A Thematic Gap Analysis of the Tasmanian Geoconservation Database: Glacial and Periglacial Landform Listings in the Tasmanian Wilderness World Heritage Area

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November 2014

Nature Conservation Report Series 14/4

Citation: Sharples, C. (2014) *A Thematic Gap Analysis of the Tasmanian Geoconservation Database: Glacial and Periglacial Landform Listings in the Tasmanian Wilderness World Heritage Area*; Resource Management and Conservation Division, Department of Primary Industries Parks Water and Environment, Hobart, Nature Conservation Series 14/4.

ISSN 1838 7403 (web)

Cover Photo: Sorted stone terraces arranged symmetrically around the summit of The Boomerang (TWWHA) are produced by currently-active periglacial processes which are also partly controlled by differing exposure to wind (and possibly precipitation). Photo by C. Sharples.

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Summary

The significance of the glacial and periglacial landforms of the Tasmanian Wilderness World Heritage Area (TWWHA), with their importance in elucidating the climatic and landscape history of southern temperate regions, were key values underpinning the inscription of the TWWHA on the UNESCO World Heritage list in 1982 and in an enlarged form in 1989.

In addition to a bedrock record of Precambrian and Permo-Carboniferous glacial periods, Tasmania has extensive landform and sediment geoheritage representing multiple Cenozoic (Pleistocene and probably some Tertiary-age) glacial and periglacial process phases. Much of this cold-climate geoheritage occurs in the mountainous and high-precipitation regions of western Tasmania, with the result that the landforms and scenery of the TWWHA are strongly characterised by Pleistocene glacial and periglacial features.

A large number of TWWHA glacial and periglacial features have been listed on the Tasmanian Geoconservation Database (TGD), both as individual features and as assemblages or glaciated regions. However, the listing of such sites on the TGD has occurred in a relatively *ad hoc* fashion, based on expert identification of notable features but without any properly systematic survey and assessment of the full extent and diversity of relevant features in the TWWHA or Tasmania as a whole. The lack of any properly systematic glacial and periglacial geoheritage assessment can be at least partly attributed to the scale of the task that would be required to do so, given that there is no consolidated database in existence that draws together records and mapping of Tasmania's glacial and periglacial landforms; instead this information remains scattered amongst numerous reports, publications and maps of differing ages, formats and accessibility.

The purpose of the project reported on here was to undertake a gap analysis of the TGD in order to identify any gaps or biases in the listing of glacial and periglacial features in the TWWHA on that database. In the course of doing so, this work has not only identified relevant gaps and biases in the listing of glacial and periglacial sites on the TGD, but has also identified key gaps in both knowledge of these features, and in capacity to assess and manage them.

As a basis for undertaking a gap analysis, a simple high-level classification was devised which classifies Tasmanian Cenozoic glacial and periglacial landforms by age, characteristic georegion and feature class or type. The purpose of this was to assess the degree to which the TGD lists features characteristic of the full spatial, temporal, feature and process diversity of TWWHA glacial and periglacial geodiversity.

It was observed that glacial and periglacial features are listed on the TGD at one of three levels, namely as predictive regions (areas in which relevant features may occur, but which do not identify specific features or assign any significance to such features as may be present); assemblages or parent sites (areas containing a complex of inter-related features that are assessed as having significant geoheritage value); and as specific features (individual features assessed as having significant geoheritage value).

Notable biases and gaps have been identified in the representation of the glacial and periglacial geodiversity of the TWWHA at each of the three levels of listing. Few systematic patterns were identified in the gaps and biases, which are probably largely related to differences in the degree of research attention that has been paid to certain types and certain areas of glacial and periglacial assemblages and features as compared to others. The strongest gap pattern identified is a notable paucity of information about relict and present-day periglacial processes and features in the TWWHA, and hence of representation of such features in listings on the TGD.

It is possible to propose a remedy to the numerous gaps at that level of TGD listing, namely that predictive regions be listed over any and all TWWHA areas where glacial or periglacial landforms are known or thought likely to exist (subject to the use of predictive regions in the TGD being continued; see below).

However short of simply listing all known glacial and periglacial features in the TWWHA (for which an argument is possible – see below), it is not possible to identify appropriate and properly representative sites at the specific feature or assemblage levels that should be listed or de-listed in order to remedy the gaps and biases in the TGD at these levels. This is because doing so requires the ability to compare the sites listed (features and assemblages) against the full diversity and distribution of actual features and assemblages known to exist in the TWWHA and elsewhere in Tasmania. Such an analysis is currently a difficult task because of significant gaps in knowledge – particularly in relation to periglacial features in Tasmania – and because (as noted above) the relevant records and detailed maps of known glacial and periglacial phenomena in Tasmania are not available in any consolidated form, but rather are spread across a wide variety of reports, publications and maps of differing ages, resolution, format and accessibility, which would make a reasonably rigorous comparative assessment to identify good suites of representative features a very difficult task.

A number of additional problems with existing TGD listings of glacial and periglacial features were also identified in the course of this analysis, namely:

- TGD listings of glacial and periglacial assemblages and parent sites generally provide few details of the specific features that constitute the sites (although there is capacity to store more information in TGD listings). This is in principle appropriate since the function of the TGD is arguably primarily to identify features and assemblages of geoheritage significance, but not to be a repository of extensive detailed data about each site. However, such detailed information is needed in order to appropriately manage to protect the values of relevant sites. At present this information can only be obtained by referring back to primary (original) data sources, which may be difficult to access and in varying formats.

- The polygon boundaries for many predictive regions, assemblages and specific features listed on the TGD are known to be partly incorrect in many cases, particularly in instances where the boundaries omit parts of sites that should be included. In most cases such inaccuracies are probably due to difficulties in accessing basic mapping of glacial and periglacial features at the time when the TGD polygon boundaries were drawn. This is an important issue since a management reliance on incorrect boundaries could result in parts of listed TWWHA glacial and periglacial features not being properly managed in respect of their values and sensitivities.

- Some glacial assemblage boundaries overlap, creating a redundancy in the TGD whereby some features (some of the constituents of the assemblages) are effectively listed twice on the TGD; this may create confusion and redundancies in analyses of TGD data.

- One notable such issue of overlaps arises where some “glacio-karst” assemblages have been listed overlapping with broader “glacial” assemblage listings, meaning that the same features have in effect been listed twice in different listings on the TGD. However in this case there is arguably a case to be made that the distinctiveness of glacio-karst may be sufficient to warrant such an overlap.

- As alluded to in respect of gaps and biases (above), it is probable that the TWWHA glacial and periglacial features and assemblages listed on the TGD are not a comprehensive and fully representative suite of sites covering the full range of glacial and periglacial geodiversity actually present in the TWWHA. This is particularly so in the case of periglacial landforms and processes – about which less is known – but is clearly also true for glacial landforms. Given that glacial and periglacial features are key values for which the TWWHA was inscribed on the World Heritage List, the TGD should at least list the best sites representative of the full diversity of such phenomena in the TWWHA, and indeed it is arguable that all glacial and periglacial features in the TWWHA could be listed (because they all contribute to a key World Heritage Value of the TWWHA).

In the light of the issues (above) identified in the course of this analysis, the following key recommendations are made:

- *Knowledge and mapping of periglacial features in the TWWHA should be improved as resources permit*. Whilst improved knowledge of glacial phenomena in the TWWHA also warrants attention, the relative lack of attention paid to TWWHA periglacial landforms and features in the past means that knowledge of these phenomena remains rudimentary. Thus, some focussed attention on periglacial phenomena is warranted in order to be able to more confidently identify the nature, types and extent of periglacial processes and features in the TWWHA.

- *The purpose of listing sites at different levels should be defined and adhered to consistently*. This means that there should be some consistency about the conditions under which assemblages versus specific features are listed as exemplars of their types on the TGD. In addition the purpose and value of listing predictive regions should be reviewed, and if these regions are maintained they should be applied comprehensively (not partially as at present).

- *Appropriate protocols for listing glacio-karstic assemblages as opposed to glacial assemblages should be determined and adhered to.* A decision is needed as to whether the redundancy involved in listing overlapping glacio-karst assemblages within 'normal' glacial assemblage listings is warranted by the distinctiveness of glacio-karstic phenomena within broader glacial assemblages.

- *A consolidated map-based GIS dataset on glacial and periglacial landforms and deposits in the TWWHA (and preferably the whole of Tasmania) should be compiled*. Such a dataset should incorporate all available mapping of glacial and periglacial landforms from the many disparate existing sources, and should be updated with all relevant future mapping and research as this becomes available. Such a dataset would be a powerful tool for many ongoing research and land management purposes, and in the context of the TGD is the necessary precursor to being able to resolve a number of the issues identified above, as listed below:

- When a consolidated GIS dataset on glacial and periglacial landforms in the TWWHA is available (per above recommendation), the following are recommended:

    - *A systematic comparative assessment should be undertaken to identify the full suite of the best representative assemblages and features exemplifying the full geodiversity of glacial and periglacial phenomena in the TWWHA*; TGD listings should be updated accordingly; or:

    - *If a decision is made to use the consolidated dataset to simply list all TWWHA glacial and periglacial features on the TGD (because all contribute to key World Heritage Values for which the TWWHA was inscribed on the World Heritage List), then it is recommended that a similar systematic comparative assessment be undertaken to establish levels of significance of features and assemblages (or at least, to identify the most important representative features as a tool for prioritising their appropriate management);* TGD listings should be updated accordingly;

    - *The boundaries of TGD listing polygons should be reviewed against the consolidated mapped data and corrected as necessary* to ensure that all relevant features are actually included within the boundaries of TGD listing polygons.

    - *Overlapping assemblage boundaries of a given type (glacial or periglacial) should be identified and rationalised to eliminate overlaps where-ever possible*, by merging or splitting assemblage listings as necessary to create mutually-exclusive polygon boundaries.

    - *The consolidated dataset should be used as necessary in conjunction with the TGD as the appropriate base layer to identify the specific features that make up each TGD listing,* so as to ensure they are appropriately managed in accordance with those listings.

1.0 Introduction

1.1 *Preamble*

The Tasmanian Geoconservation Database (TGD) is a spatial database whose purpose is to identify and list Tasmanian geological, geomorphic and soil phenomena that have been identified as having significant geoconservation value at a variety of levels. The TGD is maintained by the Geoconservation Section of the Tasmanian Department of Primary Industries, Parks, Water & Environment (DPIPWE), acting on the advice of an expert panel known as the Tasmanian Geoconservation Database Reference Group (TGDRG). The TGD is available on the World Wide Web via the DPIPWE Natural Values Atlas. Whilst it has no statutory authority, it is widely used as a management tool which identifies features whose geoheritage significance should be considered in planning developments or activities that could impact on those values.

Whereas geoheritage feature listings added to the TGD over the last 15 years have been subject to critical review and appraisal by the TGDRG, the majority of sites currently listed on the TGD were compiled in an earlier process of amalgamating a wide range of previous lists of geoheritage features (Dixon & Duhig 1996). These previous lists were compiled in a range of different ways by a variety of workers, and the resulting amalgamated list that formed the basis for the original version of the TGD has not been subjected to a systematic assessment to determine whether it includes the best known representative features of the types listed, or whether there are known features that should be listed but are not yet on the database.

The glacial and periglacial landforms of the Tasmanian Wilderness World Heritage Area (TWWHA), and their importance in elucidating the climatic and landscape history of southern temperate regions, were one of the primary values underpinning the inscription of the TWWHA on the UNESCO World Heritage list in 1982 and in an enlarged form in 1989 (DASETT 1989, Sharples 2003). A significant number of glacial and periglacial landforms located in the TWWHA are listed on the TGD, however as with most[1] other classes of geodiversity listed on the TGD, there has been no assessment of the representativeness and appropriateness of the features listed, nor has there been any systematic identification of unlisted features that warrant listing.

The purpose of the project described in this report was to undertake a gap analysis of TWWHA glacial and periglacial sites listed on the TGD, with the aim of identifying unlisted features that should be listed, and also assessing the suitability of listed features as good representative examples of their type. Whilst these aims have been partially achieved, the major outcomes of this analysis have been the identification of several issues which limit current capacity to undertake such a gap analysis comprehensively and systematically. A number of other limitations on the format and content of current glacial and periglacial site listings have also been identified which warrant attention. This report consequently provides a number of recommendations which will improve the TGD listing of glacial and periglacial features in a number of ways, including creating the capacity to undertake a properly systematic and comprehensive gap analysis of the listing of these phenomena on the TGD.

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[1] Note that gap analyses of TWWHA bedrock geology and soil features for the TGD have recently been undertaken as companion studies to this glacial/periglacial gap analysis.

1.2 *Scope*

The contracted task which this report fulfils is to provide a report that identifies gaps in the listing of glacial and periglacial values in the TWWHA on the TGD. In providing this gap analysis, this report considers only areas within the TWWHA as current at the end of 2012.

There is some potential for interpreting the scope of this project in differing ways. In the case of glacial features, the TWWHA contains both glacial (ice-contact) and glacio-fluvial outwash deposits and features produced during several periods of glacial activity that are widely separated in geological time, including Cenozoic, Permo-Carboniferous and Late Precambrian glacial landforms and deposits. Of these, the scope of this report encompasses:

- glacial and periglacial phenomena of Cenozoic age only; however it includes:
- glacio-fluvial outwash features (directly resulting from ice-melt) as well as ice-contact features.

In regard to periglacial features, it is notable that McIntosh *et al.* (2012) have recently argued that the term ‘periglacial’ has little meaning when applied in Tasmania, and they found it more relevant to an understanding of Tasmanian landscape history to instead discuss ‘extra-glacial cold-climate’ features. These may include classical periglacial features formed by freezing and thawing of ice, but also include associated phenomena formed under cold-climate conditions but not necessarily involving ice, such as terrestrial aeolian features and some types of slope deposits and cave sediment deposits. However for the practical purposes of this report it has been necessary to restrict the scope of the exercise somewhat, hence the term ‘periglacial’ has been interpreted to conform with the TGD Classification Key theme (6.4) ‘Glacial and cryogenic’; that is, ‘periglacial’ phenomena are understood to comprise:

- Non- glacial features formed by freezing and thawing of water (ice, snow).

Under this definition, cold-climate aeolian phenomena are excluded, as are slope deposits that are thought likely to have not involved ice or snow freezing or melting in their formation. In summary, this gap analysis relates specifically to features falling within Theme 6.4 (‘Glacial and Cryogenic’) of the Tasmanian Geoconservation Database Classification Key (Bradbury 2014), but including glacial outwash deposits directly attributable to melting of glacial ice.

