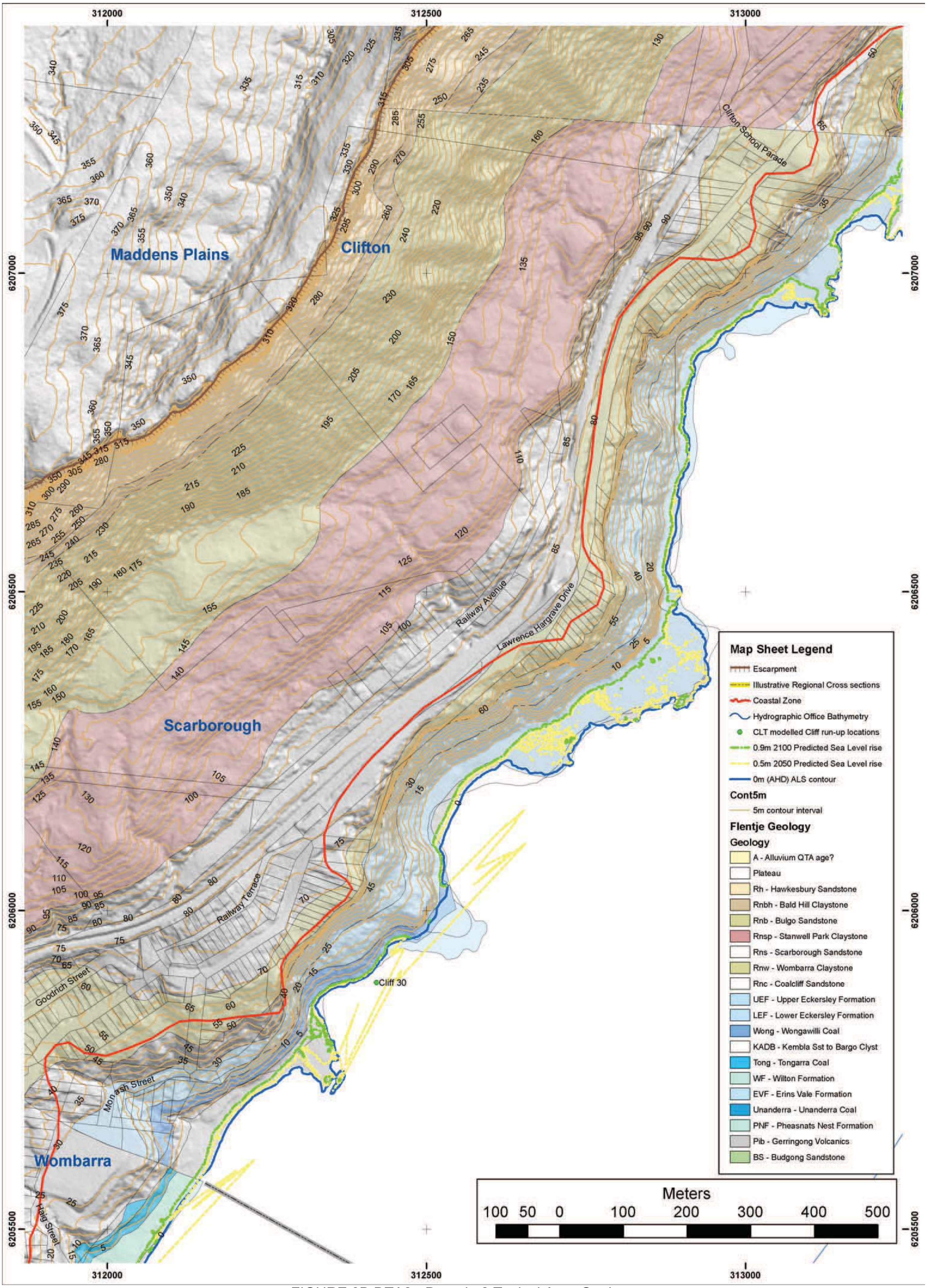

FIGURE 8B DTA2 - Domain 2 Typical Area Geology

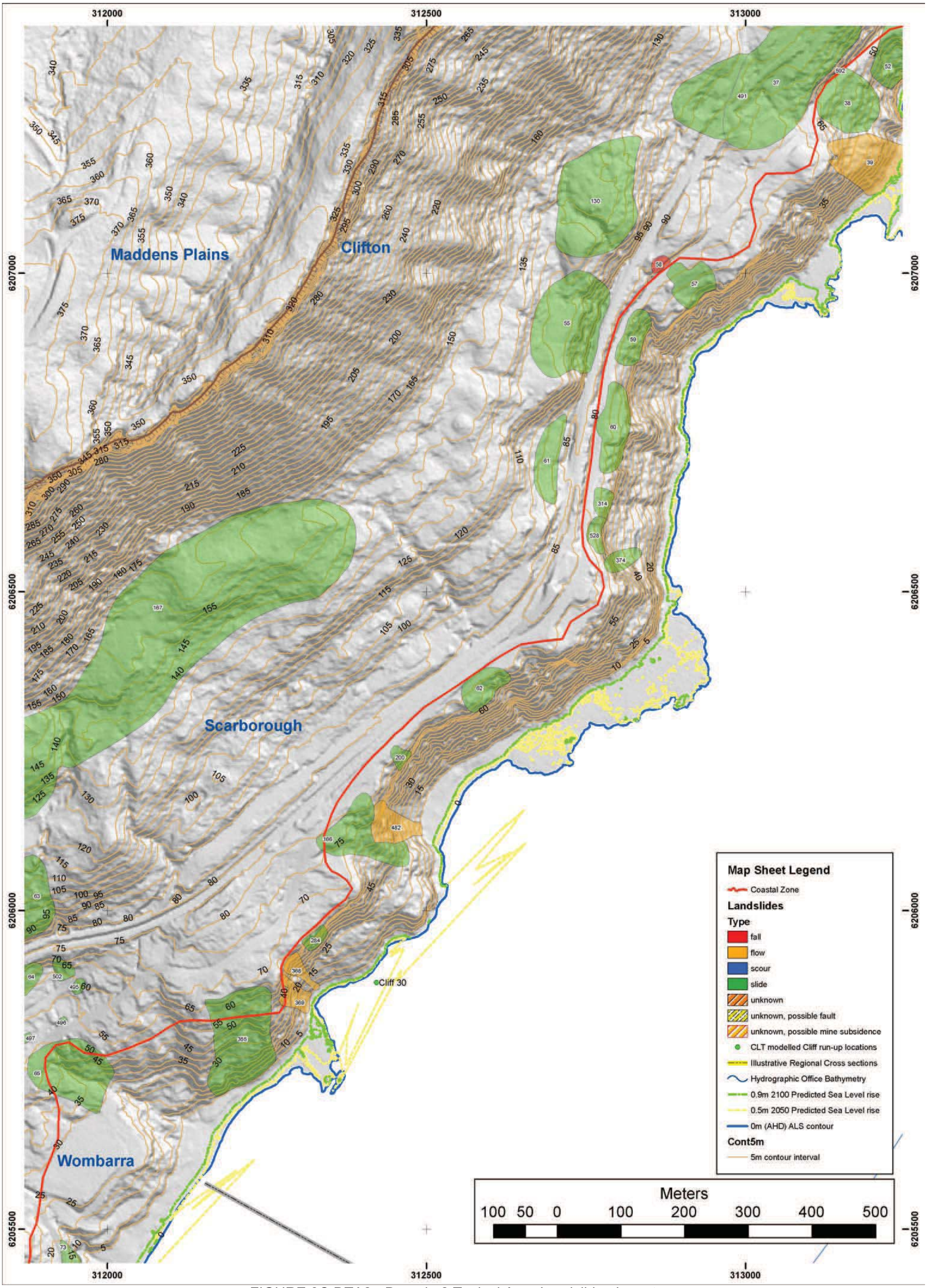

FIGURE 8C DTA2 - Domain 2 Typical Area Landslides Inventory

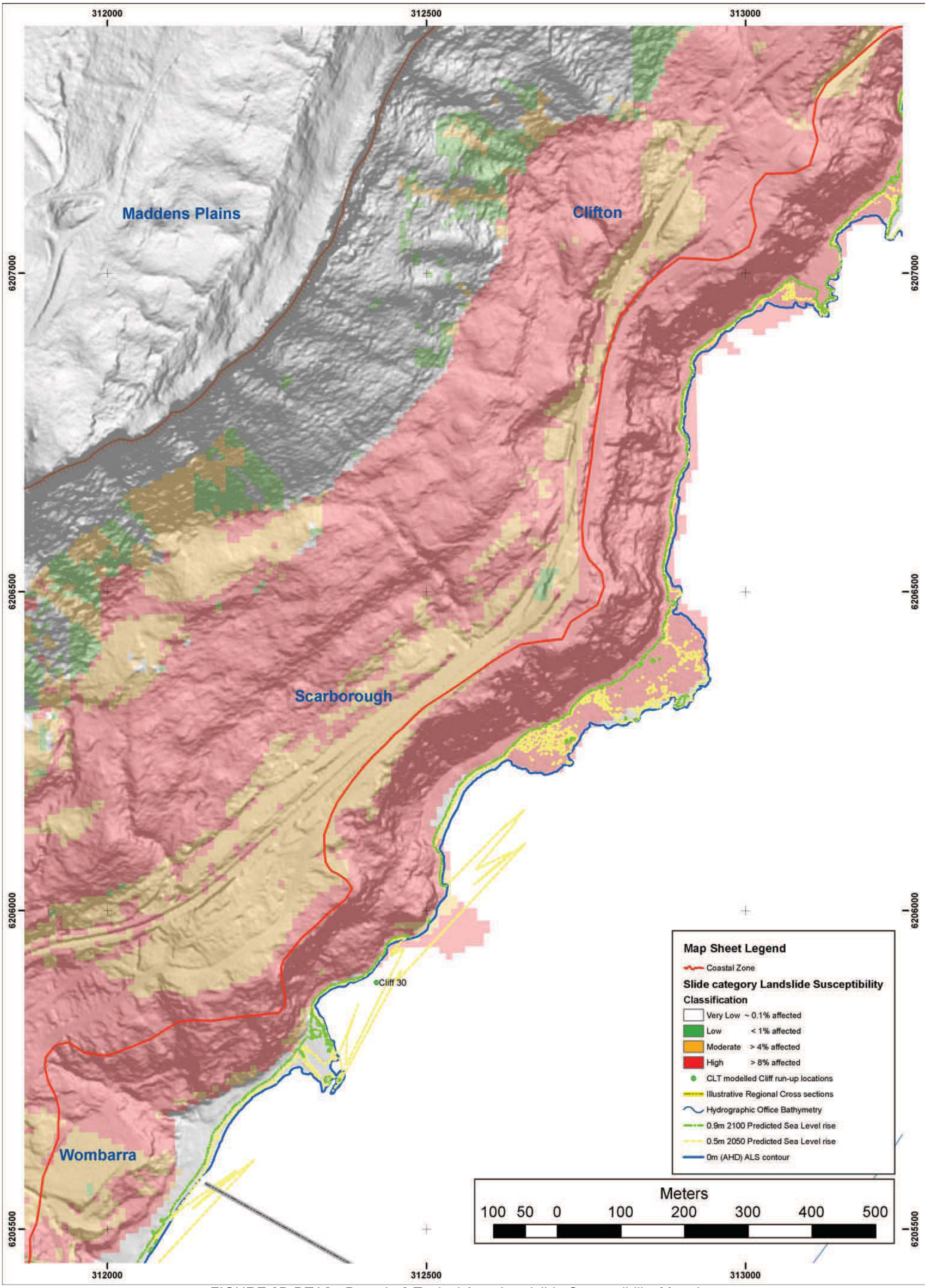

FIGURE 8D DTA2 - Domain 2 Typical Area Landslide Susceptibility Mapping

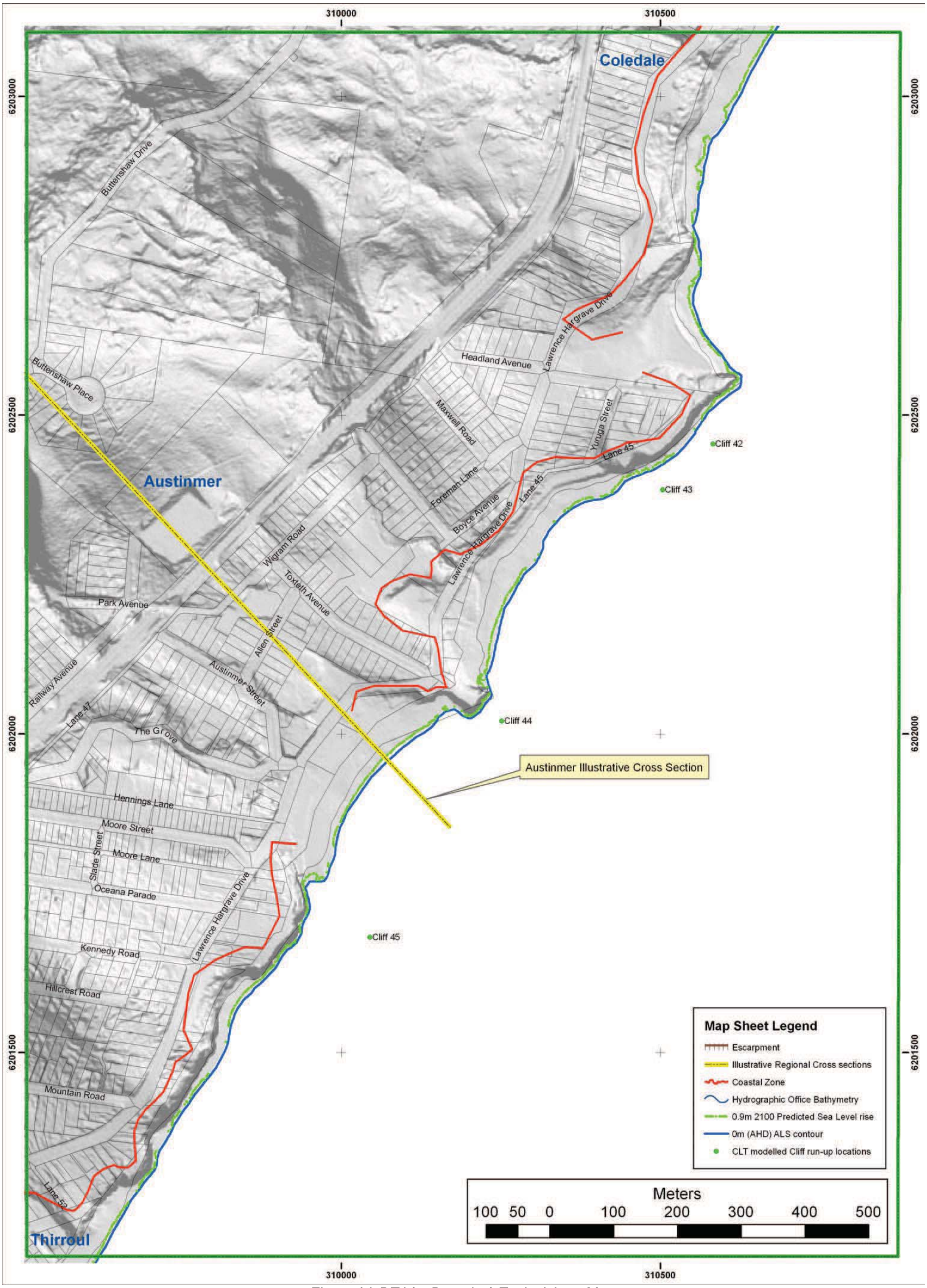

Figure 9A DTA3 - Domain 3 Typical Area Map

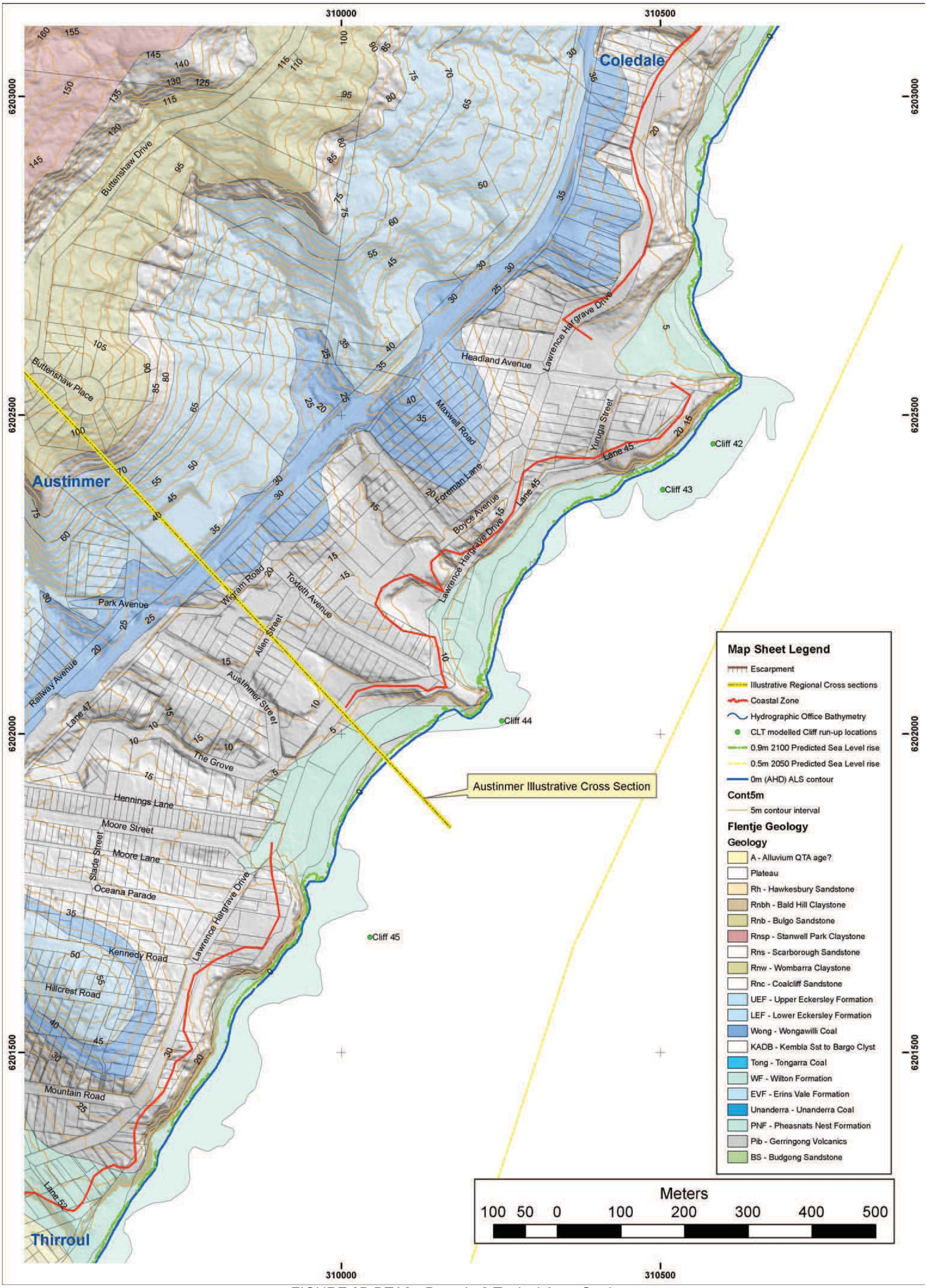

FIGURE 9B DTA3 - Domain 3 Typical Area Geology

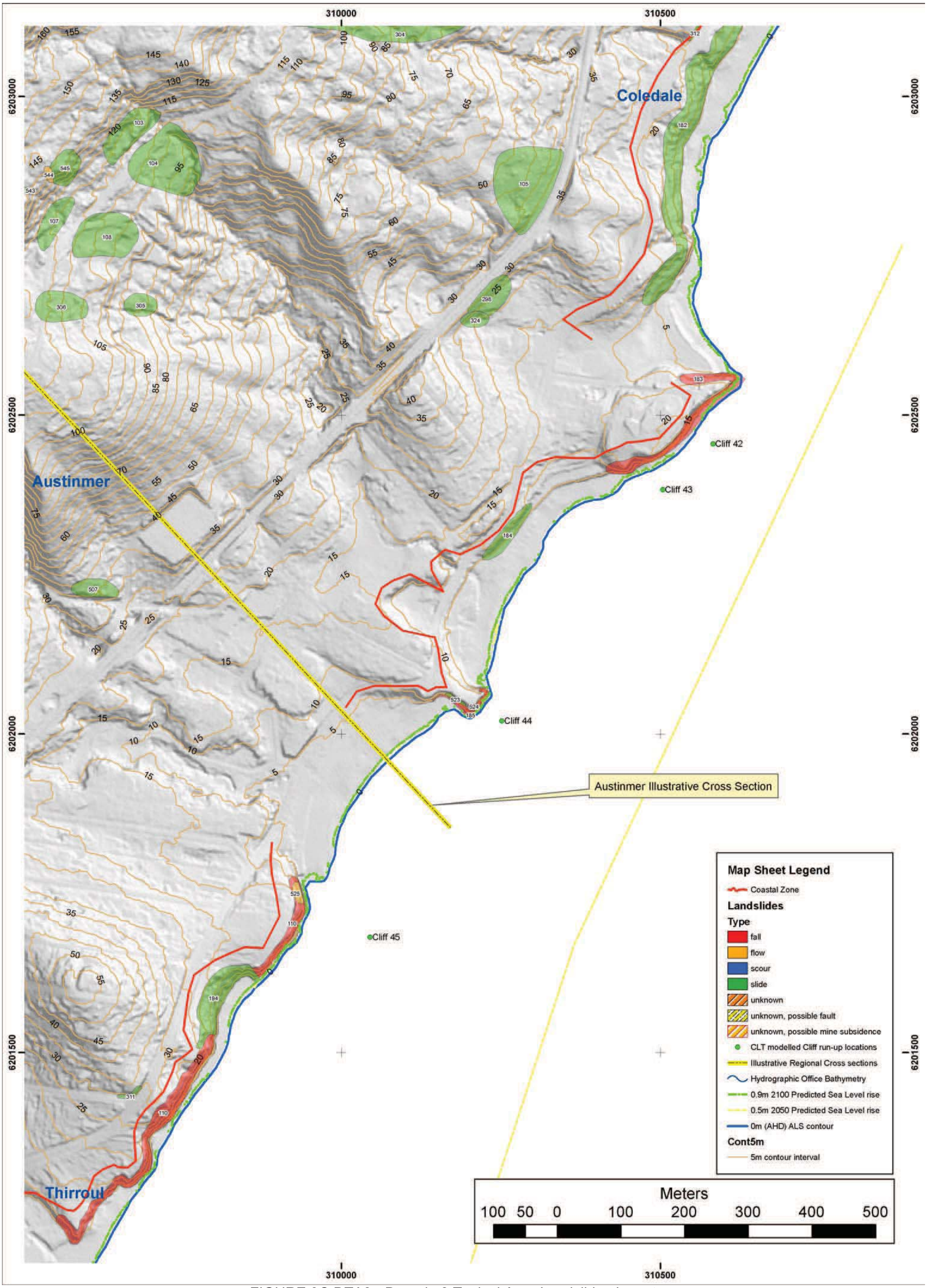

FIGURE 9C DTA3 - Domain 3 Typical Area Landslides Inventory

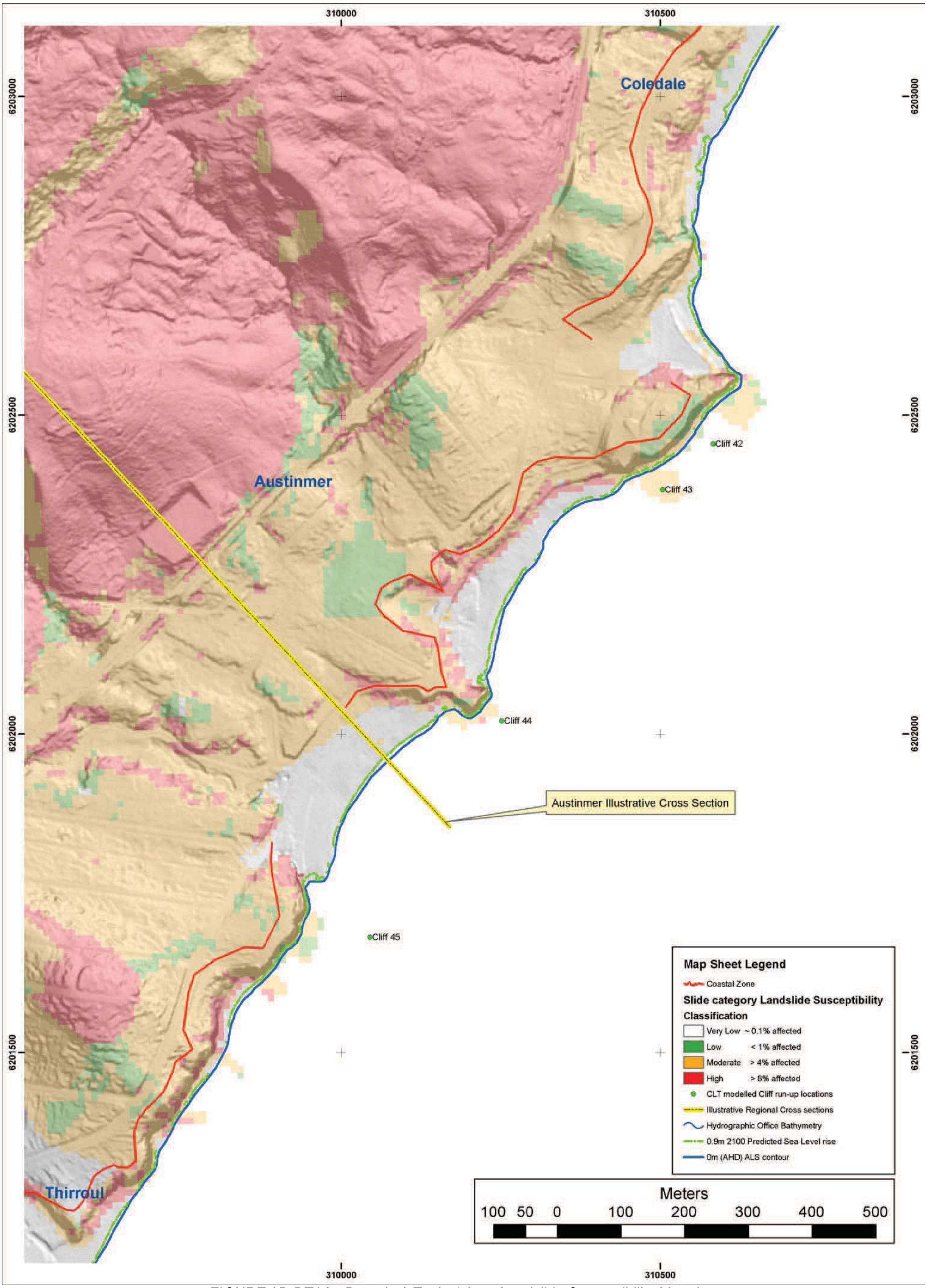

FIGURE 9D DTA3 - Domain 3 Typical Area Landslide Susceptibility Mapping

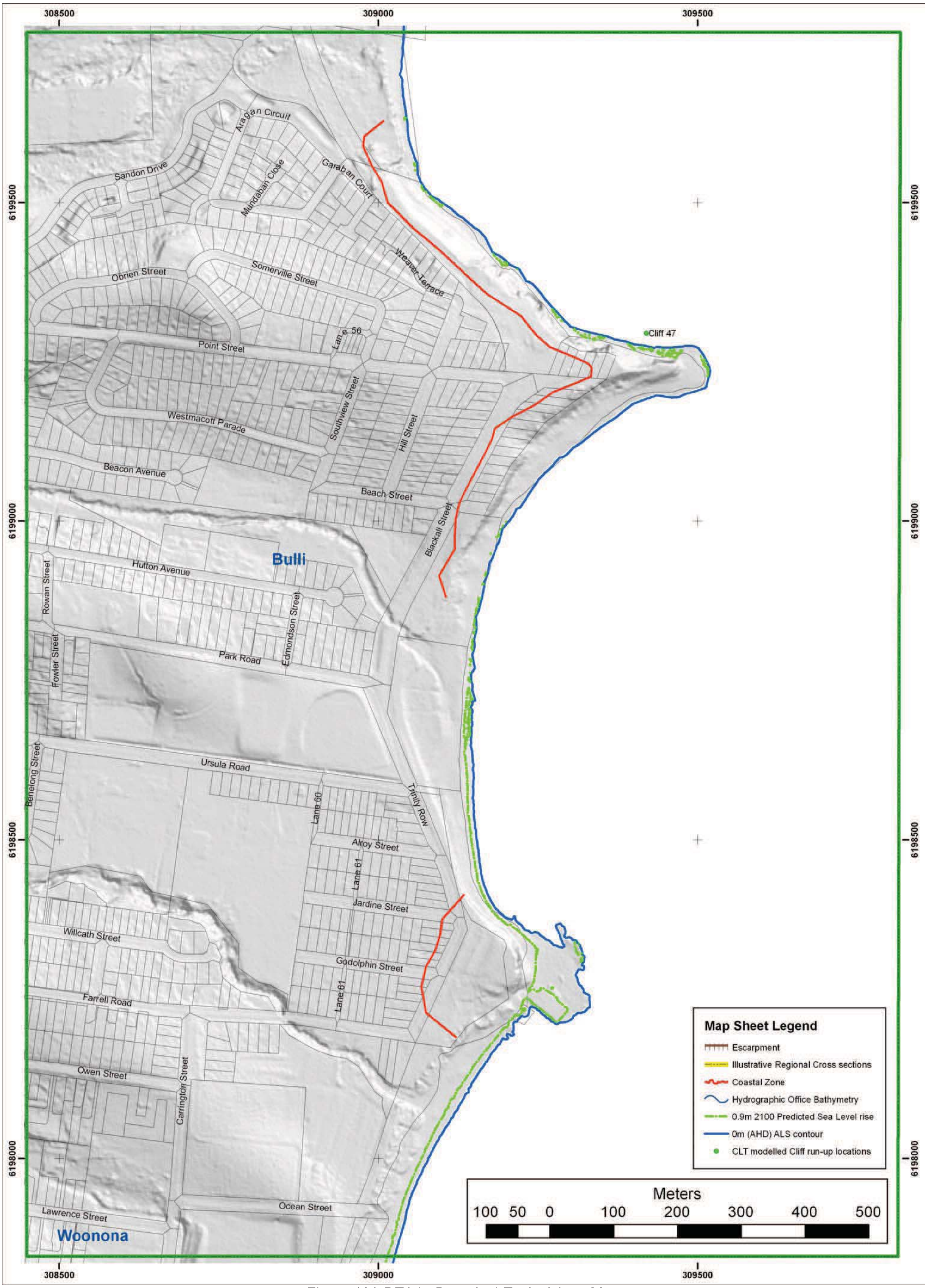

Figure 10A DTA4 - Domain 4 Typical Area Map

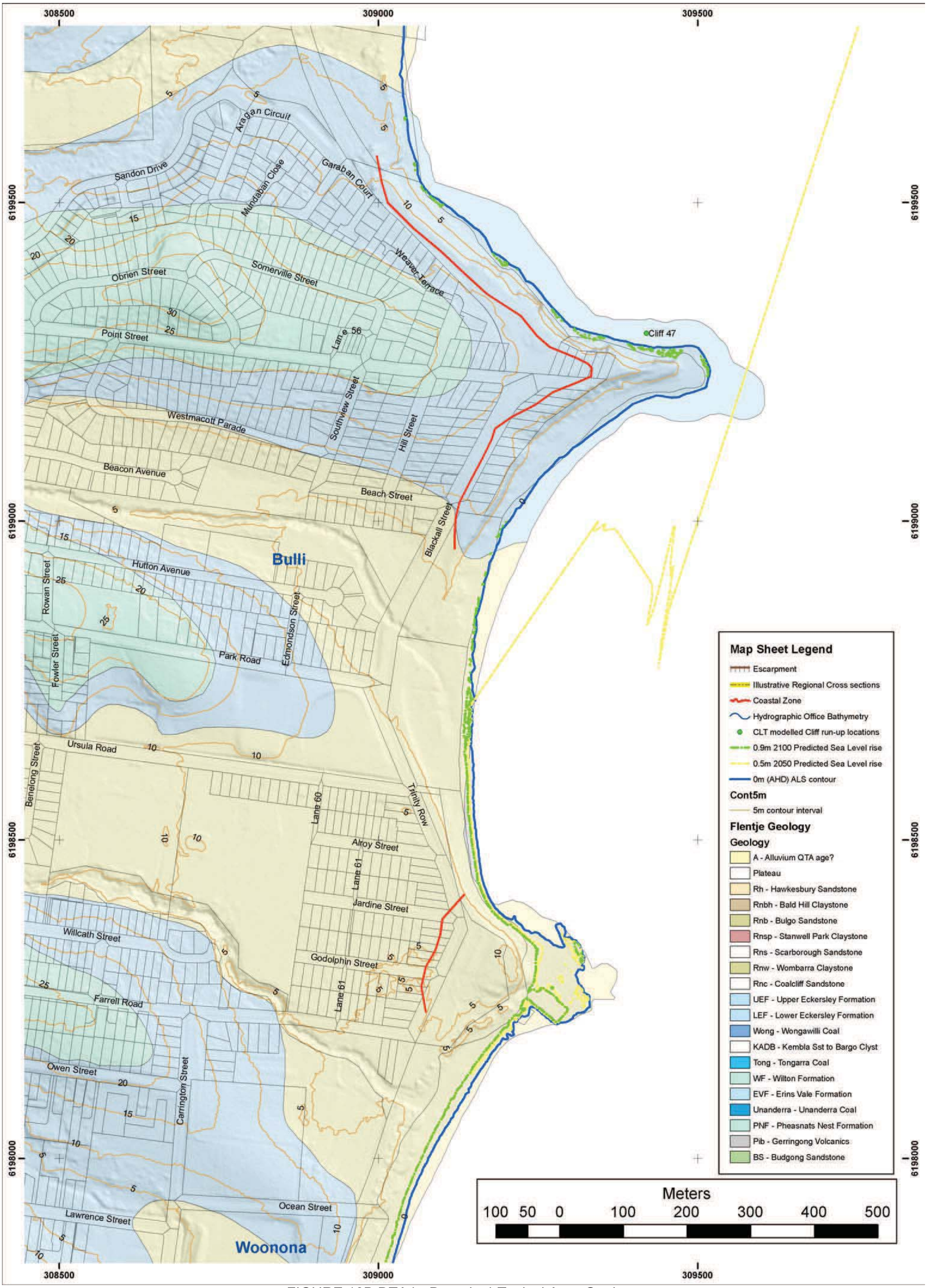

FIGURE 10B DTA4 - Domain 4 Typical Area Geology

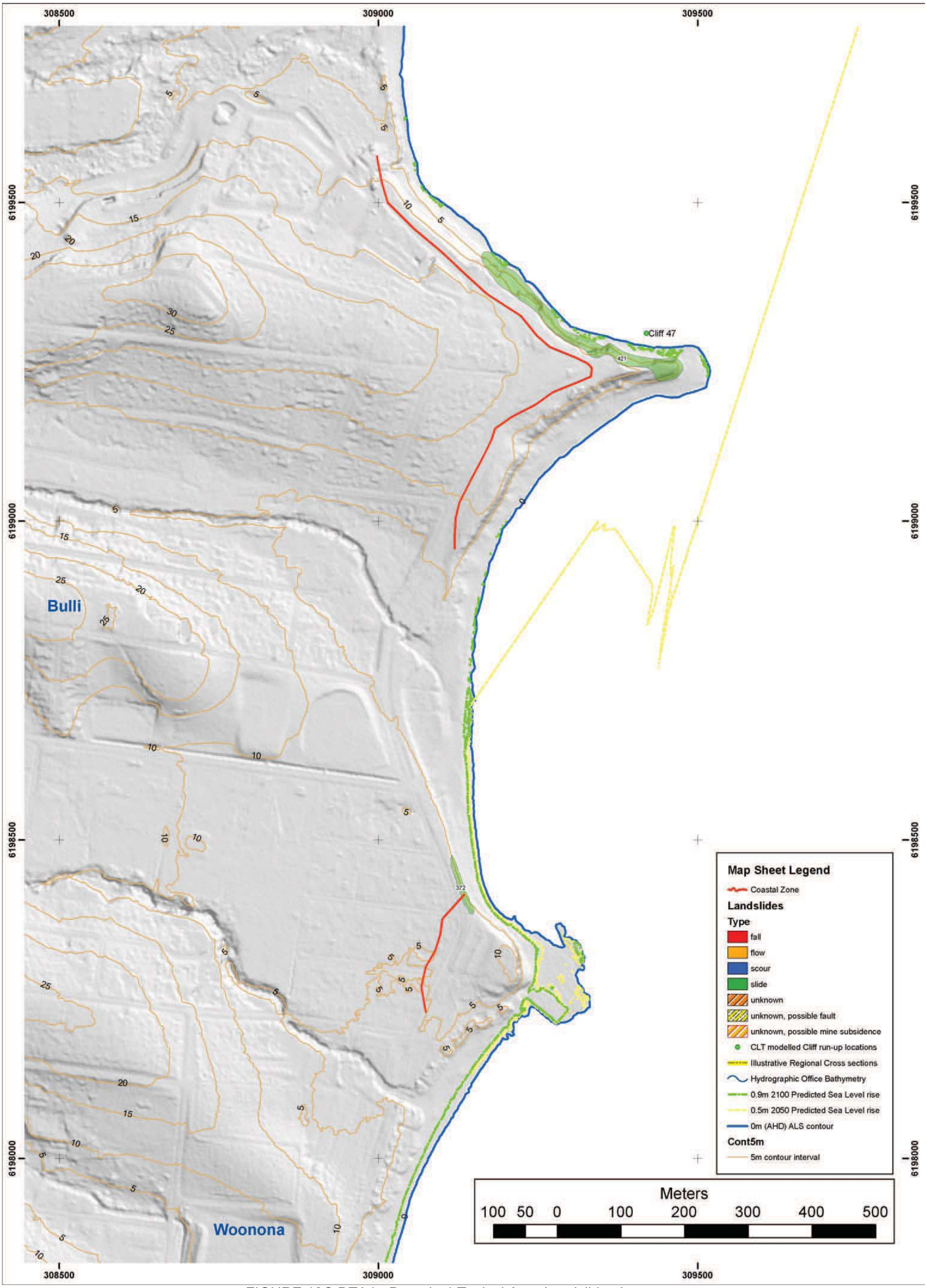

FIGURE 10C DTA4 - Domain 4 Typical Area Landslides Inventory

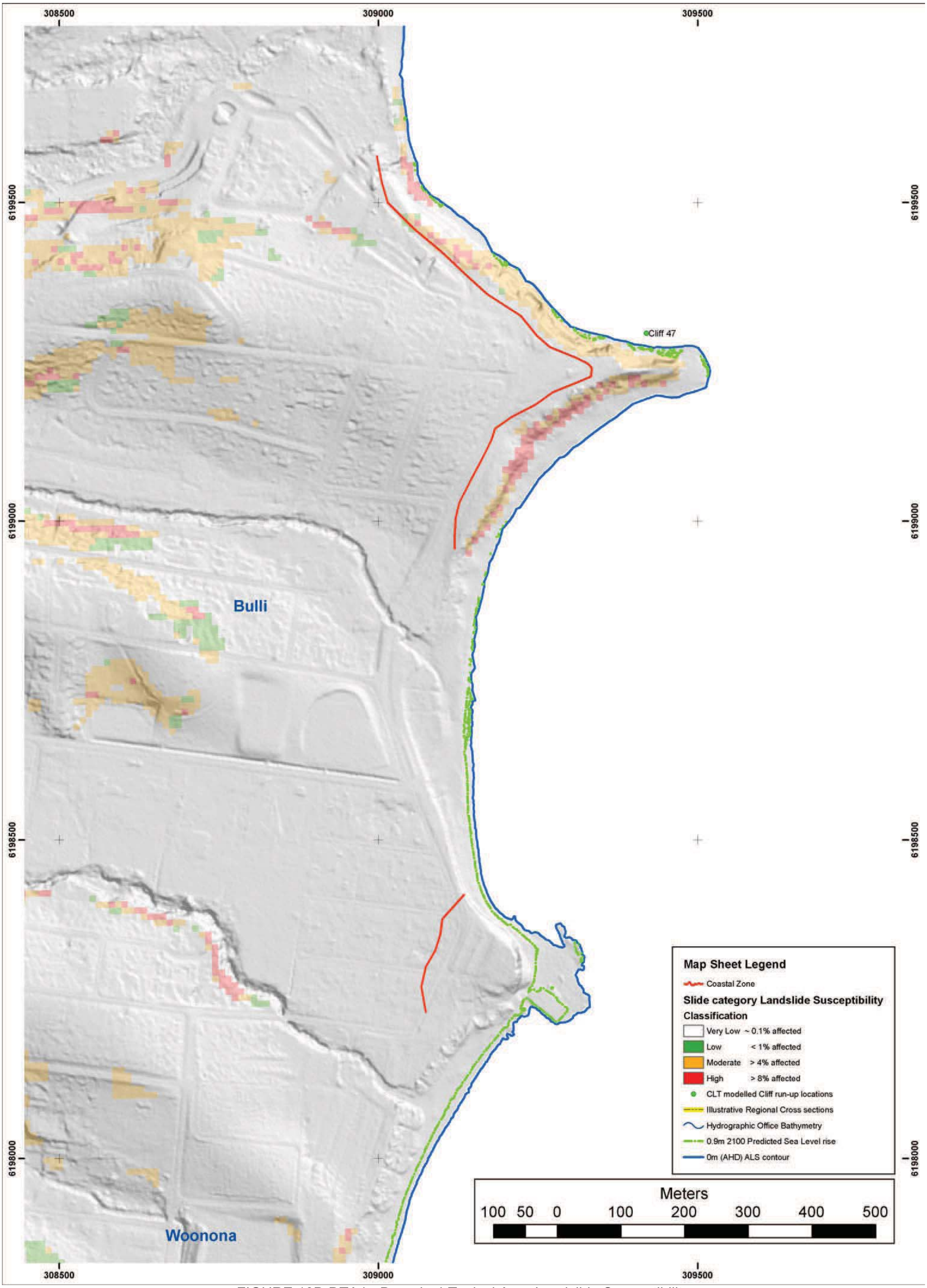

FIGURE 10D DTA4 - Domain 4 Typical Area Landslide Susceptibility

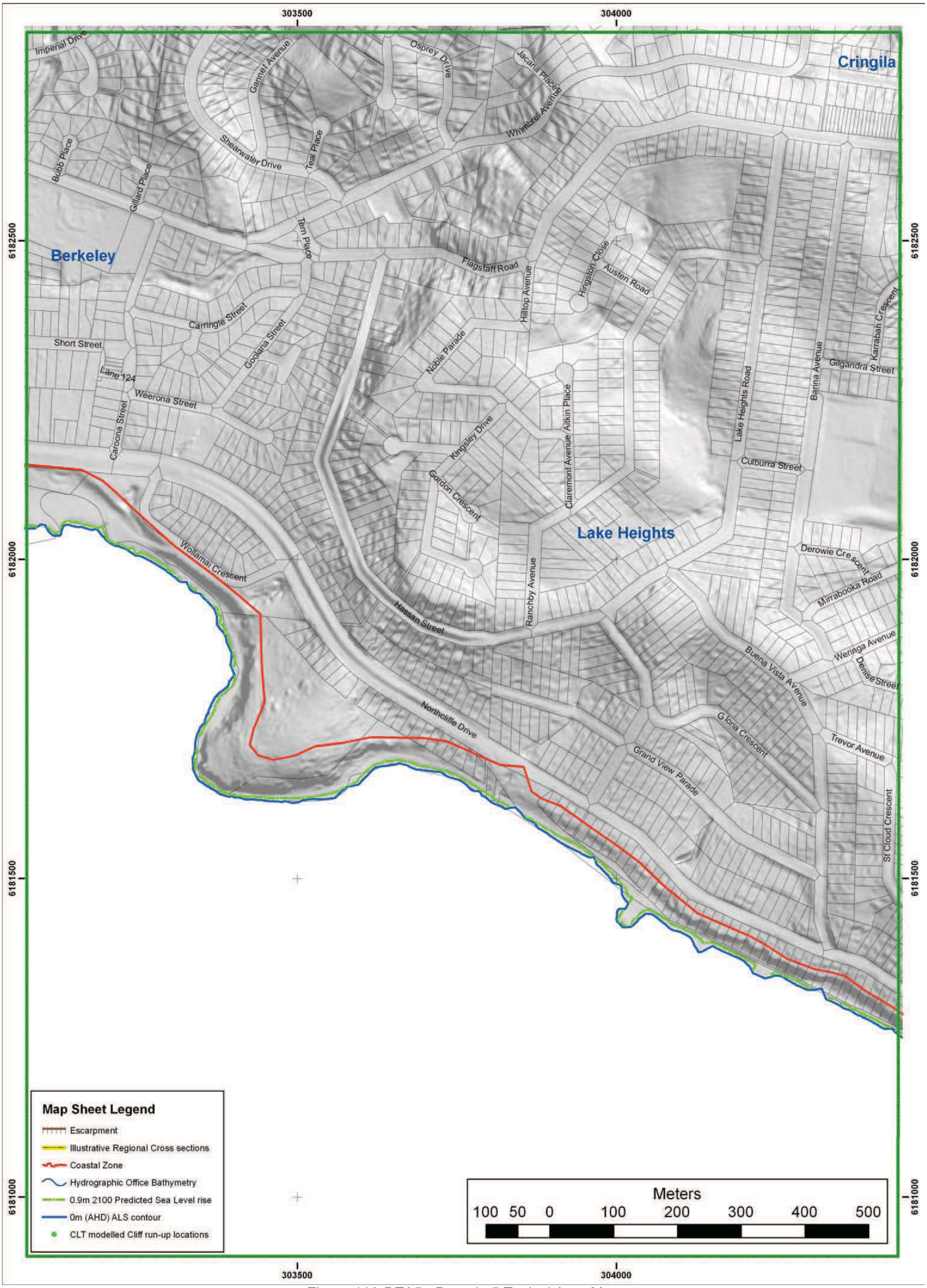

Figure 11A DTA5 - Domain 5 Typical Area Map

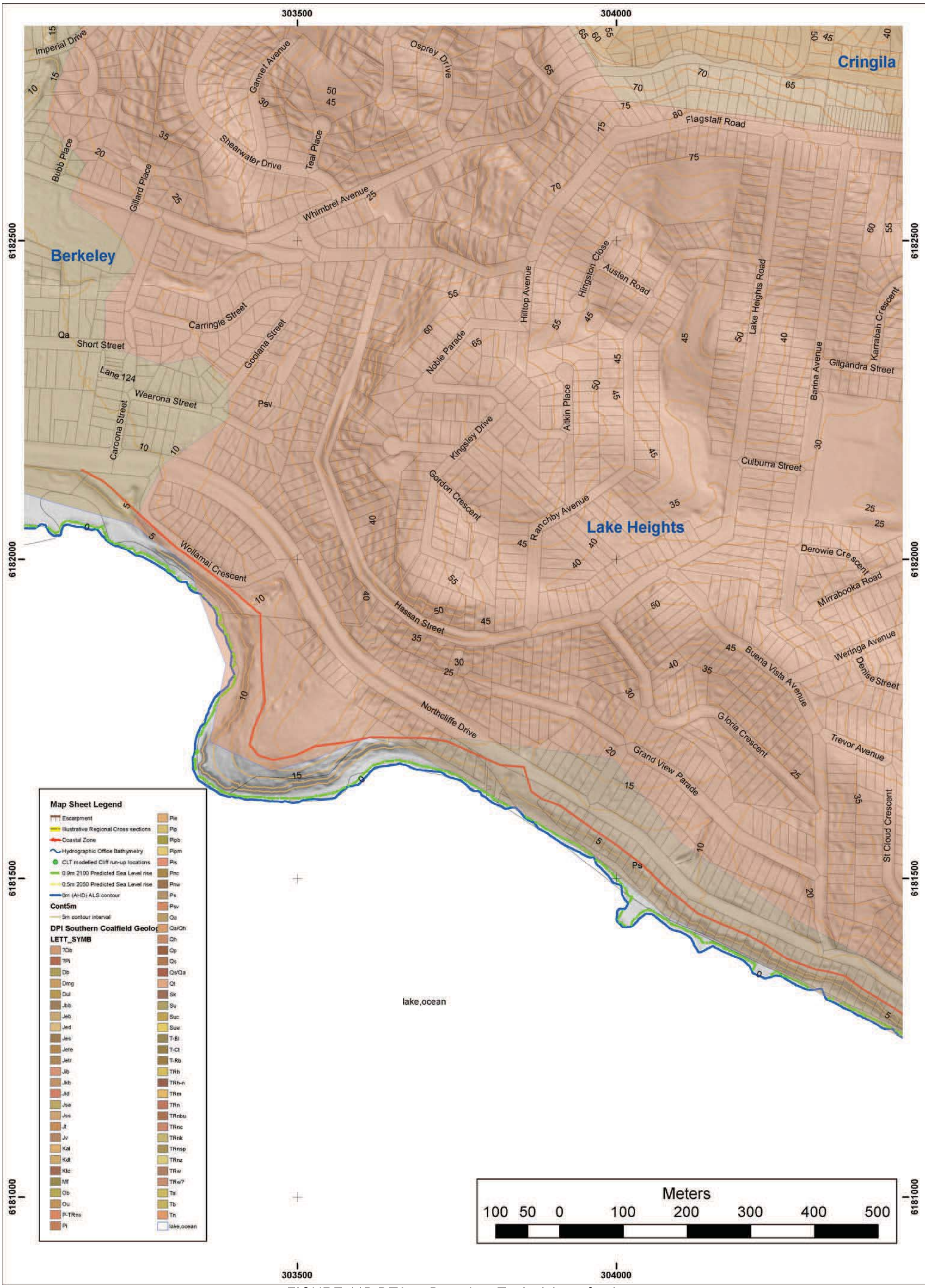

FIGURE 11B DTA5 - Domain 5 Typical Area Geology

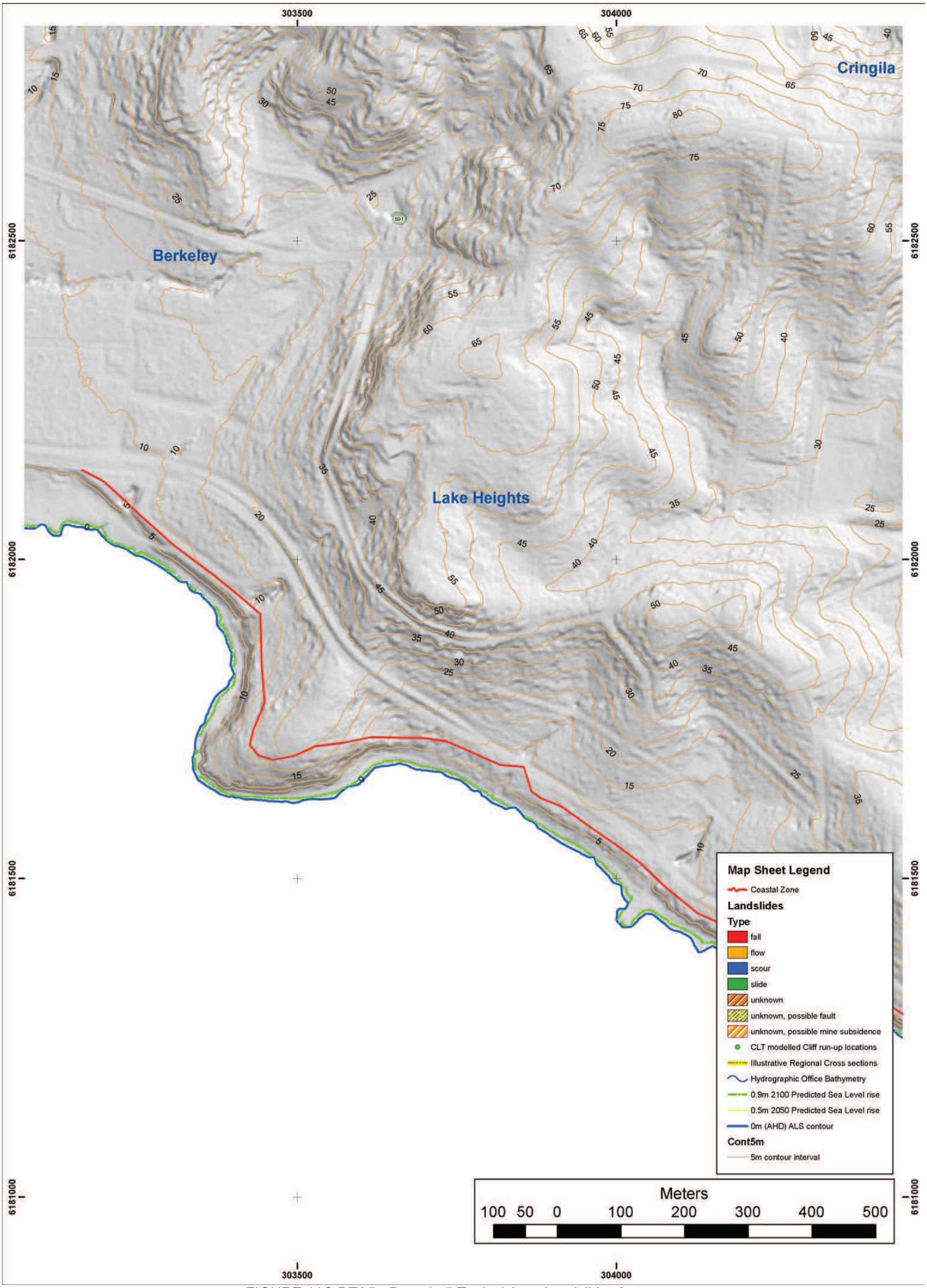

FIGURE 11C DTA5 - Domain 5 Typical Area Landslides Inventory

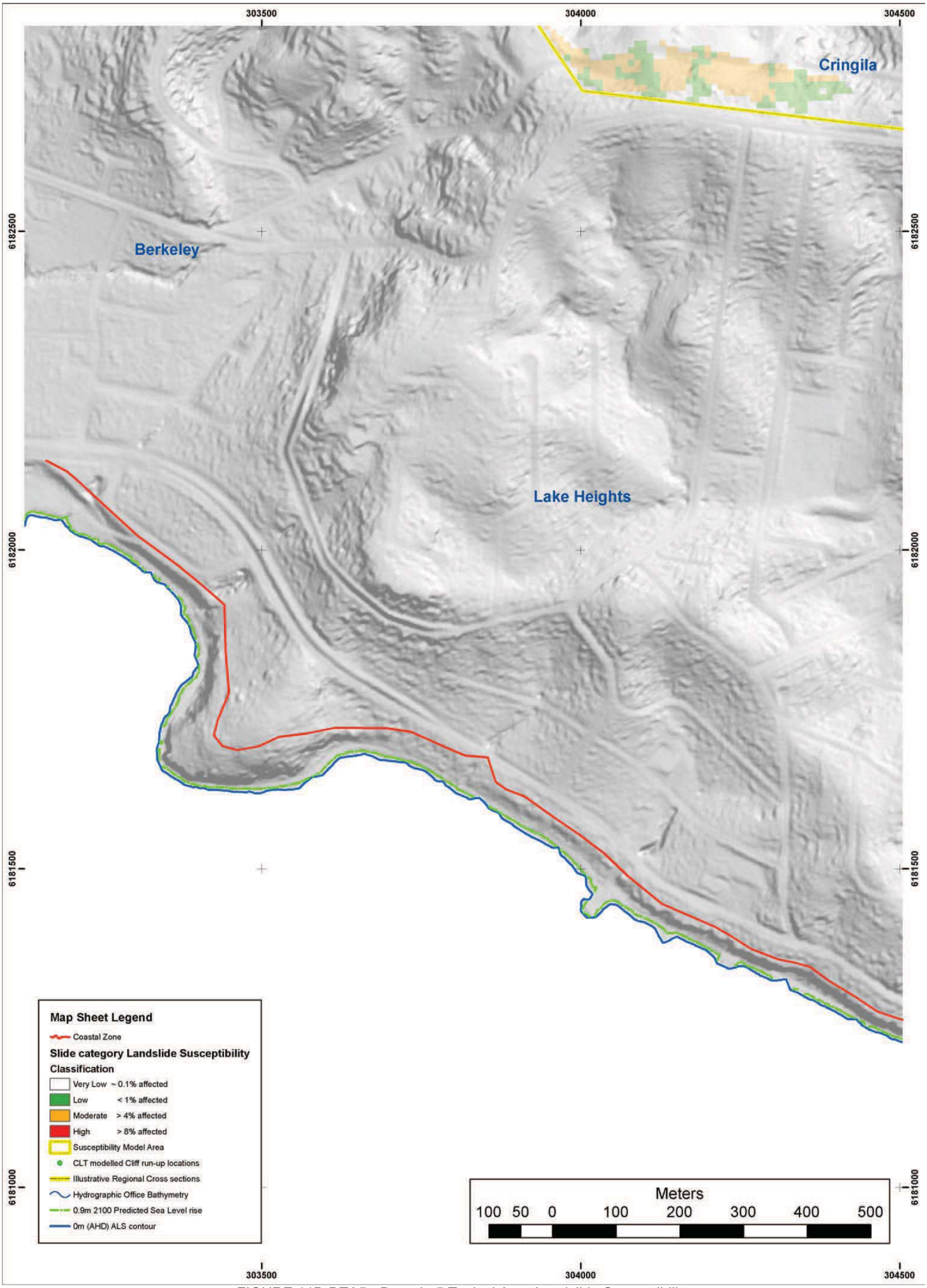

FIGURE 11D DTA5 - Domain 5 Typical Area Landslide Susceptibility