1.3 *Methodology outline*

In broad outline, this gap analysis has proceeded by the following steps:

a) A brief overview of the geomorphic history and diversity of Cenozoic glacial and periglacial geomorphic processes in the TWWHA was compiled (Section 2), as background information and in order to inform the compilation of a suitable classification of Tasmanian glacial and periglacial geodiversity suited to the purposes of this analysis.

b) A classification of the Cenozoic glacial and periglacial geodiversity of the TWWHA has been compiled (Section 3), using a landform classification organised under the framework of the TGD Classification Key (Bradbury 2014) together with the known spatial and temporal distribution of TWWHA glacial and periglacial phenomena (Section 2) as its framework. Classification sub-divisions based on the known geodiversity of the TWWHA have been defined down to a (relatively coarse) level of detail appropriate for this analysis (Section 3). The classification derived in this way is not intended to be a complete glacial and periglacial geodiversity classification (i.e., one which might apply anywhere in the world), but rather is a TWWHA-specific classification listing phenomena that are known or might be expected to exist in the TWWHA specifically.

c) This classification has been directly compared with a listing of all TWWHA glacial and periglacial phenomena that have to date been listed on the TGD (Section 4). Phenomena that are listed have been briefly assessed and ranked in terms of the number of actual TWWHA examples (features) listed in each class. Listing gaps have been identified (i.e., non-listed feature types that are likely to be present in the TWWHA). At the outset it was intended to also analyse the degree to which features listed are good examples of their type, their condition (or degradation), and whether listed features are integral systems of features or just random scattered sites; however it turned out the available TGD database is not adequate to support such analyses in a systematic fashion.

d) It was also intended at the outset that the data compiled would be used to assess the degree of comprehensiveness and representativeness of those elements of TWWHA glacial and periglacial geodiversity that are listed in the TGD and the adequacy or degree of replication of the listings for each listed class. Conversely, glacial and periglacial phenomena known or likely to exist in the TWWHA but not listed in the TGD were to be comprehensively identified, priority gaps that should if possible be filled were to be identified, and where possible suitable features that would appropriately fill listing gaps were to be noted. However, upon reviewing the available data, it was realised that the lack of any comprehensive, consolidated mapped (GIS) dataset on glacial and periglacial phenomena in Tasmania would make such a task very difficult since the required information is scattered across numerous separate (and commonly paper) documents, reports and maps.

e) Recommendations have been provided in Section (5) which aim to address the key limitations discovered in the available data, with a view to ultimately enabling the sort of comprehensive geoconservation gaps analysis that was originally intended for this project, to be undertaken in future.

Further details of each step in this methodology are provided in following sections of this report.

1.4 *Glossary of terms, acronyms and abbreviations*

This section lists and explains a number of key terms, acronyms and abbreviations used in this report:

Cainozoic	Equivalent to 'Cenozoic' (see below). Although this spelling was previously widely used in Australia, the alternative spelling 'Cenozoic' has been adopted by the International Commission on Stratigraphy.
Cenozoic	A sub-division of the geological time scale which encompasses the Quaternary and Tertiary periods, from 65 million years ago until the present. Equivalent to 'Cainozoic'.
DPIPWE	A Tasmanian state government agency, the Department of Primary Industries, Parks, Wildlife and Environment.
Geoconservation:	the endeavour or practice of endeavouring to conserve geodiversity (see Gray 2004)
Geodiversity:	"The natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform, processes) and soil features. It includes their assemblages, relationships, properties, interpretations and systems." (Gray 2004, p. 8)
LGM	Last Glacial Maximum; the time of maximum Last Glacial Phase extent of glacier ice in Tasmania, around 20,000 years ago (Late Pleistocene, OIS 2). Note this is not the same as the Maximum Pleistocene glaciation in Tasmania, during which glacier ice covered a much larger area during Early – Middle Pleistocene times about 1,000,000 years ago.
LIST	Land Information System Tasmania. A wide variety of topographic, cadastral and other mapping available online through the DPIPWE-administered LIST website.
OIS	Oxygen Isotope Stage. A distinct sequence of Quaternary glacial, stadial, interstadial and interglacial climatic phases are recognisable from layers having differing oxygen isotope ratios in deep ocean sediment cores, ice cores and other palaeoclimatic records, and are numbered conventionally in a series of stages (OIS1, OIS 2, etc).
Stadial	A sub-stage in a glacial stratigraphy or chronology.
TGD	Tasmanian Geoconservation Database: a listing of geological, geomorphic and soil phenomena in Tasmania that are considered to have significant geoconservation value. The TGD is maintained by DPIPWE.
TWWHA	Tasmanian Wilderness World Heritage Area.

2.0 A Summary of the Cenozoic Glacial and Periglacial Geomorphology of the Tasmanian Wilderness World Heritage Area (TWWHA)

2.1 *Introduction*

This summary is deliberately brief since its purpose is to provide the basis for a succinct classification of Tasmanian glacial and periglacial features, rather than to be a review of issues or of the current understanding of these themes. Recent reviews of Tasmania's Cenozoic glacial and periglacial geomorphology – from which much of this summary is drawn – include Colhoun & Barrows (2011), McIntosh *et al.* (2012) and Colhoun (2014a).

2.2 *Cenozoic Glaciation in the TWWHA*

For a period of approximately 200 million years following the great Permo-Carboniferous glaciations (circa 310 – 260 million years ago) the Earth's climate was dominantly warm with little known glaciation even at the poles. However during the Middle – Late Eocene (circa 34 million years BP) the Earth's climate changed from a dominantly warm (largely non-glacial) to a cooler (intermittently glacial) climatic mode that has persisted to the present, for reasons likely to be related to a combination of the opening of the Antarctic Circumpolar Current and a gradual decrease in greenhouse gases during the earlier part of the Cenozoic (Barker & Thomas 2004). The initiation of Antarctic glaciation is considered to have occurred at this time, and MacPhail *et al.* (1993) have previously interpreted sediments in Tasmania's Forth River valley (outside the TWWHA) to be remnant Late Eocene or Early Oligocene tills dating from this same early phase of Cenozoic glaciation. However whilst there are other indications of pre-Pleistocene Cenozoic glacial deposits in Tasmania, such as the pre-Pliocene tills reported by Augustinus & Idnurm (1993) from the Vale of Belvoir (close to but outside the TWWHA), these are very fragmentary. This is likely to be at least partly because the most extensive Cenozoic glaciation in Tasmania appears to have occurred around 1 million years ago (the Linda, Bulgobac, Thureau and correlated glaciations of mid-Pleistocene times) and probably scoured and reworked most earlier glacial landforms and deposits except in a few protected locations.

The known extent of the Mid-Pleistocene Maximum Glaciation in the Central Plateau – Central Highlands region is indicated on Figure 1, and comprised a large ice cap (some hundreds of metres deep in parts) with large radiating valley outlet glaciers. The extent of mid-Pleistocene glaciation in more southerly parts of the TWWHA and in north-eastern Tasmania is less well established but probably comprised some small ice caps, extensive valley glaciers and numerous cirque glaciers.

Following the Mid-Pleistocene Maximum glaciation there have been at least another six distinct known glacial ice advances in Tasmania (Colhoun & Barrows 2011, Fig 74.2), each slightly less extensive than the previous, which has allowed preservation of terminal moraine deposits and other evidence of each glaciation's extent since subsequent glaciers have not completely over-ridden and reworked the previous deposits. During the most recent and least extensive Last Glacial Maximum (circa 20,000 years BP) two separate smaller ice caps

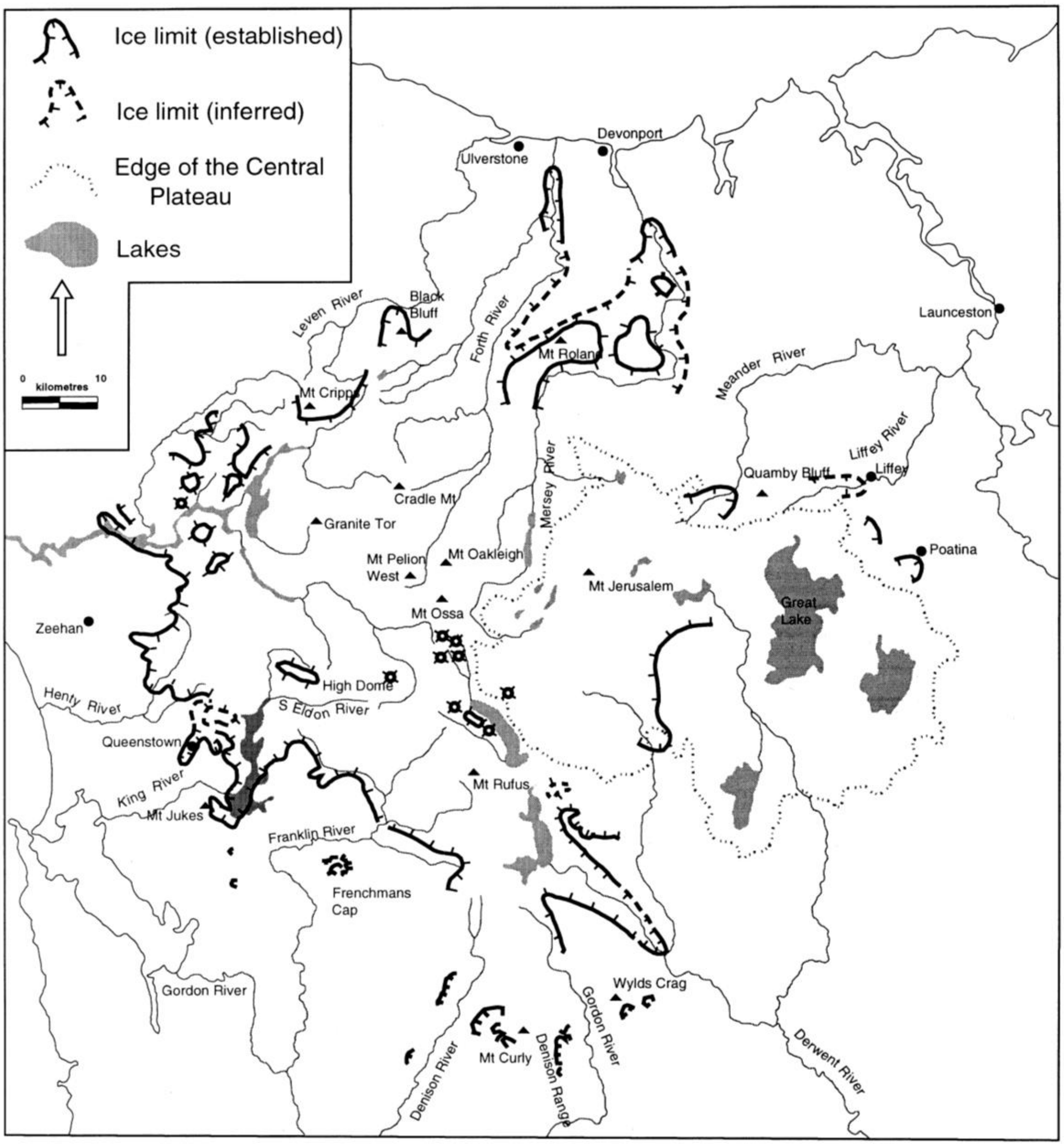

Figure 1: The maximum extent of Pleistocene glaciers in central and western Tasmania (during the Early – Middle Pleistocene Linda glaciation and correlated events). Figure by Kiernan (1990a), reproduced from Colhoun *et al.* (1996) and as used in Colhoun & Barrows (2011).

were present on the West Coast Range and Central Plateau (Figure 2), while other more southern and north-eastern ranges were mostly dominated by cirque glaciers.

By reason of its lower mountains, lower latitude and more maritime island climate, Tasmania has a more marginal glacial climate than the other two southern temperate glacial regions of New Zealand and Patagonia, and consequently is the only one of the three to have been completely lacking in glaciers for most of the Holocene up until the present day.

In addition to differing extents and styles of Cenozoic glaciation in Tasmania at different times, there has been considerable spatial variability in the glacial processes, landforms and deposits across Tasmania, due to differences in glacial system controls such as precipitation, geology and pre-existing topography. Kiernan (1996) has provided a detailed classification of the differing system controls that have influenced glacial geodiversity across Tasmania and the TWWHA, and only a few major aspects are noted here.

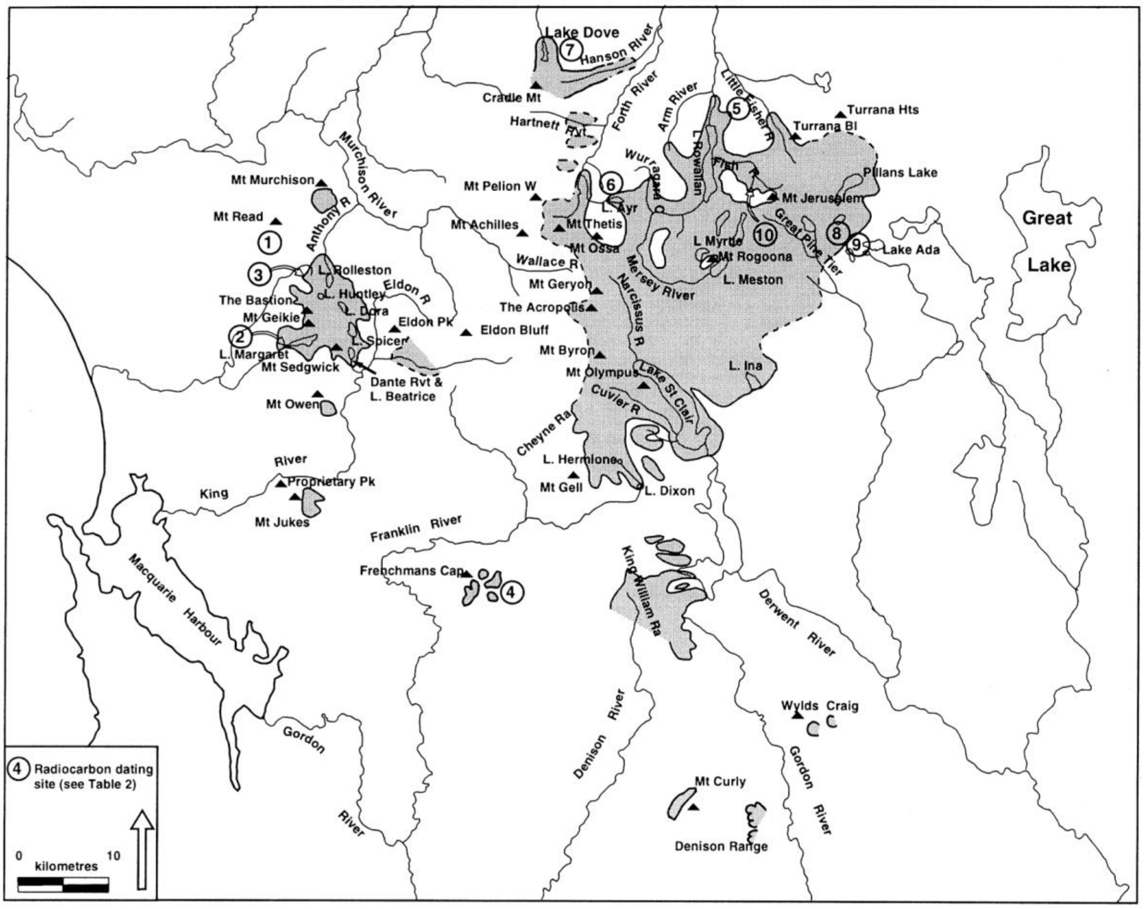

Figure 2: The extent of glacier ice in western and central Tasmania during the Late Pleistocene Last Glacial Maximum (LGM). Figure reproduced from Colhoun *et al.* (1996) and as used in Colhoun & Barrows (2011). Numbered sites refer to radiocarbon dates tabulated in Colhoun *et al.* (1996).