Appendix A

Copies of Landslide Susceptibility Papers

Flentje, P., Stirling, D. and Chowdhury, R.N., 2007.

> "Landslide Susceptibility and Hazard derived from a Landslide Inventory using Data Mining – An Australian Case Study."
>
> Proceedings of the First North American Landslide Conference, Landslides and Society: Integrated Science, Engineering, Management, and Mitigation. Vail, Colorado June 3-8, 2007. CD, Paper number 17823-024, 10 pages.

Flentje, P., Stirling, D., Palamara, D. and Chowdhury, R.N., 2007.

> "Landslide susceptibility and landslide hazard zoning in Wollongong"
>
> Common Ground, Proceedings of the 10th Australia New Zealand Conference on Geomechanics. Published by Carillon Conference Management Pty Ltd for the Australian Geomechanics Society. Brisbane, October 21st – 24th. Volume 2, pages 392 - 397.

LANDSLIDE SUSCEPTIBILITY AND HAZARD DERIVED FROM A LANDSLIDE INVENTORY USING DATA MINING – AN AUSTRALIAN CASE STUDY

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Abstract: The University of Wollongong landslide research team has developed a comprehensive GIS-based Landslide Inventory of the 550 km^2 Wollongong Local Government Area (WLGA) and surrounding regions, just south of Sydney in the State of New South Wales, Australia. This inventory includes 575 landslide sites and forms the crucial centerpiece of the methodology reported in this paper. The inventory identifies 2.95% of a 188 km^2 escarpment study area to be covered by landsliding reported during the last 120 years. With GIS-based data sets, a 'slide' category landslide susceptibility map layer has been developed using 'knowledge-based' data-mining techniques. Susceptibility zones have been classified as (a) known landslides, (b) high susceptibility with ~ 8% of the area subject to landslides (contains 57% of the known landslides), (c) moderate susceptibility with 4% of the area subject to landslides (contains 35% of known landslides), (d) low susceptibility with 0.85% of the area subject to landslides (contains 3.7% of known landslides), and (e) very low susceptibility with <0.1% of the area subject to landsliding (represents 71% of the study area). It is important to note that the high susceptibility zone identifies over 2,300 hectares of land, outside of known landslides, as being highly susceptible to landsliding. The 'slide' category susceptibility maps have been upgraded to hazard level maps with identification and labelling of site specific frequency, volume and 'profile' angles for each landslide. The average landslide frequency of occurrence for each susceptibility zone has been determined.

AIMS AND SCOPE

This paper summarises the use of a comprehensive large scale regional GIS-based Landslide Inventory, various GIS-based data sets, including large scale geology, a 10m pixel Digital Elevation Model and the development of Landslide Susceptibility and Hazard maps for rainfall triggered 'slide' category landslides (Cruden and Varnes 1996). Data-Mining techniques (Quinlan 1993) are used to develop the Susceptibility classification. Significant work has also been completed on modelling both 'flow' and 'fall' category landslide Susceptibility; however, that work will be reported elsewhere.

Processes and mechanisms of slope failure are controlled in Wollongong by factors such as stratigraphy, geotechnical strength parameters, hydrogeology, geomorphology, slope inclination pore water pressure and the actions of man. The landslide inventory contains 3 types of landslides, namely falls, flows and slides. Prolonged and/or intense rainfall is typically the trigger for significant landsliding. The average annual rainfall for Wollongong varies from 1200mm on the coastal plain and up to 1600mm along the top of the escarpment.

STUDY AREA

The city of Wollongong is nestled on a narrow coastal plain approximately 70km south of Sydney in the state of New South Wales (NSW), Australia as shown in Figure 1. Over the last 150 years of modern settlement the population of the Wollongong area has increased to about 200,000 people. The coastal plain is triangular in shape with a coastal length of 45km. The coastal plain is up to 17km wide in the south and extends north to Thirroul. The coastal plain is bounded to the north, west and south by an erosional escarpment of Neogene Age ranging in height from 300 m up to 500 m.