Glacial landforms and deposits are generally larger or more strongly excavated on the West Coast Range than elsewhere in Tasmania, and show a marked reduction in scale from west to east which provides evidence that the present-day west to east precipitation gradient across Tasmania also existed during the Pleistocene glacial advances, resulting in a greater through-put of ice on the more westerly ranges.

Prior tectonics and topography have played a major role in determining glaciation styles within the TWWHA, with the extensive high tabular Central Plateau having favoured the accumulation of Tasmania's largest ice sheets or caps, in contrast to the prominent quartzite strike ridge mountains of the southwest TWWHA region which favoured more ice accumulation in cirques and valleys on their leeward sides, more so where they were oriented north-south across the prevailing westerly air stream, and less where their orientation produced less sheltered leeward slopes exposed to more daily insolation.

Differing bedrock geology in glaciated mountains has similarly had a strong influence on both the erosional and depositional products of glaciation. Glacial erosion of the extensive dolerite mountains of the TWWHA produced the characteristic forms of soaring vertical columnar-jointed cliff faces, while the glacial sediments resulting from dolerite erosion tend to be high in clays from the weathering of feldspars and pyroxenes comprising the dolerite rocks. In contrast, the hard but complexly folded and fractured siliceous quartzite mountains tended to produce much more irregular and "jagged" erosional forms while the resulting glacial sediments are typically more quartz-rich and less clayey (albeit interbedded schists and phyllites may produce some clay content upon erosion and weathering).

A simple classification of Tasmanian glacial landforms (Section 3.0) has been used in this gap analysis to attempt to identify the most important elements of glacial geodiversity in the TWWHA, such as those noted above.

2.3 Cenozoic periglacial phenomena of the TWWHA

In comparison to glacial landforms there have been relatively few detailed and systematic studies of relict or active periglacial landforms and processes in Tasmania, with perhaps the most detailed such study being Caine's (1983) study of the dolerite mountains of north-east Tasmania. This is in notable contrast to Tasmania's glacial landforms which have been subject to a significant number of detailed studies, many of these within the TWWHA. As a result the full extent and geodiversity of periglacial phenomena within (and beyond) the TWWHA remains less well understood.

Nonetheless, in addition to occasional isolated studies and observations (e.g., Jennings 1956: patterned ground on the Central Plateau; Colhoun 1977: Pleistocene frost-fracturing and gelifluction close to present sea-level; Kirkpatrick & Harwood 1980: terraces and stone circles on Mt Bobs; Kiernan 2008: frost shattered rubbles), there have been several reviews or overviews of periglacial phenomena in Tasmania. These include early reviews by Davies (1967, p. 11-18) and Derbyshire (1973), as well as a textbook on periglacial phenomena that drew heavily on Tasmanian examples (Davies 1972). Recent reviews have been provided by McIntosh et al. (2012) and Colhoun (2014b). These latter reviewers preferred to use the term "extra-glacial" rather than "periglacial", in order to include cold climate processes such as terrestrial aeolian phenomena that are not strictly encompassed by the term periglacial, however as noted in Section 1.2 above this gap analysis is restricted to periglacial features which are here understood as being those produced by repeated freezing and thawing of water.

The most widespread periglacial landforms in Tasmania are colluvial slope mantles ranging from large boulder to pebble grade and comprising slope accumulations of material dislodged from ice-shattered bedrock outcrops (scree, talus) as well as those subsequently transported further downslope by freezing and thawing processes (rock glaciers, block streams, solifluction deposits). Stratified fine (granule-grade) screes occur commonly in association with siltstone bedrock types in parts of Tasmania, and Last Glacial dates ranging between 35 ka and 21 ka have been obtained from a number of these (McIntosh *et al.* 2012). Whilst these deposits remain somewhat enigmatic there is evidence consistent with their deposition by snowmelt water related to seasonal freeze-thaw processes on largely unvegetated slopes (McIntosh *et al.* 2012), and these may be Tasmanian examples of the stratified slope mantles that have elsewhere been referred to as "grèzes litées" (Colhoun 2014b). Terracing is in places recognisable in Tasmanian periglacial slope mantles, and may range from small-scale highly regular sorted gravel terraces such as those on the summit of The Boomerang (Kirkpatrick & Harwood 1980; see front cover photo) to much larger and cruder features in bouldery dolerite colluvium that McIntosh *et al.* (2012) referred to as 'boulder fronts'. Hummocky forms in colluvial deposits are commonly produced by slumping or creep processes unrelated to periglaciation, but may in some cases be a product of periodic freezing and thawing of colluvial mantles. Periglacial slope deposits in

Tasmania are also commonly associated with relict alluvial fans that in some cases may be produced by meltwater washouts from thawing slope deposits.

Residual highland bedrock landforms produced by the freeze-thaw and frost-shattering processes that resulted in periglacial erosion and fed debris downslope include tors, leaning tors (especially on dolerite mountains), slab topples, high altitude cliffs and arêtes, and relatively smooth, flat or rounded mountaintop crest pavements and ‘cryoplanation’ surfaces (Davies 1958). A number of nivation cirques remain currently active on some TWWHA mountain peaks (including Frenchmans Cap and The Boomerang), and relict Pleistocene-age nivation cirques are probably widespread. Patterned ground and sorted stone circles or polygons interpreted to be a result of present-day periglacial processes have been reported from the Central Plateau, and elsewhere in the TWWHA, with a notable occurrence of sorted stone polygons occurring on the summit of The Boomerang (Kirkpatrick & Harwood 1980).

Although most of the large-scale periglacial landforms preserved in Tasmania (solifluction mantles, block streams, etc) are thought to have been mainly active in regions peripheral to actual glacial ice during repeated Pleistocene glacial climatic phases (Colhoun 2014b), it is evident that some periglacial processes remain active at high altitudes in the TWWHA today, including some frost-shattering, nivation processes, active alpine screes and patterned ground processes. Pleistocene features of interpreted periglacial origin have been reported from all altitudes down to present-day sea-level (e.g., Colhoun 1977), and may have extended below present sea-levels during the coldest parts of the Pleistocene when sea-levels were as much as 130 metres below present levels. At the present (interglacial) time active periglacial features are mainly reported from altitudes above 1000 metres ASL, however frost action does occur occasionally to much lower altitudes and there is no clearly defined lower altitude limit for contemporary periglacial processes in the TWWHA.

As noted above, there have been few detailed systematic studies of periglacial landforms in Tasmania. One result of this is that it is likely that there may be classes of periglacial landform in the TWWHA that have not yet been recognised as such, and it is almost certain that the full extent and best developed examples of some recognised TWWHA periglacial landform classes are not yet known. For example, the existence of, or extent of, permafrost in Tasmania during the Pleistocene is unresolved (see Delisle 2001), and if it has been present at times there may be resulting features of related origin in the TWWHA landscape that have not yet been recognised as such. For example, Figure 5 to Figure 7 of this report (in Section 5.3.3) illustrate examples of enigmatic TWWHA landforms which may (or may not) be of periglacial origin, and which to the authors knowledge have neither been investigated nor explained to date. Another enigmatic feature that might be of partly periglacial origin is ‘The Duckhole’ near Hastings, a small lake of possibly karstic origin which is entirely surrounded by a raised rim of bouldery sediment. One possible explanation of this still-unexplained feature is that it is a collapsed pingo (Ian Houshold, *pers. comm*.), a class of periglacial feature well known from arctic regions but hitherto unrecognised in Tasmania[2].

[2] If the lake is indeed fed by a karst spring as has been widely speculated, then under Pleistocene glacial climate conditions a growing permafrost dome could have built over the spring, pushing overlying colluvial and alluvial sediments upwards and outwards. These would remain as a raised rim after the ice dome melted at the end of the glacial climatic phase.

Thus, whilst a simple classification covering periglacial phenomena currently known in Tasmania has been used in this gap analysis (Section 3.0), it is quite possible that future studies of periglacial phenomena in Tasmania will result in additional classes being recognised, and very likely that more systematic study of periglacial features in the TWWHA will result in mapping of more examples of both known and previously unknown classes than has occurred to date.

3.0 A Classification of the Glacial and Periglacial Geodiversity of the TWWHA

3.1 *Introduction*

This section describes a simple classification of Tasmanian glacial and periglacial phenomena which was developed specifically for this project, so as to enable identification of key glacial and periglacial features (landforms, sediments) which have – or have not – been identified in the TWWHA, and which have or have not been listed on the TGD

For the purposes of this classification, the glacial and periglacial geodiversity of the TWWHA is considered to have three primary elements, namely:

1. **Temporal diversity**: there has been a succession of cooler 'glacial' and warmer 'interglacial' global climatic phases during the Cenozoic, of which some (albeit possibly not all) produced glacial and periglacial phenomena in Tasmania. Given that each of these phases represents a different and distinctive stage in Tasmania's geological and landscape history, a comprehensive geoheritage listing would ideally include representative features from each phase when distinctive glacial and/or periglacial processes have been active in Tasmania.

2. **Spatial diversity**: there have been considerable differences between the extent and type of glacial and periglacial phenomena in different regions of the TWWHA, owing to a steep west-east precipitation gradient, differing pre-glacial topographies in different regions and other distinctions such as differing bedrock types that yield distinctively different erosional forms and glacial sediment types. For example the West Coast Range received the highest precipitation and thus exhibited the greatest throughput of glacial ice; the most extensive ice cap was always centred on the Central Plateau whose broad flat topography was most conducive to ice cap development; however other less extensive mountain massifs were instead dominated by cirque and valley glaciers. Ideally, a comprehensive geoheritage listing should include characteristic features representative of each of the differing spatial groupings of glacial and periglacial processes in the TWWHA.

3. **Feature and process diversity**: During each glacial and interglacial time phase, and within each key glacial and periglacial region, a diversity of deposits and landform features formed and were at least partially preserved. A comprehensive geoheritage listing should ideally capture as much of this feature and process diversity within each major distinctive temporal phase and spatial region of TWWHA glacial and periglacial processes, and preferably do so by identifying integral inter-related suites and systems of features rather than randomly selecting scattered unrelated examples.

A classification of each of these three primary elements, specifically suited to the TWWHA, has been prepared for this analysis and is provided in the following sub-sections.

3.2 Temporal diversity

3.2.1 *Introduction*

Over the Earth's geological history its climate has been through numerous glacial climatic periods interspersed with longer periods of over 100 million years from which no evidence of glaciation is preserved. The glacial climatic periods include at least two Late Precambrian glaciations that are thought to have been of global extent (the "Snowball Earth" periods: Hoffman & Schrag 2002), a prolonged Permo-Carboniferous glacial period, and the current Cenozoic glacial period which commenced circa 32 million years ago (see Section 2.2). Although geological and/or geomorphic evidence from each of the Late Precambrian, Permian and Cenozoic glaciations is present and has been documented in the TWWHA (Corbett *et al.* 2014), the scope of this gap analysis has been limited to the Cenozoic glacial period.

Within the Cenozoic glacial period there have been repeated alternations between colder 'Glacial' phases and warmer 'Interglacial' phases, albeit a reduced extent of glacial ice has probably persisted at the poles and on higher peaks during most of the Interglacial phases, as is the case during the present interglacial phase (known as the Holocene). A regular periodicity in the timing of repeatedly alternating glacial and interglacial cycles though the Cenozoic has been shown to be driven by feedbacks triggered by small cyclic differences in insolation caused by three varying components of the Earth's orbital motion about the sun; these are known as the Milankovitch cycles (Hays *et al.* 1976). Calculations of the Milankovitch cycles demonstrate there should have been several tens of glacial / interglacial climatic alternations since the onset of the overall Cenozoic glacial period circa 32 million years ago, and interpretation of deep sea sediment cores containing distal glacial outwash sediments support this inference.

Tasmania has been a marginal environment for temperate latitude glaciation which in contrast to New Zealand and Patagonia has no glaciers at all during the present Interglacial phase (see Section 2.2), but nonetheless is known to have been glaciated during at least seven separate Pleistocene glacial advances (Colhoun & Barrows 2011) and during at least two mid-Late Tertiary glaciations (see Section 2.2); it is likely that Tasmania has also been glaciated at other times for which no evidence has been preserved or has not yet been found.

In contrast to true glacial features, periglacial features have undoubtedly been actively produced in the TWWHA during both Glacial and Interglacial climatic phases. These processes would be active in areas peripheral to glacial ice during glacial phases and on higher (often formerly glaciated) peaks and plateaux during Interglacial phases.

It is generally more difficult to find evidence of older glaciations preceding the last (at least in terrestrial settings[3]), since each successive glaciation reworks much of the evidence of subsequent glaciations. The best preserved glacial landform sequences are mostly those where each successive glaciation was less extensive than the one before it, allowing a

[3] Marine sediments, and potentially some lacustrine and cave sediment deposits may have potential for preserving evidence of long glacial and interglacial sequences in situations where sedimentation is uninterrupted by erosion over long periods of time, however this is rarely the case in terrestrial environments subject to cyclic glacial and interglacial process conditions.

succession of glacial-limit landforms to be preserved, each inside the limits of the preceding one. This happens to have been the case for the sequence of Tasmanian Pleistocene glaciations from the Maximum Pleistocene Glaciation (circa 1 million years ago) until the Last Glaciation circa 20,000 years ago (Colhoun & Barrows, Fig. 74.2). However when a glaciation is more extensive than previous glaciations it will rework and destroy much of the evidence of previous glaciations. On current evidence, the most extensive ("Maximum') Cenozoic glaciation to affect Tasmania was the Pleistocene Linda Glaciation (and correlates) circa 1 million years BP, and this seems to have obliterated most evidence of what may potentially have been dozens of previous glacial advances extending back to the onset of Cenozoic glaciation in the Oligocene. Evidence of previous Cenozoic glaciations in Tasmania is rare (see Section 2.2) since such evidence is only preserved in unusual circumstances such as covered landscape depressions that were over-ridden rather than excavated by subsequent glaciers. Because of their rarity and the information they may give us about the earlier poorly-known episodes of Tasmania's Cenozoic glacial history, most such older occurrences are likely to be of significant geoheritage significance, albeit for the same reason it is likely that only a very limited diversity of features will be preserved from such earlier glaciations.

3.2.2 *Method*

Given the probable incompleteness of the glacial record in Tasmania (as noted above), it is unlikely that complete suites of glacial features have been preserved from all glaciations that have occurred here, especially those prior to the Maximum Pleistocene Glaciation. Instead, a temporal classification for the purposes of this gap analysis (Table 1) has been defined by selecting three key climatic phases considered to be of particular significance for the glacial and/or periglacial information they may or do preserve, namely the present Interglacial (active periglaciation, no active glaciation), the Last Glacial Maximum (comprising the best preserved – because most recent and intact - suite of Cenozoic glacial features), and the Maximum Pleistocene Glaciation (evidence of greatest glacial extent for Cenozoic, this glaciation would have obliterated much earlier glacial evidence but its outermost features will not have been entirely destroyed by subsequent glaciations).