The escarpment consists of slopes with moderate to steep inclinations with several intermediate benches and cliff lines. The geological sequence encountered on the escarpment comprises an essentially flat-lying sequence of interlayered sandstone, mudstone and coal of the Illawarra Coal Measures, overlain by interbedded sandstones and mudstones/claystones of the Narrabeen Group. Spectacular cliffs of Hawkesbury Sandstone (of Middle Triassic age) cap the escarpment and there is dense vegetation over most of the escarpment below these cliffs.

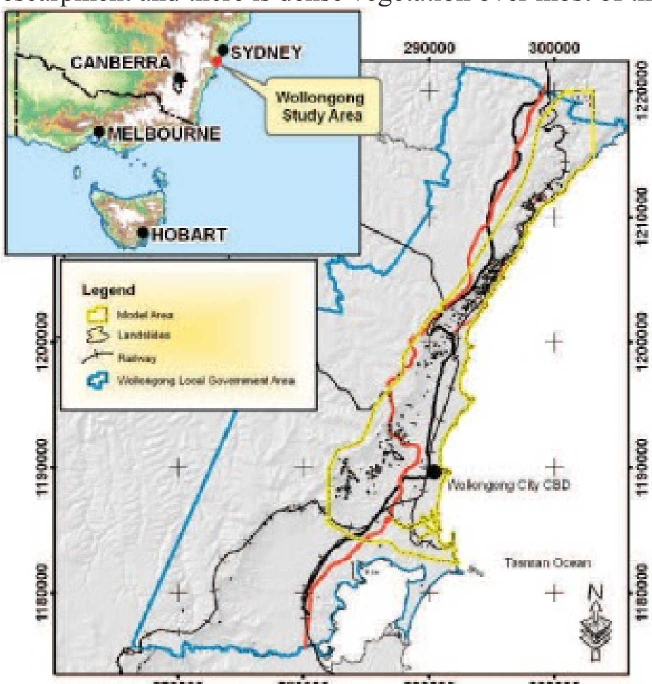

Figure 1. South Eastern Australia reference map showing the Wollongong Study Area, the Wollongong Local Government area and the GIS Model Area with known landslides.

WOLLONGONG REGIONAL LANDSLIDE INVENTORY

The Landslide Inventory, developed over the last decade, comprises a relational MS Access and ESRI ArcGIS^{TM} Geodatabase with over 70 fields of information for each landslide site (Flentje and Chowdhury 2005). Field mapping and compilation work has been carried out using maps and GIS software at 1:4000 or larger scales. Each landslide is referenced by a key Site Reference Code. The Landslide Inventory currently contains 575 landslides with a total of 965 landslide events (including first time occurrences and multiple recurrences at some sites). The 575 landslides comprise 42 falls, 43 flows and 480 slides according to the Cruden and Varnes 1996 classification. In addition, there are several scour related sites and a few that have not been classified. A total of 426 Slide category landslides are located within the 188 km^2 Model area (Figure 1). Landslide volumes have been estimated for 378 of these sites. The volumes range from <1m^3 up to 720,000m^3, with an average volume of 21,800m^3. Figure 2 shows the temporal distribution of landsliding as reported in the Landslide Inventory. This clearly shows the majority of sites have been recorded since 1950 with a marked increase since 1988.

The slides are all considered to be episodically active, being activated by elevated pore water pressures resulting from periods of significant rainfall. Previous UoW research has led to the determination of regional rainfall thresholds for triggering landslides (Flentje and Chowdhury, 2006).

Landslide monitoring and observations of slide category landslides in the Wollongong region show that these landslide types typically move a few millimetres to a few tens of centimetres in response to a given rainfall event. The velocity is thus generally in the range Extremely Slow to Slow (IUGS, 1995) while the maximum monitored velocity was a Moderate rate of almost 5mm per day for several weeks in late 2004. Ongoing landslide monitoring will lead to a better understanding of the relationship between pore water pressure, antecedent rainfall magnitudes and rates of landslide movement (Flentje and Chowdhury, 2006).

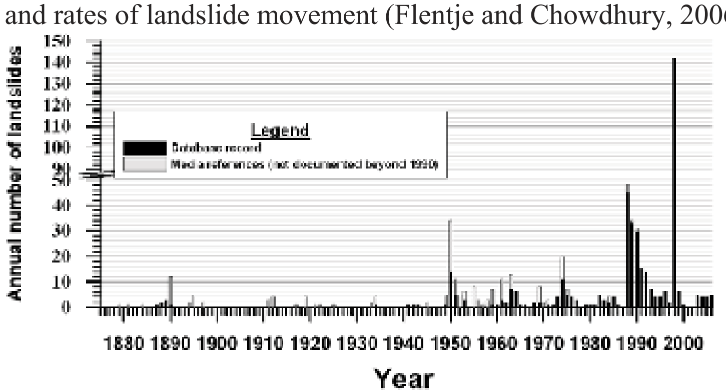

Figure 2. Temporal distribution of landslide events recorded in the UoW Landslide Inventory.

ADDITIONAL GIS-BASED DATA SETS

The landslide research team at the University of Wollongong have developed a GIS-based methodology for identifying and mapping zones of slide category landslide susceptibility. Firstly, it is appropriate to list the GIS-based data sets that have been developed for this project. Some of these digital data sets (‘maps’ in the old parlance, but in this digital age they are now significantly enhanced digital GIS-based data sets) have been developed as part of this project using fundamental engineering geological mapping principles. Additional data sets have been acquired through external agencies and others have been generated by the GIS software using the Digital Elevation Model.

In addition to the Landslide Inventory described above, ten GIS-based data sets have been compiled. These data sets are listed below. Space limitations preclude further discussion of each data set here:

- Geology (21 variables comprising the mapped geological formations)
- Vegetation (15 variables comprising the mapped vegetation categories)
- Slope Inclination (continuous floating point distribution)
- Slope aspect (continuous floating point distribution)
- Terrain Units (buffered water courses, spur lines and other intermediate slopes)
- Curvature (continuous floating point distribution)
- Profile Curvature (continuous floating point distribution)
- Plan Curvature (continuous floating point distribution)
- Flow Accumulation (continuous integer)

- Wetness Index (continuous floating point distribution)

GIS-BASED DATA PREPARATION FOR DATA MINING (DM)

GIS facilitates the overlaying of disparate data sets using the spatial properties of the data. While GIS is a great mapping tool, it also facilitates analyses that evaluate relationships between various spatial systems in order to quantify processes and phenomena. All the datasets have been assembled into one ESRI ArcMap™ document. With the aid of the GIS application extension Hawths Analysis Tools (Beyer, 2005) and the Intersect Point Tool it contains, an ASCII xyz output file was produced for the specific purpose of a Data Mining (DM) analysis using the See5 software. The ASCII xyz output file incorporates the fully attributed data from each of the 1.88 million pixels of the model, for each of the eleven input layers.

The GIS capabilities have been combined with the power of the knowledge-based DM software, See 5. Heuristic 'data mining' is the science of computer modelling of a learning process. The DM learning process extracts patterns from large databases, whether they are concerned with organisational processes or, as in this case, natural phenomena. These patterns can be used to gain insight into aspects of the phenomena, and to predict outcomes (in this case, pixels with characteristics matching those of known landslides) as an aid to decision-making. The DM process used in this application is outlined in Figure 3.

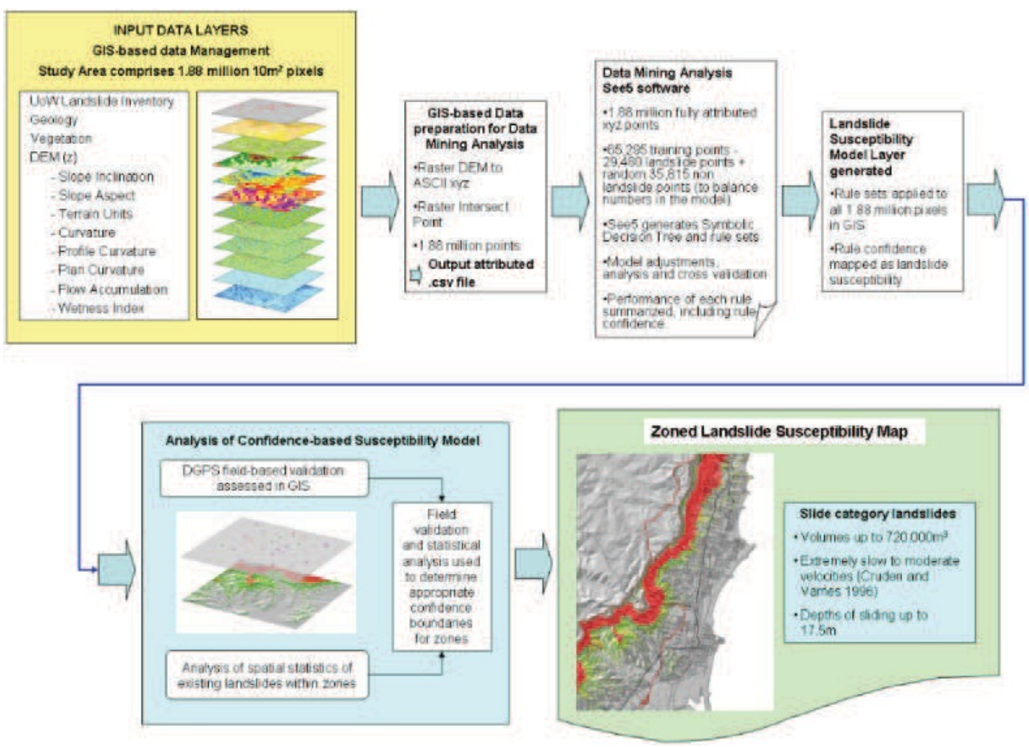

Figure 3. Flow chart outlining GIS-based and Data Mining methodology used to develop Slide Category Landslide Susceptibility Zoning Maps for the Wollongong City Council Area.

The See 5 software is a well developed commercial progression of the seminal work surrounding its predecessor, C4.5 (Quinlan, 1993). Both software products have been utilised in a diverse range of domains including, complex signal processing and control (Stirling, 2002), dynamic spatiotemporal contexts (Sun et. Al. 2006, Zulli and Stirling, 2005 and Stirling 2005), as well as numerous spatial contexts using GIS (Huang et al 2001, Xian, 2002).

Early work on this methodology, proposed by the University of Wollongong, was carried out in collaboration with Geoscience Australia (Chowdhury et al, 2002).

THE DATA MINING PROCESS

The DM approach uses a training subset of the full data set of 1.88 million pixels. The training subset includes all of the landslide xy points (29,480 points), and to balance the numerical output of the model, an approximately similar number (a whole number proportion of the remaining total non landslide points) of randomly selected non landslide xy points (35,815 points). Hence, the complete training subset (in this instance) totals 65,295 points (3.47%), each representative of the centre point of a $10m^2$ pixel, of the total 1.88 million points.

The See 5 software examines the training data and develops a symbolic Decision Tree which defines the data. Each arm of the Decision Tree defines a Rule Set (Table 1). The See 5 software examines both aspects of the training data (the landslide and non-landslide components) and cross validates the set of rules developed independently for each component with the opposing set to determine rule confidence values. The confidence values vary from -1 to 1, the non landslide 'confidence' values varying from-1 to 0, whilst the landslide 'confidence' values vary from 0 to 1. The number of rules produced by the model can be pre-set by the user and this variable determines the precision of each rule. Clearly, with more rules, the conditions defined by each rule will become more and more specific.

DATA MINING RULES

The Model, containing a number (*R*) of contextually sensitive rules, essentially maintains a judgement committee of *R* multiple hypotheses. Tow example rules from the 40 member rule set generated for this model are shown in Table 1. Each rule is ranked with a confidence factor, after evaluation and validation, by the Laplace Ratio (n-m+1)/(n+2) where n is the number of training cases that a specific rule correctly recognises and m, if it appears, is the number of cases that do not belong to the class predicted by the rule (class 1 = landslide, class 0 = not landslide). In addition, a measure of the gain potential, or lift, of each rule is also assessed, which is the ratio of each rule's confidence relative the frequency in the training set of its class prediction.

Table 1. Two example Rules from the 40 long Rule Set

Rule 3: (1629/265, lift 1.9)	**Rule 19: (1428/419, lift 1.3)**
Slope > 9.5^0	Wetness > 0.00162
Plain Curvature <= -0.14	Aspect <= 194.7^0
Geology {3, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19}	Geology = {3, 15, 16, 17}
UoW Vegetation = {4, 8, 16}	Terrain Units = 2
class 1 (landslide) [confidence 0.837]	UoW Vegetation = {0, 6, 7, 9, 11, 12}
	class 0 (not landslide) [confidence - 0.706]

When multiple rules respond in order to classify a pixel, an aggregation resolution of their individual decisions (class predictions) is formulated, using the weighted confidence of each rule. Rule sets are then applied to the entire model area. For efficiency, the trained model (represented by the rule sets) is also maintained as a compiled binary object, which can be further utilised by other programs for comparative or predictive purposes. To this end, a specialised prediction program was written to process the complete data set of 1.88 million pixels.

For every candidate pixel, the ultimate susceptibility is judged to be the aggregation of all rule confidences (positive or negative/slide or no slide) that apply, as more than one rule often applies to each pixel. Apart from this, all of the responding rules are also noted for further analysis. These predicted values and features are later merged with the pixel coordinates into an ASCII text file, which is, in turn, managed (read) by the GIS.

PERFORMANCE OF "KNOWLEDGE BASED" DATA MINING MODELLING

To aid in the post DM analyses of the modelled confidence distribution, a script was written in Visual Basic code. This code ranked the data according to decreasing model confidence and determined the cumulative percent of data each value represented in the ranked list. Figure 4 shows the distribution of DM model 'confidence' for the preferred final slide model. The graph displays two curves, the upper red curve shows the distribution of model confidence for the landslide pixels, and the green lower curve shows the distribution of model confidence for each pixel in the entire model (1.88 million points). The graph highlights the excellent performance of the modelling. High model confidence for a large proportion of actual landslides (red curve) can be noted from Figure 4. As expected, a smaller but significant proportion of the entire model area (green curve) is also predicted with a relatively high confidence.

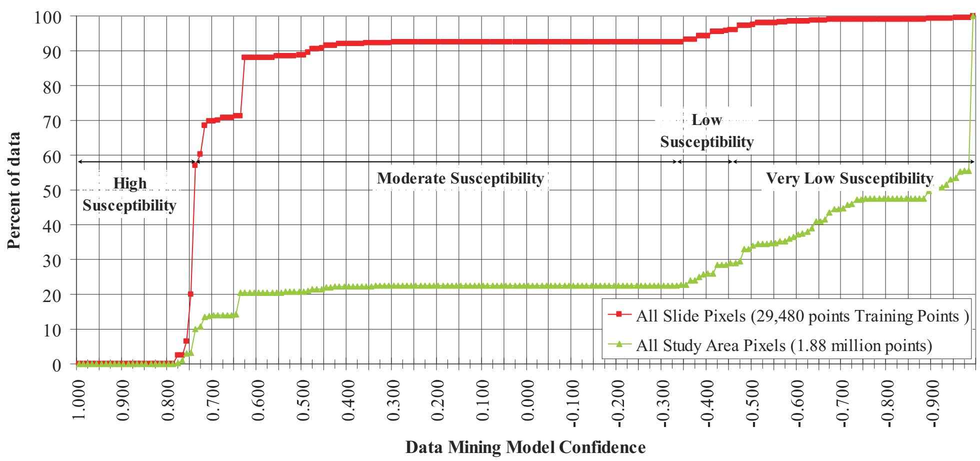

Figure 4. Distribution of model Confidence for both the landslide training points (red) and the entire model area (green) versus percent of data for the c5m75 model.