The evidence for other glacial phases (which is likely to be incompletely preserved) has been lumped together into two broader temporal groups, namely the 'other post-Maximum Pleistocene glaciations' (for which more evidence is likely to be preserved but which arguably provide less important information than the LGM or the Maximum Glaciation); and the 'pre-Maximum Late Tertiary to Mid–Pleistocene glaciations' (for which only very fragmentary evidence is likely to be preserved within the TWWHA because the Maximum Glaciation will have obliterated or reworked much earlier glacial evidence). An 'Unclassified' time phase has also been defined for use with Cenozoic glacial or periglacial features recorded on TGD but of otherwise uncertain age.

3.2.3 *Temporal diversity classes for Cenozoic TWWHA glacial & periglacial systems*

The following temporal classification of TWWHA glacial and periglacial phenomena has been used for the purposes of this gap analysis.

Table 1: Classification of key time periods for identification of significant representative elements of TWWHA glacial and periglacial geodiversity

Time phase	Glacial Phenomena	Periglacial Phenomena
Pre-Maximum (Late Tertiary to Mid-Pleistocene) glaciations'	Rare and fragmentary features preserved	Preservation unlikely – most will have been reworked by subsequent glacial or periglacial processes – but significant if identified. .
Maximum Pleistocene Glaciation (Linda Glaciation & correlates)	Most extensive Cenozoic glaciation known in Tasmania, many features preserved in distal areas (beyond LGM limits); limited preservation of proximal features (over-ridden by LGM processes), but important for evidence of maximum (distal) ice extents and processes.	Possibly some features preserved where not reworked by LGM or current periglacial processes? (e.g., older solifluction deposits, etc)
Other post-Maximum Pleistocene glaciations (not including LGM)	Many features preserved, mainly in distal areas beyond LGM, some phases may warrant separate gap analysis in future.	Likely some features preserved where not reworked by LGM or current periglacial processes? (e.g., older solifluction deposits, etc)
Last Glaciation Maximum (LGM)	Most recent glaciation in Tasmania, thus best preservation of comprehensive suites of glacial features in most areas (proximal to distal).	Wide spread relict periglacial features known and likely preserved outside LGM glacial ice areas.
Present Interglacial (Holocene / Anthropocene)	No currently active glacial processes in Tasmania.	Present-day periglacial processes, extensive contemporary active features and processes (mainly above 1000m?).
Unclassified time phase	Cenozoic features of undetermined age.	Cenozoic features of undetermined age.

3.3 *Spatial diversity (georegion diversity)*

3.3.1 Introduction

The notion that spatial diversity is a key aspect of glacial and periglacial geodiversity which should be assessed as part of any glacial and periglacial geoheritage gap analysis is underpinned by the concept of *georegionalisation* (Houshold *et al.* 1997, Gray 2004, p.283). The basis of georegionalisation is that the characteristics of landforms that develop in any given region will be determined by the nature of the geomorphic 'system controls' in that region. Geomorphic 'system controls' are those primary characteristics of a region such as bedrock types, climate (especially temperature and precipitation), topography and other regional characteristics which determine the types of landforms that develop in those regions. For example, glacial landforms and deposits in higher precipitation regions are likely to be much more topographically pronounced than those in lower precipitation regions because of the greater throughput of ice that results. Or again, glacial sediment deposits derived from glaciated dolerite bedrock terrain are likely to have much higher clay content than those derived from quartzite terrain, because of the differing mineralogies of these two parent rock types.

The consequence is that differing geographical regions with differing combinations of the key system controls determining glacial and periglacial landform development can be expected to produce differing types and assemblages of glacial and periglacial landforms. Hence it follows that in order to adequately represent the full glacial and periglacial geodiversity of a larger region (such as the TWWHA) in a database such as the TGD, there needs to be adequate representation of features characteristic of each distinctive 'georegion' within that broader region.

Dixon & Duhig (1996) used available (relatively coarse) 1:500,000 scale mapping of a range of key Tasmanian geomorphic system controls to manually draw a series of georegional maps for a range of Tasmanian geomorphic themes. In particular their glacial and periglacial georegion maps remain the only such maps created for Tasmania to date. The purpose was to enable a gap analysis of the original version of the TGD, which was compiled as part of the same project. Owing to project time and budget constraints a full gap analysis was not undertaken, however the utility of the approach was demonstrated by using the georegional maps to undertake a TGD gap analysis for Last Interglacial marine and coastal features, and Last Glacial Maximum glacial features (Dixon & Duhig 1996, Appendix 5).

Subsequently, Jerie *et al.* (2003) used digital geoprocessing and analysis techniques to generate high resolution fluvial georegions for Tasmania based on digital (GIS) mapping of key Tasmanian fluvial geomorphic system controls. These fluvial georegions have not subsequently been used for a fluvial geoheritage gap analysis, in part because the large number of relatively small finely-distinguished georegions would make this a complex undertaking.

3.3.2 Method

The present project builds on the methodologies and lessons learnt from these earlier georegionalisation projects. The approach taken here to defining glacial and periglacial georegions in the TWWHA as a means of identifying important elements of spatial diversity within these themes uses a 'lumping' rather than a 'splitting' approach to generate simpler, more broadly defined glacial and periglacial regions than those produced by Dixon & Duhig (1996). The method used here is briefly summarised as follows (points 1 to 3):

1. The glacial and periglacial system controls used by Dixon & Duhig (1996) and Kiernan (1996) are adopted (with modifications as specified below) as the basis for defining glacial and periglacial regions in the TWWHA.

Dixon & Duhig (1996) used the following system controls to define geo-regions for a range of differing geomorphic process systems (fluvial, glacial, periglacial, etc) across Tasmania:

Time period: (note that for this project time is covered by 'temporal diversity' – see Section 3.2 above).

Bedrock geology: Major litho-structural categories (irrespective of age or stratigraphy) that affect landform type development were used.

Process categories: (note that for this project the relevant process categories are pre-defined, i.e., glacial and periglacial processes).

Climate: Major differences in precipitation across Tasmania were considered of primary importance given that the strong rainfall gradient across the state profoundly affects landform development, Tasmania was divided into three zones based on present-day precipitation (<800 mm; 800 – 1400 mm, >1400mm); temperature is also a key climate variable which determines the state of water (e.g., solid vs. liquid) and hence the dominant geomorphic processes (e.g., glacial vs. fluvial).

Topography: Four major categories of topography were considered for the differing influence they have on landform development, namely plains (slopes <6°), gentle slopes (6°- 20°), steep slopes (>20°) and mountains (peaks over 1000m high with long slopes steeper than 20°).

Kiernan (1996) used the following system controls to classify and define distinctions amongst glacial process and landform regions in particular:

Bedrock geology: A range of bedrock characteristics influence glacial landform development, principally lithology, structures, juxtaposition of rock types and degree of weathering of fracturing.

Topography: Preglacial topography including presence of 'snow-fence' ridges, aspect and orientation determine susceptibility to ice accumulation and glacier formation, as well as determining glacier flow directions. Topography may be modified by glaciation which will then determine susceptibility to future glacier development.

Glacier morphology systems: Unconstrained glaciers (e.g., ice sheets, ice caps and outlet glaciers) may produce distinctively different landforms to constrained glaciers such as valley and cirque glaciers.

Climatic systems: Given the existence of a climate generally conducive to (cold enough for) glacier formation, a key climatic variable determining different styles of glacier and glacial landform development within a given climatic zone is variation in humidity or precipitation (which affects ice quantities and throughput).

Glaciological environment: Glacier properties including ice thickness, temperature, mass budget and movement velocities may affect the types of glacial landforms produced as a result.

Temporal systems: Glacial landforms may differ in character depending on the duration of a glacial episode, the timing of glaciation with respect to other processes such as tectonism, or the degree to which previous glacial episodes have already reshaped or scoured topography (which may variously inhibit or facilitate subsequent phases of glaciation).

The '*time period*' and '*temporal systems*' controls used by Dixon & Duhig (1996) and Kiernan (1996) are accounted for in this project as 'Temporal Diversity' in Section (3.2) above. The '*process categories*' (Dixon & Duhig 1996) are pre-defined as 'glacial' and 'periglacial', and the '*glaciological environment*' control of Kiernan (1996) is not considered here since it would require additional studies well beyond the scope of this project to investigate and satisfactorily determine the variability in these controls and their consequent landform effects in Tasmanian glacial systems.

With these exclusions noted, the following system controls have been used to define glacial and periglacial georegions for the purposes of this project (the definition of each georegion in terms of these controls is specified in Table 2):

- *Bedrock geology*: several key distinctions amongst glaciated Tasmanian bedrock types are related to distinctly different glacial landform styles. Key glaciated bedrock types that have yielded notably different glacial landform assemblages in the TWWHA include dolerite / Parmeener Supergroup sedimentary rock associations; dominantly quartzite and interbedded schistose metamorphic rock associations, and limestone or dolomite carbonate bedrock types.
- *Climate*: The precipitation (snow and rain) gradient across Tasmania during Pleistocene glacial phases is thought to have been similar to the steep present-day rainfall gradient across Tasmania. This is reflected in marked glacial landform variation from large scale cirques and moraines in the West Coast Range (where precipitation and this ice throughput was high) to much more subdued features on the eastern side of the Central Plateau where precipitation was lower and the ice carapace probably thinner and more sluggish. A climatic zone distinction similar to the three precipitation zones of Dixon & Duhig (1996) has been used in this project to define the key climatic variations between glacial and periglacial georegions.
- *Topography*: A number of broad topographic distinctions utilising elements of the topographic controls used by Dixon & Duhig (1996) and Kiernan (1996) have been used to define different TWWHA glacial and periglacial georegions. These include a distinction between the broad tabular high altitude (dolerite-dominated) glaciated surfaces of the Central Plateau, smaller generally tabular (dolerite and Parmeener Supergroup) plateau-topped mountains in the eastern and southern areas of the TWWHA, and the narrower dominantly north-south strike ridges and isolated peaks of the glaciated (quartzite) ranges of the west and southwest.
- *Glacier morphology systems*: Distinctions have been drawn between the ice cap and outlet-glacier dominated systems of the Central Plateau, Central Highlands and West

Coast Range areas, as compared to the cirque and valley-glacier dominated glacial systems of the southern and south-western regions of the TWWHA.

The same broadly defined geographical regions are considered as both glacial and periglacial georegions. This is based on the assumption that whether a given location is dominated by glacial or periglacial processes (or by fluvial or other processes) at any given time depends primarily on the large scale (i.e., global) climatic conditions at the time, and upon the altitude and topography of the site. However, for any given site, whenever these conditions result in either glacial or periglacial processes dominating, then the glacial or periglacial landforms that actually develop will depend upon the other system controls that characterise the site. At the level of the analysis conducted for this project, the variations within these other controls that are significant for glacial landform development are to a large extent also significant for periglacial landform development (e.g., bedrock type and the amount of precipitation leading to ice formation), therefore the same geographical boundaries have been used to define both glacial and periglacial georegions (Figure 3). The differing influence of the system controls characterising each region for glacial versus periglacial landform development in each region are identified in Table 2.

The boundaries of glacial and periglacial georegions used in this analysis have only been defined within and to the limits of the TWWHA. This is primarily because this gap analysis project brief is limited to the TWWHA, however clipping the georegion boundaries at the TWWHA boundary has the additional benefit of avoiding some complexities and uncertainties about glacial limits and georegion boundary definitions that would otherwise need to be resolved if the georegions were extended beyond the TWWHA boundaries or to the whole of Tasmania.

Note that in principle each glacial georegion would extend as far as the most extensive glacier limits during any glacial phase, and would also encompass downstream glacio-fluvial outwash limits. However such limits are in many cases not clearly defined and – at least in the case of glacio-fluvial outwash – probably extend beyond and below the present day coastline in some areas. Considering also that there is evidence (e.g., Colhoun 1977) that periglacial conditions during at least some past glacial climatic phases probably extended to present sea-level or below, the co-incident glacial – periglacial georegions used for this analysis have been extended to the present coast where this falls within the TWWHA. The combined glacial – periglacial regions so defined allow for the fact that periglacial conditions in western Tasmania may have extended to present sea-level at certain times in the Pleistocene, but are today largely confined to altitudes above 1000 metres ASL[4].

It should be noted that the adopted system of using the same region boundaries to define glacial and periglacial regions appears to work adequately for the TWWHA, where most mountain ranges have been glaciated during at least some Pleistocene glacial phases, but have been periglacial environments at other times (including the present interglacial phase). However some modification would be needed to extend equivalent georegions into eastern Tasmania, where some highland areas such as the Wellington Range, Snug Tiers and the

[4] Note this is not a clearly defined boundary for modern periglacial phenomena; frost may still occur rarely to altitudes close to present sea-level in Tasmania, which hence may arguably exhibit minor periglacial processes (e.g., soil heave).

Eastern Tiers have probably experienced strong periglacial conditions during past glacial climatic phases but may never have been glaciated at all (during the Pleistocene) – these areas would thus be covered by periglacial-only but not glacial georegions.

2. The glacial and periglacial georegions mapped out by Dixon & Duhig (1996) were referred to and used as a basis for defining broader georegions by 'lumping' together some of the more finely sub-divided georegions provided by Dixon & Duhig (1996).

3. The broad ('lumped') georegions produced have been defined on the above basis, using the writer's geomorphic knowledge and judgement to delineate regions dominated by important combinations of the systems controls specified above. These broadly defined georegions may contain sub-ordinate areas influenced by other system control combinations.

3.3.3 Glacial and periglacial geo-regions of the TWWHA

This method has resulted in a small number of broadly-defined georegions for which meaningful gap analysis can be readily undertaken in the time-frame and given the resources available for this project. These are listed (and their dominant system controls specified) in Table 2, and are mapped in Figure 3.

Not only is this the most practical and realistic approach for this project, but moreover it is arguable that the current lack of a comprehensive and consistently classified state-wide digital map of Tasmanian glacial and periglacial landforms would make a gap analysis using a more finely sub-divided georegional classification (which resolves sub-ordinate areas of differing system controls) very difficult to undertake effectively. In the absence of improved basic datasets such a detailed approach would be likely to yield unrealistically detailed and thus potentially meaningless results[5]. It is therefore suggested that a comprehensive combined spatial dataset of Tasmanian glacial and periglacial landforms is required before any attempt at a more detailed geo-regionalisation and consequent gap analysis is made.

[5] Thus, a map defining georegions in finely-subdivided detail (comparable to Dixon & Duhig 1996 or Jerie *et al.* 2003) according to each significant variation in each relevant system control would probably lead to the identification of a very large number of potential (or 'theoretical') elements of glacial and periglacial geodiversity which might be present and worthy of listing on the TGD. However in the absence of comprehensive mapping of actual features there would be no way of effectively determining which of these numerous potential types are actually likely to be present on the ground and thus capable of being listed on the TGD.

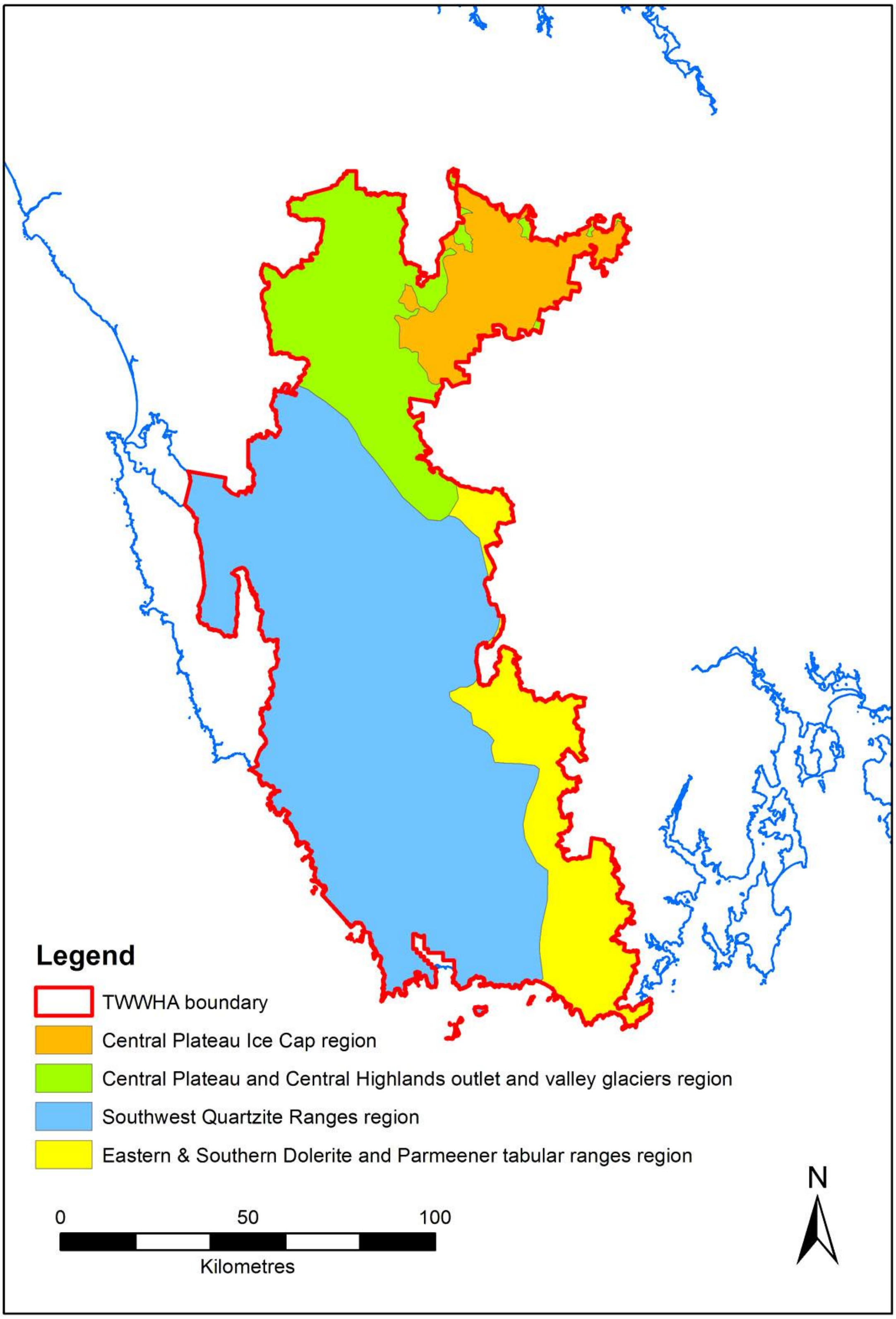

Figure 3: Broadly-defined glacial and periglacial georegions for the TWWHA, based on broad regional distinctions in the dominant geomorphic system controls of bedrock geology, climate (precipitation), topography and (for glacial systems only) glacier morphology systems (adapted from the system controls used by Dixon & Duhig 1996 and Kiernan 1996). An additional 'Quartzitic Ice cap' georegion could arguably be defined in the northern West Coast Range, but is not shown here since the West Coast Range lies entirely outside the TWWHA. The georegion boundaries shown are necessarily crudely-defined because of the lack of a comprehensive and reliable mapped dataset of Tasmanian glacial and periglacial phenomena. See Table 2 for explanation of system control definitions of each georegion.

Table 2: Broad classification of distinctive TWWHA glacial and periglacial georegions for identification of significant representative elements of TWWHA glacial and periglacial geodiversity, based on broad regional distinctions in the dominant geomorphic system controls of bedrock geology, climate (precipitation), topography and (for glacial systems only) glacier morphology systems (adapted from the system controls used by Dixon & Duhig 1996 and Kiernan 1996). The extent of these georegions is depicted on Figure 3.

Geo-region	Glacial phenomena	Periglacial phenomena
Central Plateau Ice Cap region (*strongly consistent georegion in most respects although could arguably be sub-divided on precipitation*)	Dominantly dolerite bedrock; Medium to low (W-E) precipitation gradient; High altitude extensive tabular plateau; Extensive ice cap during most or all glacial phases; *Extensive ice cap or ice sheet abraded terrain on distinctively dolerite bedrock.*	Dominantly dolerite bedrock; Medium to low (W-E) precipitation gradient; High altitude extensive tabular plateau; *Most extensive region of active present-day periglacial phenomena on distinctively dolerite substrate.*
Central Plateau and Central Highlands outlet and valley glaciers region (*extensive complex georegion, could arguably be sub-divided by geology, precipitation, dominant topography and dominant glacier morphology systems*)	Variable geology; High to low (W-E) precipitation gradient; Deeply incised valleys with many high residual peaks; Extensive outlet and valley glaciers in numerous valleys, large portions over-ridden by ice sheets / ice caps during most glacial phases; *Deeply incised glacial terrain with numerous high residual peaks.*	Variable geology; High to low (W-E) precipitation gradient; Deeply incised valleys with many high residual peaks; *Present day periglacial processes most active on peaks and high slopes, probable that glacial phase periglacial processes were also mostly active on protruding peaks (nunataks) while valleys were filled with ice.*
Southwest Quartzite Ranges region (*extensive georegion, could arguably be sub-divided on precipitation; however quite consistent in geology, topography and glacier morphology systems*)	Dominantly metamorphic quartzite bedrock (with softer pelitic sequences interbedded forming strike valleys); High to medium precipitation; Steep, commonly N-S oriented ridges with small narrow summit regions; Mainly cirque and some valley glaciers, significant variation in glacial landform development on windward and leeward mountain sides; *Dominantly isolated cirque and valley glaciers on distinctively quartzite bedrock with extensive glacio-fluvial outwash in extensive valley floors.*	Dominantly metamorphic quartzite bedrock (with softer pelitic sequences interbedded forming strike valleys); High to medium precipitation; Steep, commonly N-S oriented ridges with small narrow summit regions; *Present day periglacial processes on distinctively quartzite bedrock, most active on peaks and high slopes; probable that glacial phase periglacial processes were widespread on peaks and slopes beyond (generally restricted) glacier limits.*
Eastern and Southern Dolerite and Parmeener tabular ranges region (*extensive georegion, arguably could be sub-divided on clastic vs. carbonate bedrock types*)	Dominantly flat-lying dolerite sheet and Parmeener sedimentary rock highlands, commonly with dolomite or limestone valleys (partly over-ridden by glaciers); Medium precipitation; Mainly tabular mountain tops and ridges; Cirque and valley glaciers with extensive glacio-fluvial deposits in valleys; *Dominantly cirque and valley glaciers on distinctive bedrock associations (dolerite, Parmeener sedimentary rocks, limestone and dolomite).*	Dominantly flat-lying dolerite sheet and Parmeener sedimentary rock highlands, commonly with dolomite or limestone valleys (partly over-ridden by glaciers); Medium precipitation; Mainly tabular mountain tops and ridges; *Present day periglacial processes on distinctively dolerite and clastic sedimentary rock bedrock, most active on peaks, plateaux and high slopes; probable that glacial phase periglacial processes were widespread on peaks, plateaux and slopes beyond (relatively restricted) glacier limits.*

3.4 *Feature and process diversity*

3.4.1 *Introduction*

This part of the classification focusses on the (geo)diversity of the actual glacial and periglacial landforms and deposit types that may be produced in the temporal intervals and spatial georegions defined in sections (3.2) and (3.3). Different sub-types of each element in this diversity may be produced to differing degrees and with differing characteristics depending on the characteristics of each temporal interval and spatial georegion.

3.4.2 *Method*

A deliberately broad and 'lumped' classification of landform and process types has been defined for the purpose of this first pass gap analysis. The aim is to identify major gaps in TGD coverage; hence a more finely sub-divided classification would yield additional detail that would probably be of little use at this stage.

The TGD Classification (Theme 6.4: 'Glacial and Cryogenic') has been used as the high-level framework for classifying Cenozoic glacial and periglacial processes and features (landform and deposit types) in the TWWHA (Bradbury 2014). More detailed levels of classification within this framework have been derived – for glacial landforms - from a glacial landform classification scheme for geoheritage purposes prepared by Kiernan (1996); and for periglacial landforms from Davies (1972) and French (1976).

The glacial landform classification of Kiernan (1996) is particularly relevant to Tasmanian geoheritage since it was developed with a Tasmanian perspective. Note however that Kiernan's full classification is very detailed and has not been used here in its totality, but rather a "lumped" classification has been abstracted from Kiernan (1996) at a relatively broad or 'high' level of detail considered appropriate for this first pass gap analysis. Portions of Kiernan's classification have been used in defining appropriate classes of temporal and spatial geodiversity in Sections (3.2) and (3.3) above (Kiernan's system controls and past glaciations timescale classifications), and some other portions are beyond the scope of this analysis (Kiernan's 'glacio-marine landforms', 'landform contents' and 'human use' classifications). The classification provided here (Table 3) is primarily abstracted from Kiernan's 'Landform species and landform communities' classification tables.

In respect of periglacial landforms, the classification provided here (Table 3) is abstracted partly from French (1976), which is a widely recognised authoritative international periglacial geomorphology textbook; and partly from Davies (1972), which is a glacial & periglacial geomorphology text that was written by a geomorphologist with extensive experience of Tasmanian landforms (and which uses numerous Tasmanian examples). Although a few individual areas of Tasmanian periglacial landforms have been subsequently studied in some detail (e.g., Caine 1983), there has been no more comprehensive overview of Tasmanian periglacial landforms subsequent to Davies (1972).

Not all glacial and periglacial landforms listed in the TGD are represented as specific classes in the classification developed below. Upon working through the TGD listings it was found that a number of listed features could not easily be fitted within the draft classification. In some cases it was easy and logical to add additional high-level classes, and where this was possible these are included in the classification below. However in some other cases, adding a new classification to accommodate a specific listed feature would have required introducing a range of new classes and detailed sub-classes in order to maintain consistency within the classification (otherwise it would end up being an inconsistent mix of high-level classes in most cases with a few arbitrary cases of more detailed-level classes). In order that this gap analysis be kept to a reasonable and consistent 'broad level' of detail, this option was considered inappropriate. Instead, features not fitting smoothly into available 'high level' classes of the classification have been assigned to the nearest 'reasonably appropriate' category. For example, features comprising TGD site no. 2713 – post-glacial bedrock dilation trenches – have been assigned to the class of 'residual forms' since this is strictly correct, even though not an ideal description of the features.

3.4.3 A feature and process classification for Cenozoic glacial and periglacial systems in the TWHHA

The classification of TWWHA glacial and periglacial landforms and deposits produced for this analysis is provided in Table 3. This is a hierarchical classification of *specific* landform types to three levels (primary, secondary and tertiary), but is not a classification of landform assemblages. For the purposes of this analysis, landform assemblages are identified purely as geographically contiguous assemblages of inter-related landform features, and are grouped under geographical names only (e.g., "Mt Anne Massif Glacial Landforms", etc).

Table 3: Classification of features and processes for identification of significant representative elements of TWWHA glacial and periglacial geodiversity.

Primary level **TGD classification Key:** ***Glacial and Cryogenic*** **Theme** (except where noted)	**Secondary level**	**Tertiary level**
Glacio-marine deposits (not relevant to TWWHA Cenozoic features)	n/a	n/a
Erosional glacial landforms (produced on land)	Streamlined topography produced dominantly by sub-glacial abrasion	Areal scouring forms (incl. 'knock & lochan' topography)
		Glacial valleys (troughs & other characteristic forms)
		Breached watersheds (incl. diffluence cols)
		Obstructing rock features (domes, whalebacks, smoothed interfluves, etc)
		Sculpted rock surfaces (incl. bedrock striations, flutes and grooves)
	Partly streamlined topography (combined sub-glacial abrasion and fracturing)	Cols
		Cirques
		Valley steps
		Roche moutonnées

	Non-streamlined, residual and other topographies (produced by combinations of processes including combined glacial and periglacial processes)	Fractured and gouged surfaces (chattermarks, lunate or crescentic gouged or fractured surfaces)
		Residual forms (nunataks, horns, arêtes, gendarmes, cols)
		Others?
	Rock basin lakes (Ice scoured bedrock features currently water-filled)	Cirque lakes
		Glaciated valley lakes
		Other types of rock basin lakes
	Glacio-"tectonic" forms (ice-deformed bedrock features)	Various forms (Kiernan 1996, Table 5.1)
Depositional glacial deposits and landforms (produced on land)	Moraines (direct deposition of sediment bodies on & from glaciers)	Numerous sub-types depending on nature of glacial system (lateral & end moraines, hummocky and ground moraines, drumlins, etc)
	Erratics (individual glacially-deposited boulders)	Erratics
	Lakes impounded by glacigenic deposits (currently water-filled areas formerly occupied by glacial ice)	Moraine-dammed lakes
		Outwash-dammed lakes
		Other lakes barred by glacigenic sediments
	Glacio-"tectonic" features (ice deformed glacial sediments)	Various forms (Kiernan 1996, Table 5.1)
Glacial outwash features (part of TGD Classification Key Theme 6.8: fluvial)	Erosional outwash landforms	Sub-glacial channels cut in bedrock
		Sub-glacial channels cut in drift
		Marginal melt water channels cut in bedrock
		Marginal melt water channels cut in drift or composite
		Proglacial ('downstream') channels cut in bedrock
		Proglacial ('downstream') channels cut in drift
	Depositional outwash landforms	Ice contact outwash deposits (eskers, kames)
		Proglacial ('downstream') deposits (outwash plains or sandurs, outwash deltas, outwash valley terraces, etc)
Periglacial features (non-glacial freezing and thawing or other ice or snow contact processes including melting)	Nivation features (snow-movement or snow-melt processes)	Erosional landforms (nivation cirques or hollows)
		Depositional forms (protalus ramparts, boulder tongues)

	Ground-ice melt- forms (landforms resulting from prolonged ground-ice accumulation and subsequent melting; all fossil features in Tasmania; includes features misleadingly termed 'thermokarst' by French (1976) and Davies (1972) – see Eberhard & Sharples (2013)	Fossil pingos, other ground- ice melt depression forms
		Other fossil permafrost features (ice push features, string bogs, ice-wedge features, others)
	Freeze-thaw erosional forms	Bedrock ice-shatter features (small-scale features, 'frost-shattered')
		Tors (mountain-top, break-of-slope, valley-slope)
		Rock-cut (alti-planation or cryo-planation) surfaces and terraces.
	Freeze – thaw depositional forms	Frost-heave, frost-sorting, patterned ground (in regolith); fjeldmark features (partly aeolian erosion, partly freeze-thaw features)
		Rock glaciers, block-fields, block-streams
		Talus slopes
		Solifluction slope deposits
		Stratified and/or sorted ice or snow-melt related slope deposits (incl. grèzes litées)
		Colluvial terraces (stone-banked, turf-backed)

4.0 Gap Analysis – TWWHA Glacial & Periglacial Geodiversity in the Tasmanian Geoconservation Database

This section provides a gap analysis of TWWHA glacial and periglacial site listings on the Tasmanian Geoconservation Database. In part this gap analysis considers 'gaps' in the straightforward sense of identifying specific features or assemblages which are not listed but arguably should be. However this analysis also considers 'gaps' (or deficiencies) in several other important aspects of TGD listings of glacial and periglacial sites, for example gaps in evidence for appropriate site boundaries, or gaps in the specification of which features within a (digitised) site boundary are actually relevant to the listing (i.e., many glacial or periglacial sites listed have large boundaries containing non-glacial and non-periglacial features that are not relevant to the TGD listing, and it may not be clear to land managers which *are* the relevant features on the ground within a listed site boundary). In other words, this gap analysis endeavours to identify 'gaps' in several differing key attributes of the data contained in TGD listings.