Also shown on Figure 4, are the selected data mining 'confidence' based Landslide Susceptibility zone boundaries as summarised in Table 2. The 'confidence' values used to define the Susceptibility zone boundaries are arbitrary values. A segment of the Landslide Susceptibility map is shown in Figure 5. The quantitative review process validates the methodology and ensures it is completely transparent and open for review. Field validation is described in the following section.

Susceptibility zones have been classified as (a) high susceptibility with ~ 8% of this area subject to landslides and containing 57% of the known landslide population, (b) moderate susceptibility with 4% of this area subject to landslides (contains 35% of known landslides), (d) low susceptibility with 0.85% of area subject to landslides (contains 3.7% of known landslides), and (e) very low susceptibility with <0.1% of the area subject to landsliding and yet representing 71% of the study area. The high susceptibility zone identifies over 2,300 hectares of land, outside of known landslides, as being highly susceptible to landsliding. Furthermore, the model also identifies over 13,000 hectares as having a very low susceptibility to landsliding.

Table 2. Susceptibility Classification showing % of Study Area coverage and % of Slide category landslides population per class

Susceptibility Class	C5 Model Confidence Range	% of Susceptibility Class area affected by Slides	Susceptibility Class as % of Study Area	% of Total Slide Population in Susceptibility Class
Very Low	(min) -0.98 to -0.46	0.10	70.86	4.1
Low	> -0.46 to -0.345	0.85	6.47	3.7
Moderate	> -0.345 to 0.73	4.12	9.23	35.1
High	> 0.73 to 0.81 (max)	8.12	13.44	57.1

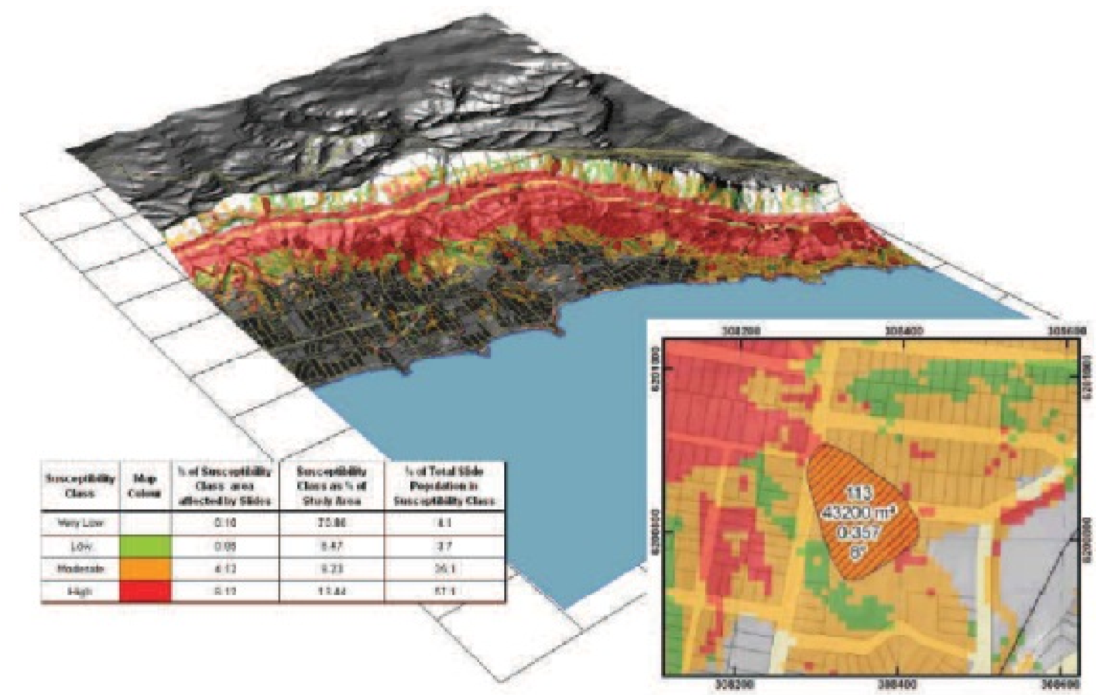

Figure 5. Segment of the Landslide Susceptibility Map. Legend as shown in Table 2. Underlying grid is 1km square and North is towards the top right diagonal of the figure. The inset shows the hazard labelling, as described below, for one landslide, Site 113.

CORRELATION BETWEEN FIELD ASSESSMENT AND MODEL PREDICTIONS

Over a 12 month period, during 18 days of field work, 759 field assessments of Landslide Susceptibility were recorded as summarised in Table 3. The field assessment work was undertaken by one engineering geologist (the first author) with 20 years of field experience in the local area and accompanied on half of the days field work by a geotechnical engineer with 20 years interstate experience (outside of the study area).

The work was completed using GPS (sub 7m resolution) and on occasions DGPS (sub 1m positioning) to record spatial positioning, and assessing the susceptibility of an area equating to a 50m diameter circle centred at the recorded location. Whilst the GIS-based modelling was completed using 10m pixels, the field assessment team concluded it was not possible to physically assess a 10m by 10m rectangular area alone, without being influenced by the surrounding terrain and conditions. It was concluded however, by both workers, that it was possible to assess, in the field, an area equating to a 50m diameter (25m radius) circle.

Numerical values of 1 to 4 were assigned to each of the field assessment locations from very low, low, moderate to high Landslide Susceptibility respectively. These assessments were completed at each location for susceptibility to slides, flows and falls (the latter two not being referred to here). Using ESRI ArcGIS™ Spatial Analyst Zonal Statistics, the mean modelled Susceptibility value within GIS generated 50m diameter circles centred on each of the GPS recorded locations was determined.

The difference, D, between the value assessed in the field and the average value predicted by the model was calculated. Th distribution of this difference is plotted in the histogram (Figure 6). Therefore the difference D = 0 indicates the count for which the correlation is perfect. Results are rounded to the nearest whole number. Almost 52% of the sites have average model results the same as they have been assessed in the field. An additional 21%, have been assessed by the computer model to be one Susceptibility class higher (the model is conservative) than that during the field assessment, and an additional 5% have been assessed to be two Susceptibility classes higher than the field assessment. A further 19% have been assessed to be one Susceptibility class less than that during the field assessment; model not conservative.

The field assessments were carried out as a field validation exercise. However, such assessments are often difficult and involve subjective judgements. Even so, the field assessments have been extremely useful in calibrating the model, particularly in the identification and delineation of susceptibility category boundaries.

Table 3. Summary of slide category field Susceptibility Assessment.

Susceptibility Class	Field Assessment	Count
Very Low	Class 1	157
Low	Class 2	203
Moderate	Class 3	193
High	Class 4	206

HAZARD ASSESSMENT

The ‘Slide’ category Susceptibility maps described above have been enhanced with additional detail regarding each landslide site and averages per zone such that they can be regarded as ‘Slide’ category Hazard maps. The Susceptibility and Hazard zones have the same boundaries. On both the Susceptibility and Hazard maps, each landslide site is identified and labelled with its own unique Site Reference Code. On the Hazard Maps each landslide is also labelled with its specific landslide frequency, landslide volume and ‘profile’ angle as shown in Figure 5. Furthermore, the average landslide frequency of occurrence for each zone has been determined. This is the main descriptor for each Hazard zone on this map.

The average landslide volume per zone has been determined with the GIS, based on the zone in which the central point of each landslide was located. The average landslide volume per zone is another descriptor for Hazard on this map, as summarised in Table 4.

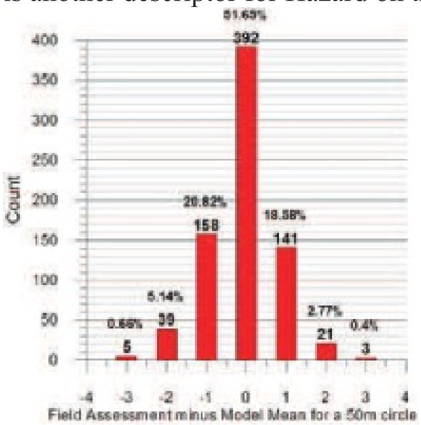

Figure 6. Difference between the Field and Modelled Landslide Susceptibility values.

Landslide Frequency has been calculated from the total number of known recurrences at each landslide site. The specific landslide frequency for each landslide appears as the third label for each landslide. The average annual landslide frequency has been determined for all landslides within each Hazard Zone and is another descriptor for Hazard on this map, as summarised in Table 4. Figure 2 displays a summary of the temporal distribution of landslides within the UoW Landslide Inventory and highlights the scarcity of data relating to landslides prior to 1950. The average distribution of landslide frequency between the years 1880 to 2006, and for the period 1950 to 2006 is shown in Table 4. The later period is based on more complete data and is considered to be more reliable.

The 'profile angle' of each Slide Category landslide has been determined by digitising a point mid way along the rear main scarp and at the toe and querying the elevation at each of these points using a 2m DEM elevation grid. The profile angle of known landslides is considered important as it has implications for landslide mobility. It is also very useful to consider the distribution of the profile angles and this is included here. The average 'profile angle' is 17º. The profile angle for each landslide is shown as the fourth label for each landslide.

Table 4. Summary of Hazard Assessment based on Landslide Inventory.

Hazard Description	Landslide Annual Average Frequency (1880 - 2006)	Landslide Annual Average Frequency (1950 - 2006)	Maximum Landslide Volume (m^3)	Average Landslide Volume (m^3)
Very Low	0.0098	0.0165	36,300	3,500
Low	0.0102	0.0172	4,700	1,450
Moderate	0.0125	0.0221	45,000	5,700
High	0.0144	0.0247	720,000	28,700

SUMMARY

A comprehensive, large scale regional GIS-based Landslide Inventory has been used with other GIS data and Data Mining techniques to develop a transparent, entirely data-driven Landslide Susceptibility and Hazard model. The modelling methodology is flexible, quantifiable and non-subjective and readily allows the generation of GIS-based map outputs, the scale of which are determined by input data alone. The modelling technique is already being applied to other areas and at other scales within Australia. The authors look forward to reporting the results of this continuing work at a later time.

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Landslide susceptibility and landslide hazard zoning in Wollongong

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Keywords: Landslide, Inventory, Susceptibility, Hazard, Zoning, GIS.

ABSTRACT

This paper describes 'knowledge-based' data-mining techniques, developed for the assessment of landslide susceptibility and hazard with particular reference to its application in the Wollongong area. Large scale maps of geology and a comprehensive Landslide Inventory with regional coverage have been prepared. GIS-based derivatives of the digital elevation model including slope, geomorphology, curvature, flow accumulation and wetness index have been developed. Model performance has been assessed as part of a refined methodology for validation, including field inspections. Susceptibility zones outside known landslide areas have been classified as (a) high (b) moderate, (c) low and (d) very low susceptibility. Results show the high susceptibility zone covers 10% of the study area and contains 60% of known landslides, the moderate zone covers 12% of the study area and contains 32% of known landslides, the low zone covers 6.4% of area and contains 3.3% of known landslides and the very low zone covers 71% of the study area and contains 4% of the landslides. The susceptibility maps have been upgraded to hazard level maps with identification of individual zone landslide likelihoods, specific landslide frequency, volume and 'profile' angles. The paper concludes with a preliminary landslide susceptibility map for a segment of the Sydney Basin Region developed using the methodology described in this paper.

1 INTRODUCTION AND STUDY AREA

This paper complements another by the same authors recently presented and published in the proceedings of the First North American Landslide Conference (Flentje et al, 2007) and is herein referred to as the companion paper. Together, both papers outline the methodology, GIS-based datasets and zoning maps that have been developed by the University of Wollongong landslide research team (LRT) for the assessment of landslide susceptibility and hazard in the Wollongong Area. The numbers reported herein present updated information to that reported in the companion paper. The main element of this methodology comprises a comprehensive large scale GIS-based Landslide Inventory with regional coverage. The landslide inventory contains 3 main types of landslides - falls, flows and slides. Additional GIS-based data sets, including large scale geology, vegetation, a 10m pixel Digital Elevation Model (DEM) and various derivatives have also been developed. Data-Mining, and Machine-Learning techniques (Quinlan 1993) are used to develop the Susceptibility classification. As these elements have been discussed in the companion paper, they are only mentioned briefly herein.

Landslide frequency information has been determined from the Landslide Inventory. This work has been undertaken over an extensive period and yet it is generally in accordance with the principles of the recently developed Guidelines on Landslide Zoning published by the Australian Geomechanics Society in March 2007 (AGS 2007a) of which the first author is a Working Group member.

The city of Wollongong is located on a narrow coastal plain approximately 70km south of Sydney in the state of New South Wales (NSW), Australia. The population of the Wollongong area is approximately 200,000 people. The plain is triangular in shape with a coastal length of 45km and is up to 17km wide in the south and extends to its apex in the north near the suburb of Thirroul (figure 1). The coastal plain is bounded to the north, west and south by an erosional escarpment of Neogene Age ranging in height from 300 m up to 500 m.

Processes and mechanisms of slope failure are controlled in Wollongong by factors such as stratigraphy, geotechnical strength parameters, hydrogeology, geomorphology, slope inclination pore water pressure, rainfall and the actions of man. Prolonged and/or intense rainfall is typically the trigger for significant landsliding. The average annual rainfall for Wollongong varies from 1200mm on the coastal plain and up to 1600mm or more along the top of the escarpment.

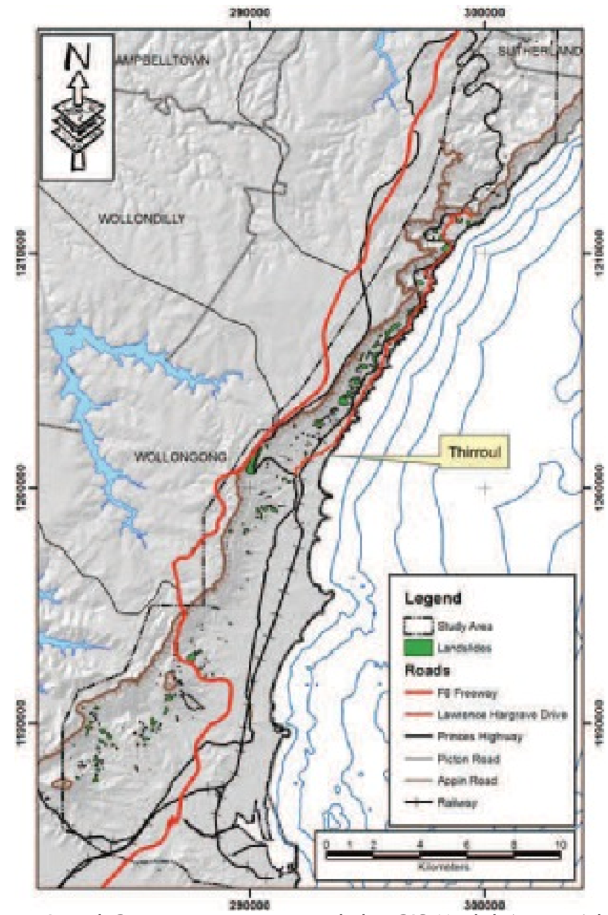


Figure 1. The Wollongong Local Government area and the GIS Model Area with known landslides.

2 WOLLONGONG REGIONAL LANDSLIDE INVENTORY AND OTHER GIS-BASED DATA SETS

The Landslide Inventory, developed over the last decade, comprises a relational MS Access and ESRI ArcGIS^{TM} Geodatabase with over 70 fields of information for each landslide site in related tables (Flentje and Chowdhury 2005). Each landslide is referenced by a key Site Reference Code. The Landslide Inventory currently contains 586 landslides with a total of 976 landslide events (including first time occurrences and multiple recurrences at some sites). The 586 landslides comprise 42 falls, 43 flows and 491 slides in accordance with the Cruden and Varnes 1996 classification.