Recommendations to remedy gaps identified here are provided in the Recommendations section (5.3) of this report.

4.1 *Procedure*

The TGD has been systematically reviewed to identify all listed sites falling wholly or partly within the TWWHA that have glacial or periglacial phenomena listed as all or part of their listing values. All these sites have been listed in Table 8 at Appendix 1, which provides a brief summary of the landform classes and other information contained within each listing.

Parts of this information are depicted in map form on Figure 4 (Section 4.2.2), and in Table 5 (end of Section 4.2) the data has also been analysed to summarise the number of occurrences of each listed spatial, temporal and feature class (as defined in Section 3.0) on the TGD. This basic analysis provides information on spatial, temporal or feature classes of glacial and periglacial features that do or could exist in the TWWHA and are either well- or poorly-represented in the TGD (or absent). This aspect of the gap analysis is described in Sections 4.2.2 and 4.2.3 below, and constitutes a simple gap analysis of what representative or outstanding glacial and periglacial phenomena in the TWWHA are or are not adequately listed on the TGD.

In the course of inspecting the TGD data to undertake the basic gap analysis described above, a number of other issues and deficiencies (or 'gaps') in the TGD listings of glacial and periglacial features in the TWWHA also became apparent. These are described in Sections 4.2.4 to 4.2.8 below.

4.2 *Results*

4.2.1 *Introduction – listed TWWHA glacial and periglacial sites*

This section (4.2) lists and discusses results of the analysis described in section (4.1) above.

As at 2012, the TGD contained 84 listed sites whose listing details include glacial or periglacial geomorphic features, and which lie wholly or partly within the boundaries of the

TWWHA[6]. These listings ranged from sites comprising a single specified feature, to larger assemblages of inter-related features, to extensive predictive regions with no specific features listed. They include some sites listed primarily under other geomorphic themes, but which specify glacial or periglacial features as part of the site values (e.g., glacio-karst sites). Table 8 (provided in Appendix 1) provides information tabulated for each such listed site, noting in particular the glacial / periglacial classes into which the elements of each listed site have been classified in terms of the classification described in Section (3.0) above. It is important to note that the classes into which each site has been classified are *only* those which are explicitly specified in TGD listings; listed sites are not classified as including features which in theory might be present but which are not actually specified in the listing. This approach is taken on the grounds that a TGD user or land manager will not necessarily recognise all relevant features within a site polygon as being glacial or periglacial and thus part of the TGD listing unless the listing actually specifies them as such (noting that many listing polygons may also contain non-glacial/periglacial features that are not relevant to the listing).

The classification developed for the purposes of this gap analysis in Section (3.0) is a "three dimensional" classification which allows glacial and periglacial sites listed in the TGD to be classified into four meaningful spatial regions, six key time periods, and 45 landform classes, plus geographically-defined assemblages, parent sites, and predictive regions. The basic information on the glacial and periglacial classes that are specified in each TGD listing is compiled in Table 8 at Appendix 1. From this basic data, Table 5 (at the end of Section 4) analyses the comprehensiveness and representativeness of the diversity of glacial and periglacial sites listed on the TGD by considering the actual and potential representation on the TGD of each landform class within each region or from each time period. That is, for each such possible combination, Table 5 indicates whether such features are listed on the TGD, are not listed but are likely to or may be present in the TWWHA, or are not listed and not likely to exist in the TWWHA. Based on the premise that the TGD ideally should *at least* list a suite of features representative of the full diversity of glacial and periglacial phenomena found in the TWWHA, the basic site listing gaps in the TGD are those features (including features from specific time periods or in specific regions) which probably exist in the TWWHA but are not listed.

Whereas 1080 unique classes can be defined using the '3D' classification described in Section 3.0, for the purpose of this gap analysis Table 5 analyses only the 450 basic combinations of landform class vs. spatial region and landform class vs. time period. These 450 classes encompass the full spatial, temporal and feature diversity of periglacial and glacial landforms listed on the TGD, with the additional 630 possible classes merely repeating various combinations of the basic 450 classes.

[6] Note this excludes TGD site ID 2697 (a fluvial feature consequent on a glacial feature listed separately as site 2696). The sites listed are only those falling wholly or partly within TWWHA boundaries as they stood in 2012.

4.2.2 *Listing of sites at differing levels*

The TGD lists glacial and periglacial sites at what may be considered four levels as follows:

- *Specific landforms (features)*
- *Assemblages of landforms (features)*
- *Parent Sites*
- *Predictive regions*

It should be noted that the TGD listings of specific features or assemblages are not explicitly classified as 'feature' or 'assemblage' listings within the TGD as it currently stands; however the distinction between the two types of listings is self-evident and arguably worth noting and discussing as is done here.

The following table defines each of these levels and notes the number of TWWHA examples of each listed on the TGD:

Table 4: Definition of site listing levels on the TGD, and the number of glacial or periglacial listing of each type that fall wholly or partly within the TWHHA (based on analysis of Appendix 1, Table 8).

Listing level (type)	Definition	Number of listings
Predictive region	Region in which glacial or periglacial features are known or thought likely to exist; but no particular features or assemblages identified.	8
Parent site (assemblage or group of assemblages)	Umbrella site listing covering multiple sub-listings, which may themselves be feature or assemblage listings. Essentially a higher-level "Assemblage" listing.	1 West Coast Range glaciated terrain, mostly (but not completely) outside TWWHA
Assemblage	Integrated assemblage of related features listed for a specified area, but with only a few or in some cases no specific features within the assemblage identified.	24 Mainly glacial, only 3 (arguably) periglacial assemblages listed (TGD sites 2486, 2487 & 2712); glacio-karst systems are also regarded here as assemblages but are discussed separately (Section 4.2.8) from 'pure' glacial assemblages (Section 4.2.3).
Feature	Specific geomorphic feature considered of geoheritage significance in its own right (typically part of larger assemblage, but this is not necessarily described or alluded to in the listing).	51 Individual features specified as listing focus; may range in scale from valley troughs to outcrop-size features.

Issues arising

The use of these four levels of listing within the TGD has been *ad hoc* to date. In particular:

- Predictive regions have been listed for only some glacial landform regions and for no periglacial regions at all (see Section 4.2.3 below). Given that Predictive regions do not list specific features or assemblages as significant geoheritage, but merely serve to indicate that some such *could* be present, it would seem logical that if Predictive regions are to be used at all in the TGD then they should be extended to cover all areas where glacial (and periglacial?) features and assemblages of geoheritage significant might be present. If this is considered inappropriate then it would seem difficult to justify retaining any Predictive regions at all.

- The assemblages and individual features listed on the TGD are mostly derived from a wide range of previous geoheritage lists (Dixon & Duhig 1996), and were essentially listed on the TGD on the basis of having previously been identified as sites of geoconservation significance; however there was no real assessment of the representativeness of listed individual features or of listed assemblages as a whole. As a result the analysis in Section 4.2.3 shows that there are a number of major and undoubtedly important TWWHA glacial assemblages that have not been listed on the TGD (e.g., Eastern Arthurs Range, Denison Range, most of the Pelion & Du Cane Ranges), as well as a great number of specific glacial features that are not identified although at least some of these must be individually significant at some level.

- In a few areas (mainly the Central Highlands) many specific notable features are individually listed as sites, as well as assemblages containing these being listed as such. However over much of the TWWHA most listings are assemblages with few details or individual listings of specific features within them. Thus there is a marked difference in the level of attention given to identifying significant features as opposed to assemblages in different regions. This undoubtedly results in part from differences in the levels of detail in underlying geomorphic data, but nevertheless represents an evident bias within the TGD. Ideally this should be remedied by a combination of the availability of a more comprehensive basic dataset on glacial and periglacial landforms to select representative sites and assemblages from (see Section 5.3.2 recommendation); and a more rigorous application of appropriate definitions of the *purpose* of specific feature versus assemblage listings (see below).

In view of the currently somewhat *ad hoc* implementation of the four levels of listing within the TGD, there is arguably a need to review the purposes of the four levels of listing; to decide whether to retain or modify the four listing levels in the TGD; and if so to review, edit and add to existing glacial and periglacial listings so as to bring them in line with the agreed purposes of each listing level.

It is proposed here that the appropriate purposes of each listing level could be seen to be the following, or something similar:

Predictive regions	These are not “significant site listings”, but rather a means of alerting planners and managers to the fact that significant features may be

	present in an area (and hence should be considered in planning management processes affecting the predictive region). As such, predictive regions for any given geodiversity theme (e.g., glacial or periglacial) should arguably be defined to cover all areas in which representatives of the theme could be present.
Parent sites	A means of identifying meaningful broader assemblages that are themselves composed of multiple sub-assemblages which themselves warrant listing as separate distinctive assemblages.
Assemblages	Inter-related glacial or periglacial process systems (past or present) which have high geoheritage value <u>as</u> systems or assemblages. It is conceivable that cases may exist where no individual constituent feature is sufficiently significant to warrant a specific feature listing, but taken as a whole the entire assemblage of such features constitute a significant system worth listing.
Specific features	Individual features of high geoheritage value, irrespective of the broader integrated values of any assemblage they form part of.

Recommendations to review the purpose of differing site levels and consequently implement consistent usage of these are provided at Section (5.3.4)

4.2.3 *Bias and gaps in site listings*

This section provides a gaps and biases analysis of glacial and periglacial site listings on the TGD in the straightforward sense of identifying sites or features that are not listed on the TGD but arguably should be; and conversely identifying sites or (in particular) feature types that are arguably over-emphasised in TGD listings compared to other under-emphasised types that may arguably be of equal importance in a properly representative glacial and periglacial geoheritage list.

This listing of gaps and biases is based on inspection of the TGD data tabulated in Table 5 and Table 8 , and associated digital mapping of TGD listing polygons (see Figure 4). Biases and gaps in the TGD listing of glacial and periglacial phenomena on the TGD are here analysed at the four levels of site listings identified in Section (4.2.2) above, namely at the *Predictive Region* level, at the *Assemblage* or *Parent Site* listing level, and at the specific *Features* level.

In virtue of the nature and purposes of the four levels of site listing, “gaps” in listings of *Predictive Regions* comprise essentially any known glaciated or periglacial geographical areas that are not listed; gaps in *Assemblages* or *Parent Sites* comprise notable and ostensibly important representative assemblages (as geographical areas) within the four broad glacial or periglacial regions defined for this analysis (see Section 3.3) that are not listed; and gaps (or biases) in *Specific Features* refers to gaps or biases in landform feature

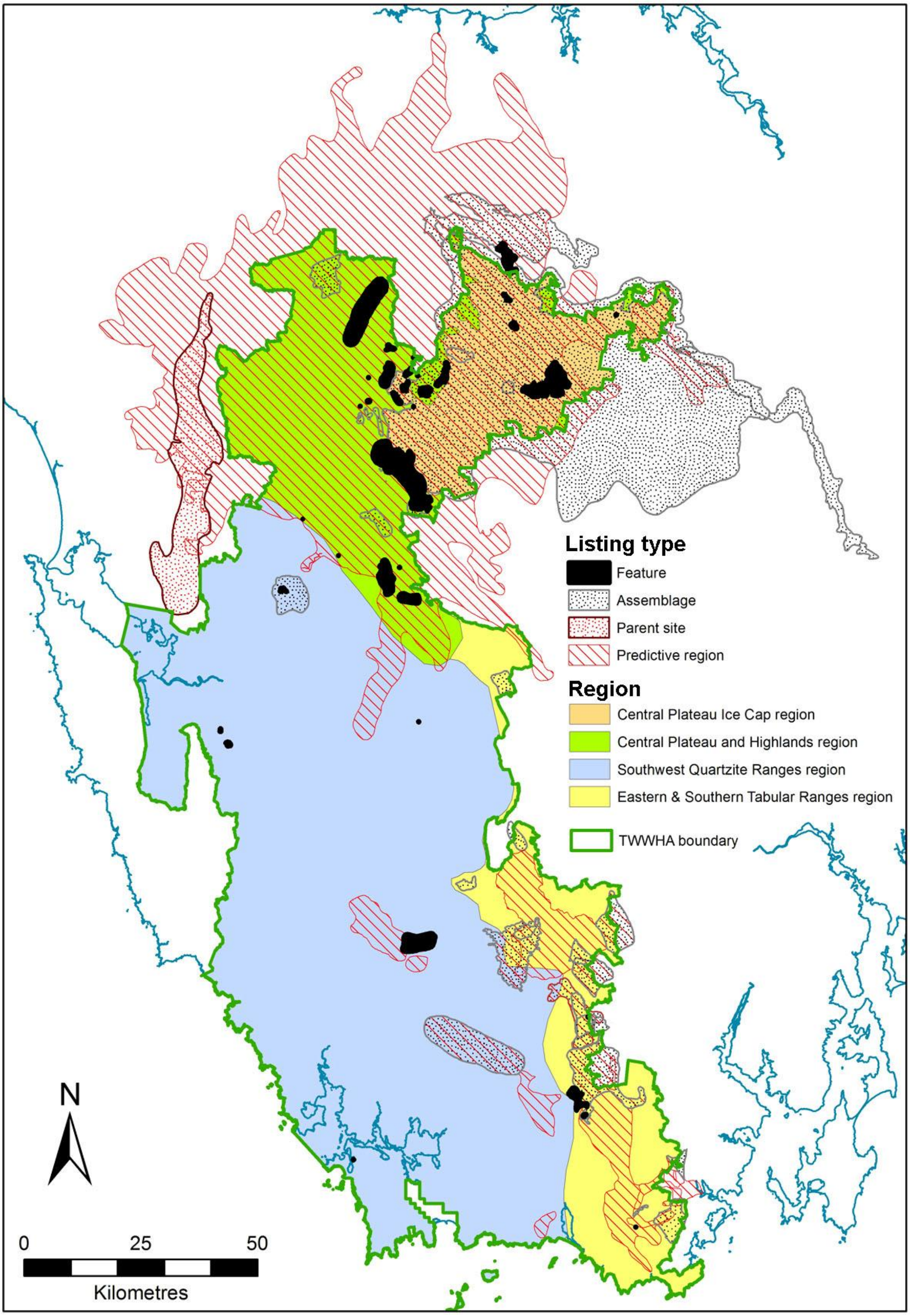

Figure 4: TGD listing types for glacial and periglacial phenomena in the TWWHA, with glacial / periglacial regions as defined in Section (3.3) indicated.

classes or types that are listed (rather than primarily to geographical gaps in actual specific geographical features listed).