In addition to the GIS-based landslide inventory, other GIS-based data sets have been developed for this project including engineering geological mapping, data acquired through external agencies and data sets generated by the GIS software using the Digital Elevation Model. In total, ten GIS-based data sets have been compiled. The data sets include:

- Geology (21 variables representing the mapped geological formations)
- Vegetation (15 variables representing the mapped vegetation categories)
- Slope Inclination (continuous floating point distribution)
- Slope aspect (continuous floating point distribution)
- Terrain Units (buffered water courses, spur lines and other intermediate slopes)
- Curvature (continuous floating point distribution)
- Profile Curvature (continuous floating point distribution)
- Plan Curvature (continuous floating point distribution)
- Flow Accumulation (continuous integer)
- Wetness Index (continuous floating point distribution)

The Data Mining (DM) process has been discussed in the companion paper and hence will not be repeated here. Suffice to say that the process involves the use of known landslide areas as one half of the model training, the other half comprising randomly selected points from within the model area outside known landslide areas. Using a fully attributed data set representing all the above data sets, the DM analysis undertakes a process of pattern recognition and develops a rule set which defines the data set. This process is automated by the DM software and is confined by several user defined parameters, such as the number of rules required and the number of occurrences required before a rule is generated, etc. Each rule is assigned a numerical confidence value defined by the Laplace ratio. Rules which relate to the presence of a landslide are assigned positive confidence values and rules which indicate the non-presence of a landslide are assigned negative confidence values. The rule set is then re-applied within the GIS software using the ESRI Model Builder extension to produce the Susceptibility grid with floating decimal point values ranging from 1 to -1.

3 ANALYSIS OF "KNOWLEDGE BASED MODEL" AND LANDSLIDE SUSCEPTIBILITY ZONING

To aid in the post DM analyses of the Susceptibility grid and particularly to aid the definition of credible Susceptibility Zone categories and zone boundaries, a script was written in Visual Basic code to produce the distributions shown in Figure 2. This code ranked the complete 1.88 million data points and separately all the landslide pixels (29,480 points) according to decreasing model confidence and determined the cumulative percent each data value represented in the ranked list. Figure 2 shows the distribution of DM model 'confidence' for the preferred final slide model. The graph displays two curves, the upper dashed curve shows the distribution of model confidence for the 'known landslide' pixels, and the lower dash-dot curve shows the distribution of model confidence for each pixel in the entire model (1.88 million points). Also shown on Figure 2, are the landslide Susceptibility zone boundaries. The confidence values used to define the Susceptibility zone boundaries are arbitrary values. However, the simple logic has been followed whereby the maximum numbers of known landslides are incorporated into the highest Susceptibility zones, whilst at the same time keeping the extent of these highest susceptibility zones to a minimum.

The graph highlights the excellent performance of the modelling with approximately 70% of the known landslides being identified with a high model confidence. This same strong result is also reflected for the entire model area where a smaller but significant proportion of the entire model area (~10%) is also predicted as being highly susceptible to landsliding with a relatively high confidence.

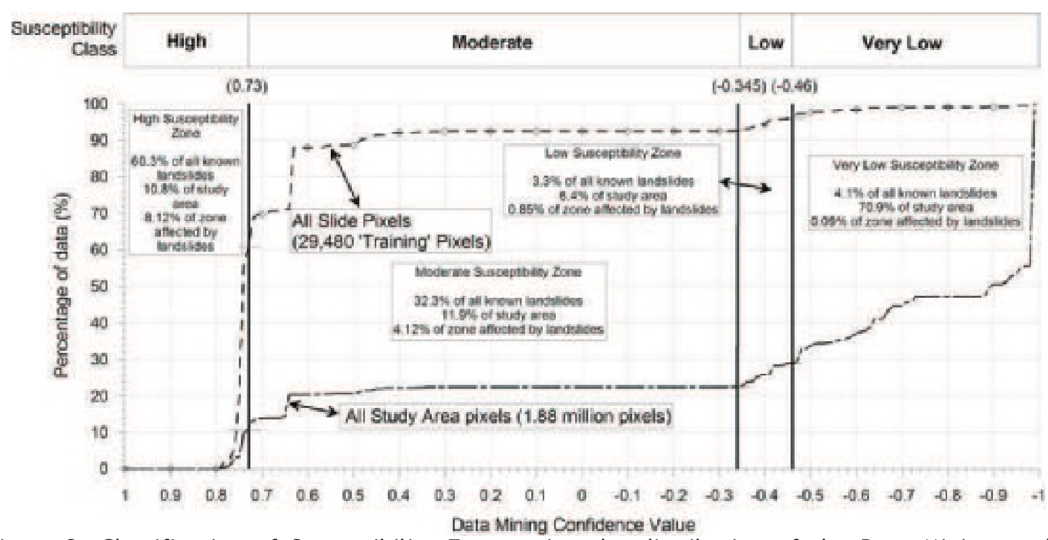


Figure 2. Classification of Susceptibility Zones using the distribution of the Data Mining model confidence for both the Training data and the complete model area.

This quantitative 'review' validates the methodology to a significant extent, and ensures that the process of susceptibility zone classification it is completely transparent and open for review. Some field validation work has also been undertaken and this has been reported in the companion paper.

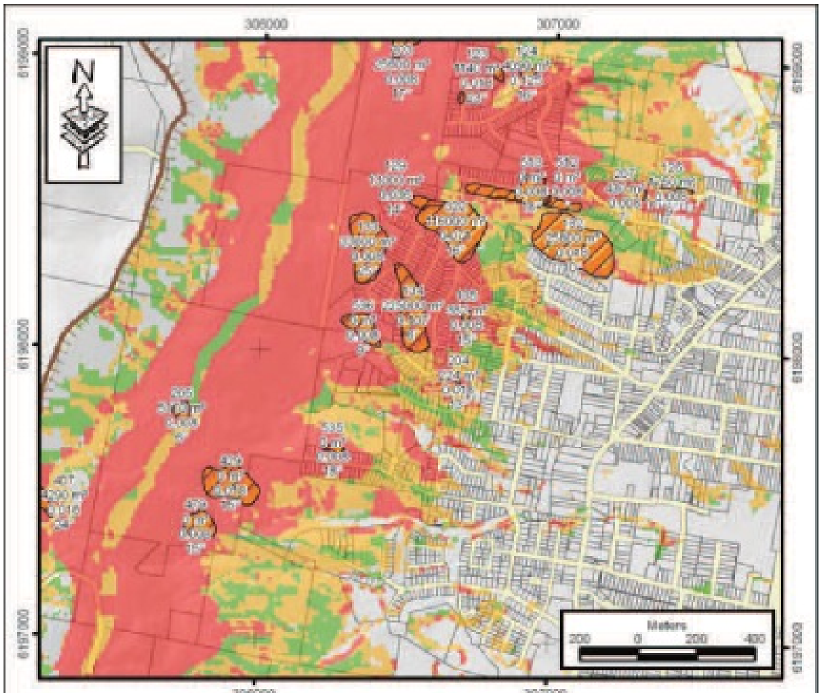
In summary, the susceptibility zones have been classified as (a) high susceptibility with 8.12% of this area subject to landslides and containing 60.3% of the known landslide population, (b) moderate susceptibility with 4.12% of this area subject to landslides (contains 32.3% of known landslides), (d) low susceptibility with 0.85% of area subject to landslides (contains 3.3% of known landslides), and (e) very low susceptibility with 0.09% of the area subject to landsliding (contains 4.1% of known landslides) and yet representing 70.9% of the study area. These statistics are compatible with Table 4 of AGS (2007a). The high landslide susceptibility zone identifies over 2,300 hectares of land, outside of known landslides, as being highly susceptible to landsliding. Furthermore, the model also identifies over 13,000 hectares as having a very low susceptibility to landsliding.

4 LANDSLIDE HAZARD ASSESSMENT AND ZONING

The spatial frequency of landsliding has been determined for each Susceptibility Zone as summarised in Table 1 and thereby giving each zone Hazard status. Here, the percentage of each zone affected by landslides has been normalised and divided by the number of years represented by the coverage of the Landslide Inventory. In this case, the Wollongong landslide Inventory covers a period of 126 years, 1880 to 2006. Other techniques of assessing annual likelihoods of landsliding (i.e. process rates) are being investigated.

Table 1. Summary of landslide zoning frequency and volume.

Hazard Description	Map Colour	% of Zone affected by Slides (S)	Zone area as % of Study Area	% of Total Slide Population in Hazard Zone	Landslide Annual Average Frequency (1950 - 2006)	Relative Susceptibility of Zone (S/Stotal) = Sr	Relative Annual Likelihood (Hazard) (Sr/T) where T = 126 years	Maximum Landslide Volume (m³)	Average Landslide Volume (m³)
Very Low		0.10	70.86	4.1	1.65E-02	7.36E-03	5.84E-05	36,300	3,500
Low		0.85	6.47	3.7	1.72E-02	6.46E-02	5.13E-04	4,700	1,450
Moderate		4.12	9.23	35.1	2.21E-02	3.12E-01	2.48E-03	45,000	5,700
High		8.12	13.44	57.1	2.47E-02	6.16E-01	4.89E-03	720,000	28,700



Hazard Description	Map Colour	% of Hazard Zone area affected by Slides (S)	Hazard Zone area as % of Study Area (Sa)	% of Total Slide Population in Hazard Zone (Sp)	Relative Annual Likelihood (Hazard) (Sr/T)
Very Low		0.10	70.86	4.1	5.84E-05
Low		0.85	6.47	3.7	5.13E-04
Moderate		4.12	9.23	35.1	2.48E-03
High		8.12	13.44	57.1	4.89E-03

Figure 3. Segment of the Landslide Hazard Map.

The landslide hazard zoning maps have been enhanced with additional detail regarding landslide volume, frequency and travel distance (Table 1 and Figure 3). This information appears as unique landslide site labels for each site and with text boxes appearing on the AO map sheet frames outlining the distributions and averages of these values for each of the individual hazard zones.

On both the landslide Susceptibility and landslide Hazard maps, each landslide site is identified and labelled with its own unique Site Reference Code. On the Hazard maps, the label for each landslide also includes its volume (m^3) as the second label component. Landslide Frequency has been calculated from the total number of known recurrences at each landslide site as recorded in the Landslide Inventory. The specific landslide frequency for each landslide appears as the third label for each landslide.

The 'profile angle' appears as the fourth label for each landslide site. This profile angle has been determined by digitising a point mid way along the rear main scarp and at the toe and querying the elevation at each of these points using a 2m DEM elevation grid. The profile angle of known landslides is important as it has implications for landslide mobility. It is also very useful to consider the distribution of the profile angles (the average is 17^o) and this is also featured in one text box.

5 PRELIMINARY SYDNEY BASIN WIDE SUSCEPTIBILITY ZONING

To further investigate and validate the DM methodology, it is currently being applied to the entire Sydney Basin region and we are currently assembling data sets to refine this modelling process. At 25m pixel resolution, this involves a GIS-based raster grid of approximately 220 million pixels not withstanding that this is at a resolution significantly coarser than is preferable. Using similar data sets as described above for the Wollongong study (at 25m pixel resolution), a preliminary landslide Susceptibility model (proof of concept ONLY) has been developed for a trial area of the Sydney Basin region extending from Sydney Harbour in the south and extending north to include Lake Macquarie and the southern Newcastle area. This trial area involves a raster grid of approximately 15 million pixels.

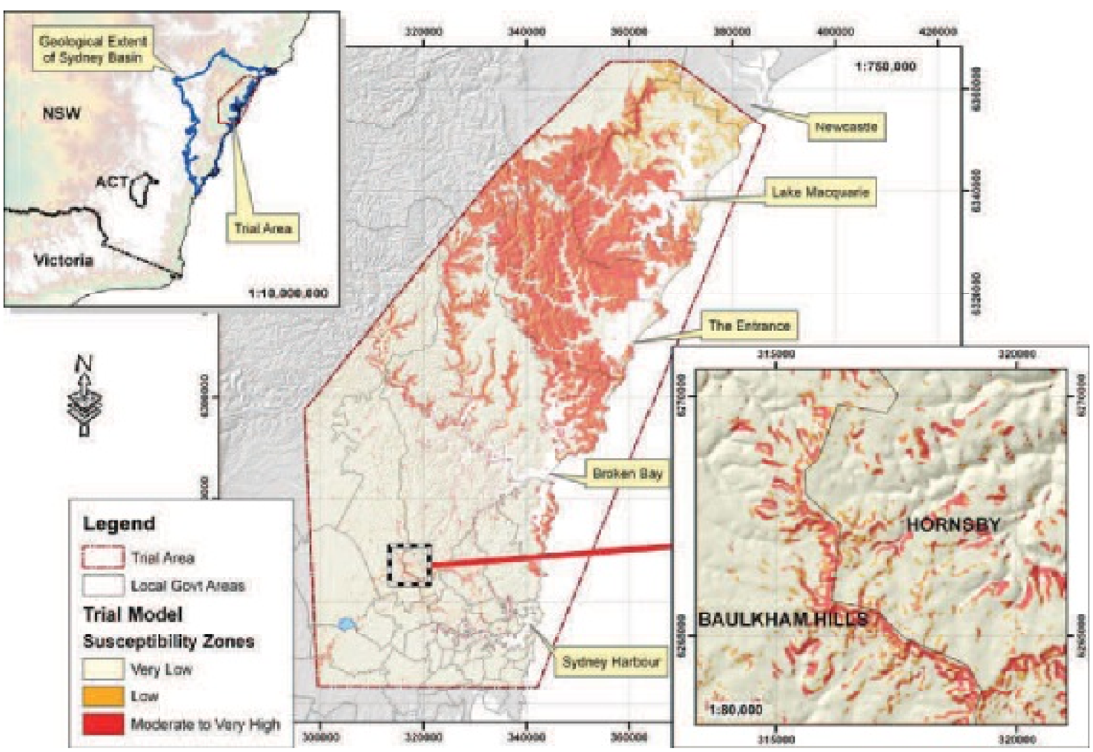


Figure 4. Preliminary Susceptibility Zoning for the Sydney to Newcastle trial area.

The same regional Landslide Inventory, complemented by additional coverage of the Sydney and Central Coast region provided by the Geoscience Australia's National Landslide database (downloaded from the GA online web portal), has been used to develop the 'training data set'. This combined inventory includes 575 'slide' and 'flow' category landslides within the geological extent of the Sydney Basin. This training data, and hence the output model, will be greatly improved as the Landslide Inventory coverage of this area is enhanced and we are working towards that.

Over the next 1 - 2 years, as the GIS-based data sets are assembled and refined and as the Landslide Inventory coverage is developed and refined with external assistance, we are confident that this wider area regional modelling will be successful. This type of regional modelling, which can be carried out at quite high resolution (large scale) given input data of sufficient resolution, will assist decision makers determine which areas need further landslide zoning investigations, as are also recommended by the guidelines published in AGS 2007.

6 SUMMARY

A comprehensive, large scale regional GIS-based Landslide Inventory has been used with other GIS data and Data Mining techniques to develop a transparent, entirely data-driven non-statistical Landslide Susceptibility and Hazard model. The modelling methodology is flexible, quantifiable and non-subjective and readily allows the generation of GIS-based map outputs, the scale of which are determined by input data alone. The modelling technique is already being applied to other areas and at other scales within Australia. A preliminary model of a wider area application is also presented. It is important to note that for the susceptibility zoning, only landslide outlines and landslide classification is required, which simplifies the requirements of the landslide inventory for this level of mapping. The authors look forward to reporting more and detailed results of this continuing work at a later time.

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Rev No.	Author	Reviewer		Approved for Issue		
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0	Ben Rouvray	Peter Stone	*Peter Stone*	Peter Stone	*Peter Stone*	
1	Ben Rouvray	Peter Stone	[signature]	Peter Stone	[signature]	30/6/10

Appendix G

Management Issues

Issue ID	Location	Specific Location	Issue Description	Keywords	Issue Cross-Ref
1	Bulli Beach	Northern end of beach, walkway to the baths.	Blockage of the culvert under the walkway has stopped the transport of sediments north to Sandon Point. The culvert used to act as a sand bypass.	Sediment	5
2	Bulli Beach		Sand accretes in the children's baths. Council regularly cleans the sediment from the baths.	Human Usage	5
3	Bulli Beach		The rock shelf near the baths used to be good fish habitat that was popular for fishing. However, the northerly transport of windblown sand has caused this reef habitat to become covered in sand.	Ecology	5
4	Bulli Beach		Introduced animal species present in dune vegetation including rabbits, rats and snakes.	Ecology, Human Usage	10
5	Bulli Beach		Dune stabilisation works have resulted in changes to local sedimentary and hydrodynamic (wave) processes, including negative impacts in terms of sedimentary accretion in the northern end of the beach, with secondary impacts on recreation and beach safety resulting.	Sediment, Human Usage	1, 2, 3, 4
6	Bulli Beach		Erosion is affecting the cliff face behind the baths, exposing the roots of the pine tree on the cliff top.	Sediment, Ecology	
7	Bulli Beach		Sightlines to the beach are impaired by the dunes and associated vegetation. A viewing tower has been established in an effort to address this issue. Council also occasionally trims the dune vegetation.	Human Usage	5
8	Bulli Beach		The SLSC members have difficulty transporting equipment on and off the beach due to the presence of higher dunes. Council clears a path through the dunes approx. two times per season and the Club has purchased a 4WD vehicle to assist in transport of equipment.	Human Usage	5
9	City Beach		Issues with the windblown transport of sand by southerly winds from the beach and dunes and over to Marine Parade and the Lions Park area. Historically this has consisted of such large volumes of sand as to necessitate the closure of Marine Parade and require Council clean up. However, in more recent years, there was only a couple of inches of sand transported.	Sediment, Human Usage	
10	City Beach		Introduced animal species present in dune vegetation including rabbits, foxes, rats and snakes.	Ecology	4

Issue ID	Location	Specific Location	Issue Description	Keywords	Issue Cross-Ref
11	City Beach		Use of informal beach access points across the dunes south of Crown Street, e.g. at Banks Street.	Human Usage	
12	City Beach		Historic undermining and damage to the old surf club necessitating temporary emergency protection works, the laying of rock armouring and ultimately relocation of the surf club.	Human Usage, Coastal Hazards	
13	Port Kembla Beach		After the beach face is eroded due to a storm event, the beach can become impassable by foot on high tides.	Human Usage, Coastal Hazards	
14	All		Historic formal and informal dumping of waste materials in various locations along the shoreline.	Human Usage	
15	All		Introduced weed species in the dune vegetation (e.g. Bitou Bush).	Ecology	
16	Whartons Creek		Undercutting of beach access points due to entrance break out.	Sediment, Human Usage	
17	South Thirroul		The sea cliff is slumping here from Corbett Street and further north.	Geotechnical,	18
18	South Thirroul	3 Craig Street	The historic DH Lawrence house Wyewurk is at risk due to erosion of the cliff at this location.	Heritage	17
19	Fairy Meadow Beach		Subject to erosion due to storms that result in a high erosion scarp.	Sediment	
20	Fairy Meadow Beach		Foreshore walkways are vulnerable to coastal blow-outs.	Sediment, Human Usage	
21	All		Inadequate resources available for dune management.	Ecology	
22	Austinmer, Thirroul		Historic loss of foreshore infrastructure due to coastal hazards during storm events, for example: - Car park behind Thirroul Beach, 1976/77 - Toddlers rock pool, 1998 - Walkways washed away, May 2009.	Sediment, Human Usage	
23	Austinmer, Thirroul		Complete loss of sand from the beach due to storm bite (i.e. down to the underlying clay).	Sediment, Human Usage	
24	East Corrimal	Parker Road Arm of Towradgi Lagoon	Foreshore inundation (private properties) during high tide.	Coastal Hazards	
25	All		There is no specific reference to management of coastal hazards (e.g. erosion risk) in Council's existing Emergency Management Response Plan.	Coastal Hazards	

Issue ID	Location	Specific Location	Issue Description	Keywords	Issue Cross-Ref
26	All	Tidal rock pools	The nine tidal rock pools (baths) along the coastline are all showing signs of decay, thought to be due to the combined effects of aging on the structure and coastal hazards. Many of these pools have some heritage significance.	Coastal Hazards, Human Usage, Heritage	
27	All	Tidal rock pools	Sand accretion is an issue requiring regular maintenance.	Sediment, Human Usage	
28	Warilla Beach		This beach is generally quite vulnerable to coastal hazards during storm events.	Coastal Hazards	
29	All		The historic foreshore building lines currently applied by Council require re-assessment with up to date information to assist in land use planning.	Planning	
30	All		At present a policy instrument guiding the type and manner of development in the coastal zone is lacking.	Planning	
31	Sandon Point	Surf Life Saving Club	Can be subject to inundation due to waves when ocean water levels are high (via the roller doors on the southern side of the building).	Coastal Hazards	
32	All		The type of vegetation used for dune stabilisation works grows quite high and obscures sight lines to the beach.	Human Usage	
33	Wollongong	Between the cutting and the Continental Pool.	Undermining of the seawall protecting the coastal cycleway.	Coastal Hazards, Human Usage	34
34	Wollongong	Between the cutting and the Continental Pool.	Overtopping of the cycleway during an easterly swell.	Coastal Hazards, Human Usage	33
35	All		There are a number of heritage seawalls, wharves and other structures along the coastline, some of which are subject to decay due to affectation by coastal processes.	Heritage	
36	Coalcliff	Coalcliff Colliery	The heritage mine shaft under the sea cliff bridge will likely be vulnerable to sea level rise.	Heritage	
37	Wollongong	Wollongong Harbour	The heritage listed conservation area in this location is vulnerable to coastal processes. Overtopping and sea level rise were raised as potential issues.	Heritage	
38	North Beach		The historic tramway and associated seawall is collapsing. These items are listed on the State Heritage Register.	Heritage	

Issue ID	Location	Specific Location	Issue Description	Keywords	Issue Cross-Ref
39	Fairy Meadow		The historic Puckey's saltworks and Seafield House are both at risk due to coastal processes.	Heritage	
40	All		There are a number of sites with Aboriginal cultural heritage significance that are located in the coastal zone and are vulnerable to coastal processes. Some of these are becoming exposed due to erosion at present, and there are concerns as to the ongoing effects, particularly in a climate change context.	Heritage	
41	All		Council does not currently have in place a strategy for dealing with the impacts of coastal processes on heritage items.	Heritage	
42	All		Sand drift is a big problem, particularly in Bulli and Bellambi.	Sediment	
43	All		Bitou Bush is outcompeting native species in the dune systems. In some locations the Bitou Bush has grown fairly high and there is dead vegetation underneath - this represents a fire hazard.	Ecology	
44	All		Inadequate resources are available for dune stabilisation and maintenance works.	Ecology	
45	Warilla Beach		Historic sand mining activities have depleted the dunes at this location, with the result that intervention is required to protect the shoreline.	Sediment	
46	All		High dunes and dune vegetation obstruct views of the ocean and impact on visual amenity.	Human Usage	
47	All		There is conflict between residents, with some being in favour of dune restoration works (for ecological and foreshore protection purposes) and others being against dune restoration works (for visual amenity reasons).	Human Usage	
48	All		There are not enough recreational facilities, particularly along the coastal walkway. Desired facilities include seating and bubblers.	Human Usage	
49	All		Rubbish accumulates on the beaches.	Human Usage	
50	All		There is on occasion conflict between off-leash dog walkers and other beach users in relation to safety and other animal management issues. Hot spots include Austinmer and Coledale and where there is a transition between on-leash and off-leash areas.	Human Usage	

Issue ID	Location	Specific Location	Issue Description	Keywords	Issue Cross-Ref
51	Towradgi		Loss of the swimming area at East Corrimal Beach has put additional pressure on the rock pool at Towradgi.	Human Usage	
52	All		There are not enough bag dispensers for the disposal of dog wastes.	Human Usage	
53	All		Vandalism is an issue for recreational facilities.	Human Usage	
54	Towradgi		The accumulation of sand in the rock pool increases the risk to public safety where patrons dive into the pool.	Human Usage	
55	All		There is at times conflict between the different user groups (e.g. walkers and cyclists) using the coastal walkway.	Human Usage	
56	Thirroul		There is inundation of parts of Bath Street, Thirroul, during king tides. At these times the water brings with it sand, which remains deposited on the street.	Coastal Hazards, Human Usage	
57	Lake Illawarra		Lake Illawarra cannot be accessed from the open ocean by a vessel with a draught of approx. 5m (thought to be due to the ingress of sand at this location).	Human Usage	
58	All		There are concerns regarding the lack of information provided by Council and transparency, particularly in relation to large coastal developments.	Human Usage	
59	All		There are concerns regarding development intensities in vulnerable coastal areas, particularly where these areas are subject to hazards of a long duration.	Human Usage	
60	Thirroul		Disturbance related to local youths camping in the bush behind the surf club.	Human Usage	
61	Thirroul, Windang		Disturbance related to the use of dirt bikes.	Human Usage	
62	All		Pest species are an issue. Rabbits are a common problem. Deer have been observed as far south as Corrimal and Bellambi.	Ecology	
63	All		There are concerns regarding the exposure of heritage sites, particularly sites of cultural significance to the local Aboriginal people, due to coastal processes.	Cultural Heritage, Coastal Hazards	

Issue ID	Location	Specific Location	Issue Description	Keywords	Issue Cross-Ref
64	All		There are concerns regarding the historic management of Aboriginal cultural heritage sites, particularly where these have become exposed either by coastal processes or during works. As a result, there is a general lack of confidence in the ongoing management of heritage issues.	Cultural Heritage, Coastal Hazards	65
65	All		There is a historic lack of protection of vulnerable Aboriginal heritage sites.	Cultural Heritage	64
66	All		There are issues associated with the way the Aboriginal Community has been engaged and consulted with.	Cultural Heritage	64
67	All		It is important to recognise and conserve sites of European heritage significance.	Cultural Heritage	
68	Wollongong Harbour		Siltation affects access in some parts of the Harbour.	Sediments	
69	Wollongong Harbour		Seiching represents a hazard to access and general safety.	Coastal Hazards	
70	Austinmer		There is periodic siltation of the small boat ramp in Austinmer near the Headlands Hotel.	Sediments, Human Usage	
71	All		There is insufficient access to slipway services for boaters in the study area.	Human Usage	
72	All		There are not enough boat launching ramps in the study area.	Human Usage	
73	All		The remains of the historic jetties and wharves located in the north of the study area have historically been a hazard to surfers, although it is not sure if this continues to be an issue.	Human Usage	
74	All		Opportunities for certain growing tourism markets have not been fully realised, such as: - Whale watching, - Health tourism, - Drive tourism, and - Pet tourism.	Human Usage	
75	All		The limited number of tourism precincts identified for Wollongong limits the potential expansion of the tourism industry.	Human Usage	
76	Wollongong		There is a need to consolidate existing foreshore eating areas to form a walking food precinct.	Human Usage	

Issue ID	Location	Specific Location	Issue Description	Keywords	Issue Cross-Ref
77	All		There is totally inadequate boating infrastructure available.	Human Usage	
78	All		Educational tourism opportunities are not being realised (such as for rock pool tours or other marine activities).	Human Usage	
79	All		There is a need to capitalise on the unique landscape features and visual experiences of the landscape (e.g. via lookouts).	Human Usage	

Appendix H

Storm Erosion Hazard and Stability Zones

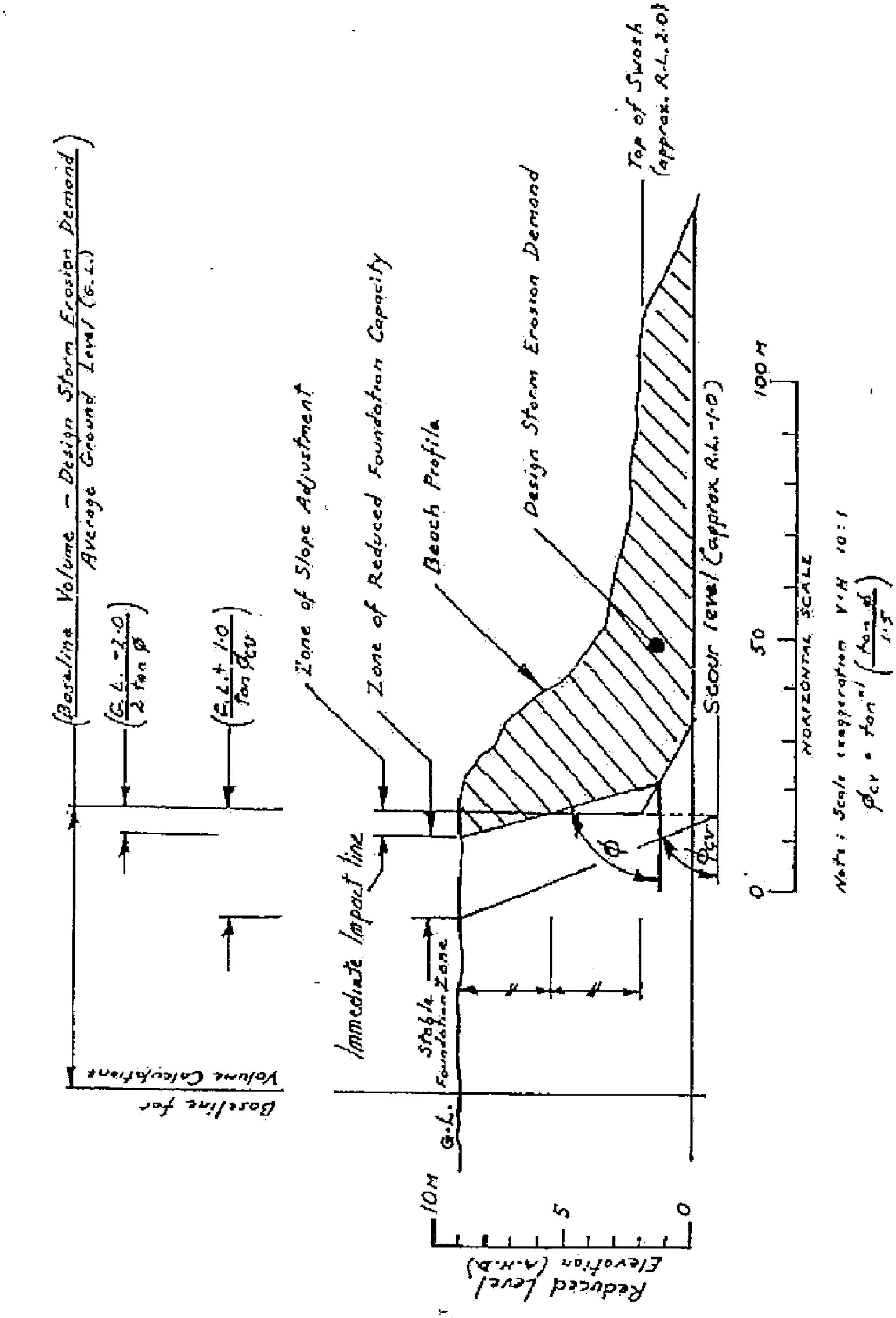

FIGURE H.1
STORM EROSION HAZARD AND STABILITY ZONES
Neilson *et al* (1992)