Bias and Gaps in Predictive regions listed

The following areas of known glacial landforms falling at least partly within the TWWHA are listed as predictive regions in the TGD:

- West Coast Range - Central Highlands – Central Plateau ice cap and outlet glaciers;
- Eastern Central Plateau ice cap (Poatina area);
- Mt Anne Range – Schnells Ridge – Weld Valley;
- Frankland Range (boundaries very inadequate, excludes significant adjacent glacial features including Wilmot Range, Companion Range, Lake Pedder);
- Snowy Range, Mt Weld;
- Manuka Valley – Mt Picton – Middle Huon Valley glacial systems;
- Eastern and Western Arthur Ranges, Crest Range;
- Southern Ranges – Mt Bobs region – Picton Range – part Hartz Mountains only - Picton Valley;
- Ironbound Range.

No regions have been listed as predictive regions for periglacial phenomena.

The following areas of known glacial or periglacial landforms in the TWWHA are not covered by any predictive regions listed on the TGD:

- Frenchmans Cap Massif (but listed as an assemblage);
- Mt Humboldt – Spires – Lake Curly – Denison Range glaciated region;
- Wyld's Craig – Mt Shakespeare glaciated massif (but listed as an assemblage);
- Mt Mueller – Fossil Lake – Upper Florentine glaciated area (but partly listed as an assemblage);
- Gallagher Plateau (at least one leewards side cirque omitted);
- Mt Wedge – Boyd River glaciated area (but listed as an assemblage);
- Hamilton Range – Wilmot Range glaciated regions;
- Lake Pedder (the natural lake) and associated features and outwash deposits;
- Mt Maconochie, Companion Range;
- Part of Hartz Mountains – Adamson's Peak glaciated region;
- Mt Norold (likely glacial lake);
- All potential periglacial phenomena areas (i.e., none listed).

The following key points stand out from this listing of areas covered by or omitted from TWWHA TGD glacial and periglacial predictive regions:

- By implication any areas covered by predictive regions include not only spatial diversity but also all temporal, feature and process diversity within those regions. Thus predictive regions cover all relevant elements of glacial and periglacial geodiversity if (and only if) all areas where these phenomena are known or thought likely are covered by predictive regions.

- Predictive regions for glacial phenomena fully cover the known glaciated parts of the Central Plateau Ice Cap Region, the Central Plateau and Central Highlands Outlet and Valley Glaciers Region, and much (but not all) of the glaciated parts of the Eastern and Southern Dolerite and Parmeener Tabular Ranges Region within the TWWHA;
- However significant glacial regions in the Southwest Quartzite Ranges Region are not covered by predictive regions, and for those areas that are covered the polygon boundaries are commonly inadequate and do not cover some known glacial areas immediately adjacent;
- Some (but not all) areas listed as Predictive Regions for glacial landforms are also covered by glacial assemblage listing polygons;
- Some (but not all) known glacial landform areas not listed as Predictive Regions are instead listed as glacial landform assemblage polygons;
- No predictive regions have been defined on the TGD for periglacial phenomena;

Issues arising from this analysis are discussed further below, and consequent recommendations are provided in Sections (5.3.4) and (5.3.7).

Bias and Gaps in Assemblages or Parent Sites listed[7]
The following assemblages of known glacial or periglacial landforms falling at least partly within the TWWHA <u>are</u> listed as assemblages or parent sites on the TGD:

<u>Glacial</u>:
The whole Central Plateau ice cap region has been listed as a glacial assemblage with several sub-ordinate overlapping assemblages:

- Central Plateau glaciated terrain;
- Talinah Lagoon end moraine complex;
- Great Western Tiers Escarpment;

Within the Central Plateau and Central Highlands outlet and valley glaciers region, only a small proportion of the glacial assemblages present have been listed:

- Cuvier Valley moraine complex;
- Mt Geryon – Acropolis glacial geomorphology site;
- Cynthia Bay moraines;
- Labyrinth Glaciated Terrain;
- Narcissus Valley Fluted moraines;
- Cradle Mountain Glacial features;
- Upper Franklin Valley glacial features area;

Within the Southwest Quartzite Ranges region, only two glacial assemblages have been listed:

- Western Arthur Range glaciated terrain;
- Frenchmans Cap glacial area;

[7] To simplify analysis, this assemblage analysis does not include karst assemblages listed as including glacio-karstic features, although these have been separately considered in this gaps analysis in Section 4.2.8 below).

Note that the West Coast Range parent site lies adjacent but mostly outside the TWWHA in the Southwest Quartzite Ranges region.

Within the Eastern & Southern Dolerite and Parmeener Tabular Ranges region, a substantial proportion of glacial assemblages present have been listed:

- Wyld's Craig – Mt Shakespeare glaciated massif ('Florentine Valley glacial areas');
- Part of Mt Mueller – Upper Florentine glaciated area ('Florentine Valley glacial areas');
- Mt Wedge – Boyd River glacial area;
- Mt Anne Massif glacial area;
- Lower Weld Valley Glacial site (area);
- Snowy Range glacial features;
- Manuka Valley – Mt Picton – Middle Huon Valley glacial assemblages;
- Picton Valley glacial systems;

<u>Periglacial</u>:
The following periglacial landform assemblages have been listed:

- Mt Olympus rock glaciers;
- Mt Rufus solifluction terraces;
- Walls of Jerusalem Last Glacial ice window;
- Moonlight Ridge periglacial features;
- The Boomerang solifluction steps;

The following known assemblages of glacial or periglacial landforms falling at least partly within the TWWHA <u>are not</u> listed as assemblages on the TGD:

<u>Glacial:</u>
Within the Central Plateau and Central Highlands outlet and valley glaciers region, most glacial assemblages present have <u>not</u> been listed, including:

- Glacial assemblages in the Eldon and Pelion Ranges, most of the Du Cane Range, and numerous other adjoining glaciated areas;

Within the Southwest Quartzite Ranges region, most glacial assemblages present have <u>not</u> been listed, including glaciated areas in:

- The Frankland – Wilmot Ranges;
- Lake Pedder (note that the original Lake Pedder is listed on the TGD as a feature (it is an outwash-dammed glacial lake), however the listing cannot be considered as an assemblage listing since it does not specify or fully include within its boundaries the associated assemblage features (e.g., the outwash barrage itself which dams the lake);
- The Mt Humboldt - Spires – Denison Range area;
- The Eastern Arthurs, Crest Range and Mt Norold areas;
- The Ironbound Range.

Within the Eastern and Southern Dolerite and Parmeener Tabular Ranges region, a number of glacial assemblages present have <u>not</u> been listed, including:

- Southern Ranges glacial terrains;
- Most of the Hartz Mountains glacial assemblage;

Periglacial:
All other known and likely periglacial landform assemblage areas in the TWWHA have not been listed, including:

- Central Plateau (known present day patterned ground; terracing and ice shatter features; last glacial features beyond ice limits);
- Mt Anne massif (nivation hollows, terracing, potential patterned ground, etc);
- Mt Gould – High Dome alpine Parmeener ridges (terraces and patterned ground likely);
- Numerous other alpine areas (present day features possible);
- Extensive other alpine to sub-alpine areas (Last glacial areas beyond ice limits - wide range of Last glacial periglacial features possible);

The following key points stand out from this listing of areas covered by or omitted from TWWHA TGD glacial and periglacial assemblage or parent site listings and polygons:

- It is implicit that all assemblages or parent sites include the full diversity of feature types and processes, and temporal diversity (stage of glaciation) for which evidence is preserved within the mapped assemblage boundaries. Thus assemblage and parent site listings and polygons cover all relevant elements of glacial and periglacial geodiversity if (and only if) all areas where these phenomena are known or thought likely are covered by assemblage boundaries.
- Only a small and seemingly arbitrary proportion of known glacial and periglacial phenomena assemblages in the TWWHA are listed as assemblages on the TGD;
- Only the Central Plateau Ice Cap region has been comprehensively listed as a glacial assemblage, namely the "Central Plateau glaciated terrain" (albeit with few details provided);
- A substantial proportion of glacial assemblages in the eastern and southern Dolerite and Parmeener Tabular ranges region have been listed, although the Southern Ranges glacial area is a significant omission;
- However only a very small proportion of known glacial assemblages in the other two spatial regions (Central Highlands and Southwest region) have been listed;
- Some (but not all) areas listed as glacial assemblages are also listed as predictive regions for glacial phenomena;
- However some areas of glacial phenomena not listed as predictive regions are instead listed as glacial assemblages (e.g., Mt Wedge, Frenchmans Cap massif);
- Only a very small proportion of areas that are likely to exhibit Last Glacial age or present-day periglacial phenomena have been listed as assemblages; this reflects at least partly the poor state of both knowledge and mapping of periglacial features in the TWWHA.

Issues arising from this analysis are discussed further below, and consequent recommendations are provided in Sections (5.3.2), (5.3.3), (5.3.5) and (5.3.7).

Bias and Gaps in Specific Features listed

The spatial and temporal coverage of individual feature listings in the TGD is sporadic and limited across all four spatial regions defined for this analysis (see Figure 4). Although some individual non-listed features are undoubtedly significant and are likely to warrant listing on the TGD (for instance, Federation Peak glacial horn and arêtes), no systematic attempt has been made to identify and list specific glacial and periglacial features that are not presently listed but may warrant listing. This is because the practical identification of a list of specific features warranting listing ideally requires systematic and preferably consolidated data on all known features in order to conduct a proper comparative significance assessment. Such data is not currently available in any consolidated form that could be readily analysed, and instead two key recommendations of this report are that a suitable consolidated database should be prepared (Section 5.3.2), following which a systematic significance assessment and listing process for assemblages and specific features should be carried out (Section 5.3.5).

Instead, this bias and gap analysis of individual glacial and periglacial feature listings on the TGD concentrates on evaluating the degree to which there are biases and gaps in the types or *classes* of features listed, using the feature classification derived for this analysis as a basis (see section 3.4).

Specific glacial and periglacial features are listed on the TGD either as individual feature listings or as specific features cited as parts of listed assemblages (see Section 4.2.2 above). This analysis of bias and gaps in listings of specific glacial and periglacial features on the TGD has been made by reference to Table 5, which in turn has been compiled by analysing the data compiled from TGD listings in Appendix 1. Note that whilst Table 5 tabulates the number of times particular feature types (classified as described in Section 3.0) have been listed on the TGD, this does not necessarily equate to the number of individual site or assemblage listings, as some listings may specify features belonging to more than one class, which are therefore tabulated separately in Table 5.

By reference to Table 5, it is evident that the following are common amongst listed glacial and periglacial features:

<u>Glacial</u>

- Moraines, till deposits and erratics (multiple examples listed for all spatial regions and glacial temporal periods);
- Glacio-fluvial (outwash) sediments or landforms (mostly multiple examples listed for all spatial regions and all but one of the glacial temporal periods);
- Cols, breached watersheds;
- Cirques, and glacial valleys;
- Non-streamlined residual forms such as nunataks and horns (examples listed for most but not all spatial regions and glacial temporal periods);
- Certain streamlined ice-abraded features, notably striations, roches moutonnées and valley steps;
- Glacial lakes (in a range of glacially-formed basins);

Periglacial

- Nivation landforms (nivation cirques)
- Rock glaciers, blockfields, block streams
- Talus slopes, solifluction slope deposits
- Alpine-zone active sorted stone terraces (mainly vegetation-banked)

The representation of some other glacial and periglacial features (such as eskers, ice-wedge features, periglacial tors or stratified slope deposits) listed in the classification used in Table 5 is patchy, with such landform classes listed only for one, two or three of the four spatial regions and/or six temporal periods for which they are likely to occur within the TGD.

In contrast, notable categories of glacial or periglacial landforms in the classification used in Table 5 (based on Section 3.0), which do or may exist in the TWWHA but are only poorly or not at all listed on the TGD, include the following:

Glacial

- 'Knock and lochan' topography: the Central Plateau is an excellent expression of this important type of glacial landscape in Tasmania, and whilst it is covered by a TGD predictive region and a glacial landform assemblage polygon/listing, 'knock and lochan' topography is not specified as an element of either listing;
- Obstructing rock features including domes, whalebacks and smoothed interfluves;
- Fractured or gouged surface features
- Sub-glacial, marginal or proglacial meltwater channels

Periglacial

- Ground ice melt depression features (e.g., pingos);
- Bedrock ice-shatter features;
- Bedrock cryo-planation surfaces and terraces (e.g. inferred examples documented in State forest beyond the TWWHA near Butlers Gorge by Sharples 2006a);
- Frost heave and patterned ground features (e.g., well-developed stone polygons on The Boomerang (TWWHA): authors personal observations);
- Fjeldmark features (common in TWWHA, none listed);
- Moderate to large scale stone-banked terraces (relatively common and moderate to large scale in dolerite colluvium, inferred to be Last Glacial – age periglacial features, none listed, mostly unstudied but examples have been noted by the present writer in State forest areas peripheral to the TWWHA);

The following key point stands out from this listing of specific feature classes covered by or omitted from TWWHA TGD glacial and periglacial specific feature listings and polygons:

- Certain classes of both glacial and periglacial landform are much more commonly specified in the TGD (either as specific feature listings or by mention in Assemblage listings) than others. It is not clear whether such biases and gaps arise because of:
    - a lack of intention or ability (due to data limitations) to identify all relevant constituent landforms in glacial or periglacial assemblages listed on the TGD; and/or:

- actual absence of certain feature types from Tasmanian glacial or periglacial terrains; and/or:
- because certain features are simply more obvious (e.g., moraines) and are thus noted more frequently in TGD listings; and/or
- because of a lack of recognition of certain landform types that are present in the TWWHA but whose type have not been identified or studied in that region.

Issues arising from this analysis are discussed further below, and consequent recommendations are provided in Sections (5.3.2), (5.3.3), (5.3.5) and (5.3.6).

Issues arising

In summary, the key issues that can be seen to arise from the identified gaps and biases in TGD listings of glacial and periglacial phenomena can be summarised as follows within the framework of the four differing levels of TGD listing:

Predictive Regions

The inclusion of predictive regions for glacial and periglacial phenomena on the TGD is incomplete and arguably arbitrary, with for example good coverage of the Central Plateau and outlet glaciers regions, poor coverage of the Southwest Quartzite Ranges glacial regions, and no coverage of periglacial landform regions at all.

If the recommendations in Section (5.3.4) on the appropriate purpose and use of predictive regions in the TGD are adopted (following the discussion in Section 4.2.2 above), then a key element of implementing those recommendations will be to extend coverage of glacial and periglacial predictive regions to cover all known areas of glacial and periglacial phenomena, thereby resolving this issue (see Section 5.3.7). Alternatively, if in response to the recommendations it is decided to discontinue the use of predictive regions in the TGD, then this issue will equally be resolved thereby.

Assemblages and Parent Sites

The essential issue arising from the identified gaps and biases in the listing of glacial and periglacial assemblages is – as for predictive regions – the arbitrary and incomplete nature of the listings, with some ostensibly very important glacial assemblages - and many likely important periglacial assemblages - not being listed on the TGD. However, whereas in the case of predictive regions it is arguable that all known areas of glacial and periglacial phenomena should be included on the TGD (in virtue of the purpose of predictive regions), this is not necessarily the case for assemblages and parent sites.

Instead, the purpose of assemblages and parent sites is to identify and list *significant* assemblages of glacial or periglacial geoheritage value. As such it follows that not all known sites will necessarily be listed (although they might be); rather assemblages or parent sites will be listed only if they are assessed to have some significant degree of geoheritage value as representative or outstanding exemplars of their type. (Note however there is an argument that all glacial features in the TWWHA should be listed because they are collectively one of the key values for which the TWWHA was listed as World Heritage by UNESCO; see further note on this below).

The somewhat arbitrary and incomplete nature of glacial and periglacial assemblages listed on the TGD reflects the *ad hoc* compilation of the TGD up to the present time. There has not to date been a systematic assessment of glacial and periglacial features listed on the TGD, and until this happens the listing of assemblages and parent sites will remain arbitrary. At present the capacity to undertake such a systematic assessment is limited by two factors, firstly by gaps and limitations in knowledge of glacial and (especially) periglacial phenomena in the TWWHA, and secondly by the lack of a consolidated database on all such known phenomena, which would provide an essential first step towards undertaking a properly systematic assessment and identification of the best glacial and periglacial assemblages representative of their georegions.

A number of recommendations responding to these issues are provided in Section 5 of this report, namely:

- a recommendation that more information be obtained on poorly understood aspects of TWWHA glacial and (in particular) periglacial phenomena (Section 5.3.3); and:
- a recommendation that a consolidated digital (GIS) database of TWWHA glacial and periglacial features be created and maintained (Section 5.3.2); and:
- a recommendation that a systematic assessment and identification of key representative (and outstanding) TWWHA glacial and periglacial landform features and assemblages be undertaken once a suitable comprehensive dataset is available (Section 5.3.5).

It is likely that many of the TWWHA glacial and periglacial assemblages not currently listed on the TGD should in fact be so listed, and indeed it may be arguable that *all* glacial assemblages in the TWWHA should be listed in view of the fact that glacial values are one of the key values for which the TWWHA was registered as a World Heritage Area.

If the latter view is adopted, then the addition to the TGD of comprehensive predictive regions as recommended above (and see Recommendation 5.3.7) could be upgraded to listing all those regions as Assemblages rather than as predictive regions.

However it will be difficult to define appropriate assemblage polygon boundaries, and to conduct any systematic comparison of geoheritage significance between assemblages, until a consolidated GIS dataset for glacial and periglacial sites is available as per Recommendation (5.3.2). It is therefore recommended that:

- listing and boundary definition of TWWHA glacial and periglacial assemblages determined to warrant listing on the TGD through a systematic assessment (as per Recommendation 5.3.5) should be conducted when a suitable consolidated GIS dataset is available on which to base such an assessment and boundary definition (see Section 5.3.7).

However, exceptions to this should apply for any assemblages subject to focussed assessment in advance of a consolidated dataset becoming available. Hence, if focussed studies of periglacial features (as per Recommendation 5.3.3) reveal assemblages obviously meeting significance and condition requirements for TGD listing, then these should be listed irrespective of progress on a consolidated dataset (Recommendation 5.3.7). Similarly if focussed studies on any unlisted TWWHA glacial assemblages demonstrate they warrant listing, these too could be listed in advance of a comprehensive systematic assessment.

Specific Features
As noted above, evident gaps and biases in listings of specific glacial and periglacial features on the TGD may be due to one or more of the following causes:

- a lack of intention or ability (due to data limitations) to identify all relevant constituent landforms within glacial or periglacial assemblages listed on the TGD; and/or:
- actual absence of certain feature types from Tasmanian glacial or periglacial terrains; and/or:
- because certain features are simply more obvious (e.g., moraines) and are thus noted more frequently in TGD listings; and/or
- because of a lack of recognition of certain landform types that are present in the TWWHA but whose type have not been identified or studied in that region.

Consideration of these possible causes of gaps and biases points towards a number of recommendations as follows:

In regard to the (high) likelihood that our knowledge of the full range of glacial and periglacial landforms in the TWWHA is incomplete, further study of these features and associated processes is clearly warranted in the context of glacial geomorphology having been a key value for which the TWWHA was listed as World Heritage. However at the present time it is likely that further study of periglacial landforms in particular will be more fruitful in filling major gaps in our knowledge, since these have been comparatively neglected by past studies relative to glacial features. Such studies may lead to better understanding of the range of glacial and especially periglacial features that are actually present in the TWWHA, and hence to filling such gaps in the TGD, or confirming that certain gaps are mostly likely due to actual absence. Section (5.3.3) provides recommendations to this effect.

In regard to features which are (or will in future be) known to be present in the TWWHA but which are either over- or under-represented in the TGD, there are some significant differences in the implications of this for landform assemblage listings as opposed to listings of specific individual features:

It is arguable that the TGD is not the appropriate framework for identifying all individual glacial or periglacial features that belong within landform assemblages listed on the TGD, and that as such the existing lack of comprehensive feature lists in TGD Assemblage listings is therefore not necessarily problematic. The purpose of the TGD is to identify things (including whole landform assemblages) that have been assessed as having significant geoheritage value. It is arguable that it is more efficient for the TGD to define why assemblages are significant (with reference to specific features where necessary for this purpose) but to rely on a separate 'underlying' geomorphic mapping dataset to provide the actual details of the full range of known glacial or periglacial features in the assemblage. Sections (5.3.2) and (5.3.6) provide recommendations to this effect.

In respect of stand-alone listing of individual glacial and periglacial features, it is recommended in Section (5.3.4) that a decision should be made as to whether the TGD should continue to differentiate between assemblage listings and specific feature listings (as it currently does). Individual listing of specific features is arguably warranted when such features are considered to be significant as good representative exemplars of their particular landform type, irrespective of the broader significance of any assemblages they may also be a part of. However the listing of specific (individual) glacial and periglacial features on the TGD has to date generally been undertaken on an *ad hoc* basis using professional judgement, and this has resulted in some gaps and biases as noted above. In order to more systematically identify a comprehensive range of representative (and 'exemplary') individual features for listing, there is a need for a consolidated database on glacial and periglacial landforms, which can then be subject to a systematic assessment to identify a comprehensive listing of representative specific features and thereby resolve gaps and biases. This issue is further discussed in Section (4.2.6) below, and relevant recommendations are provided at sections (5.3.2) and (5.3.5).

In lieu of the sort of systematic assessment proposed above, it is problematic to suggest specific unlisted features that ought to be listed on the TGD, since this would involve the same *ad hoc* assessment style that has resulted in the gaps and biases in the listing of specific features on the TGD to date. Hence no recommendation is made here for such new listings, although it is recognised that specific *ad hoc* nominations may arise from time to time in advance of a systematic assessment that clearly warrant listing on their own merits.

4.2.4 *Degree of detail within listings*

As noted in Section 4.2.2 above, most TGD listings of glacial or periglacial Parent Sites or Assemblages provide very little detail of the constituent landforms and deposits. Inspection of TGD listing records in the course of this analysis has shown that in most cases only a small subset of what can be inferred to be a more diverse set of relevant significant features are actually identified in the listings. Table 8 in Appendix 1 lists all individual feature types that are noted specifically in each glacial or periglacial listing in the TGD; in the case of most listed assemblages, it is obvious that the feature classes listed constitute only a subset of the relevant glacial or periglacial features that occur within each assemblage. Some TGD entries are poorly defined and inadequately described. For example, the polygon for Snowy Range Glacial Systems (TGD site 3034) appears intended to cover the full glacial assemblage including highland features, however the database description refers only to distal valley features and specifies only tills. Again, the Central Plateau Terrain (site 2684) is cited only as an 'ice-cap glaciated terrain' and amongst other omissions does not note that this is arguably Tasmania's best and most extensive 'knock and lochan' ice-scoured terrain; yet this is critical to understanding the regions significance and managing it appropriately.

Issues arising

This lack of specific detail raises a number of issues in regard to the utility of the TGD as a land management tool, including:

- It is not clear that the boundaries of all glacial and periglacial sites actually include all inter-related features that the site should implicitly include. It is likely that in many

cases the boundaries may be based on assumptions rather than actual data, resulting in the inadvertent exclusion of features that should be included, or conversely the inclusion of substantial peripheral areas that do not actually include glacial or periglacial features (see also section 4.2.5 below).
- The listings and digitised site polygons do not enable land managers to determine which features within the listed area are actually glacial or periglacial features requiring appropriate management, and which are unrelated features that simply happen to lie within the area of glacial or periglacial landforms.
- The lack of specific details on the significant landform or deposit types within areas listed as significant hinders the ability to plan to avoid detrimental impacts on significant features (which may respond differently to various activities depending on their type).

As the TGD listings currently stand, it would be necessary for land managers or those providing them with geoconservation advice to undertake new field surveys and/or refer back to the original geomorphic source data on which the listings are based, in order to actually determine the spatial location and specific characteristics of particular features requiring consideration in the course of any planning process that may have physical impacts on significant features. Collating the original data – which may be scattered through numerous and sometimes obscure papers and reports - or undertaking new field mapping are both time consuming procedures, and it would clearly be inefficient to need to repeat these each time a new management issue arose in regard to a particular TGD listing.

On the other hand however, it is arguably not the purpose of the TGD itself to contain all relevant detailed information about each listed site, assemblage or parent site, but rather simply to serve as a means of identifying significant sites and areas so that they are brought to the attention of land managers as necessary.

These considerations point to the need for an additional layer of information bridging the gap between the TGD and the wide range of underlying data sources on which it is ultimately based. It is argued here that what is needed to resolve the concerns described above is a single consolidated, comprehensive and consistently mapped GIS dataset for glacial and periglacial landforms in Tasmania, that would serve a role similar to that which has previously been implemented for a range of other geological and landform themes in Tasmania including karst and coastal landform themes (consolidated mapping prepared for these themes by Kiernan 1995 and Sharples *et al.* 2006 respectively). This would provide the information that managers need in order to appropriately manage those sites that are listed on the TGD, and yet would also provide additional benefits irrespective of the TGD since it would additionally serve as a tool to facilitate a wide range of other useful land management and pure research functions.

See recommendations in Section (5.3.2) for further explanation of the recommended consolidated dataset, and Section (5.3.6) for recommendations regarding the use of such a dataset to resolve issues surrounding the need for detailed information on the specific features that form integral parts of each TGD listing.

4.2.5 *Adequacy of listing boundaries*

A related issue arising from the lack of detail in TGD listings of glacial and periglacial features (Section 4.2.4 above) concerns the digitised polygon boundaries for each listing. Inspection of the polygons (depicted at small scale on Figure 4) and comparison of these with the writers own knowledge of the spatial distribution of related geomorphic features has demonstrated that in many cases the polygon boundaries for – in particular – predictive regions and assemblages have been drawn roughly or schematically and do not include all known features that should arguably be included.

For example, Gallagher Plateau (TWWHA) is partly included within two predictive regions and one assemblage polygon for glacial and glacio-karstic assemblages, yet none of these polygons cover a well-developed Last Glacial cirque and cirque lake on the south side of the plateau (visible in Figure 6). Similarly, the Southwest Tasmania Glacial Areas predictive region polygon (TGD site 2787) omits several probable glacially-dammed lakes in the heavily glaciated Eastern Arthur Range, and arbitrarily includes only part of a very prominent moraine (Lancaster's Lead) on the north side of the West Cracroft Valley. Conversely, many assemblage polygons also include areas that probably do not contain any known or likely glacial or periglacial features.

Whereas some TGD polygons have defendable rationales (e.g., the Central Highlands Cenozoic Glacial Area (site 2953) polygon is based on maximum Cenozoic ice limits inferred by Kiernan 1990a; see Figure 1), others have evidently been drawn in a more arbitrary fashion based on little mapped glacial or periglacial data. Moreover, even where some mapped rationale such as known ice limits has been used, these polygons may still exclude related features such as glacial outwash deposits beyond ice limits, and moreover inevitably involve data gaps which must be judgementally extrapolated across in order to produce closed polygon boundaries for the TGD.

Issues arising

Although there are always likely to be some gaps in fundamental data on the distribution of glacial and periglacial features in the TWWHA, it is also the case that existing data demonstrates numerous inadequacies in TGD polygon boundaries for glacial and periglacial phenomena that can be corrected with available data (as in some of the examples above). Given that one important function of the TGD is to alert planners and land managers to the presence of significant features requiring consideration, it is clearly detrimental to good planning in the TWWHA if it is possible for known glacial and periglacial features to be located outside of polygon boundaries which should reasonably be expected to encompass them. In the worst case this could lead to damage of significant features by inappropriate management practices, despite all required procedures – including consulting the TGD – having been correctly carried out.

As is the case for several other desirable improvements to the TGD, a major part of the reason why some polygon boundaries have been drawn inaccurately, and remain difficult to correct, is the lack of a consolidated comprehensive mapped dataset on known glacial and periglacial features in the TWWHA (and Tasmania as a whole). As long as it remains necessary to search out a wide range of original data sources in order to check polygon boundaries for accuracy, it will be impractical to comprehensively review and correct TGD glacial and periglacial polygon boundaries within time frames and thus budgets that are likely to be available for this purpose.

The recommended solution to this problem is the same solution that this report advocates for several other TGD problems raised by this analysis; namely that a comprehensive consolidated digitally-mapped (GIS) database of all currently known TWWHA (and Tasmanian) glacial and periglacial phenomena be prepared, and that once available this dataset be used to review and edit TGD polygon boundaries in an efficient manner.

Recommendations for these two actions are provided in Sections (5.3.2) and (5.3.6) of this report respectively.

Whilst it is acknowledged that improved mapping data will not solve all boundary problems since there will probably always remain some basic source data gaps which cannot be resolved, nonetheless polygons drawn using a comprehensive mapped dataset consolidating all known glacial and periglacial features will provide considerable improvements over the current TGD polygon boundaries.

4.2.6 *Appropriateness of listed features as representative or outstanding exemplars of their type*

One purpose of a geoheritage list or database is typically held to be that it identifies features or phenomena which are considered to be amongst the best representative or outstanding examples of their type (i.e., the most ‘significant’ of their type). This allows limited management resources to be preferentially focussed on features considered most important from a geoconservation perspective. One aspect of this gap analysis was to evaluate the degree to which the listing of glacial and periglacial phenomena on the TGD achieves this purpose.

Although most glacial and periglacial features and assemblages listed on the TGD were nominated on the basis of a professional judgement that they were good examples of their type, there is no evidence within the listings of any more systematic assessment of the relative significance of each listed example as compared to other available examples of its type. The main indicator of this within the TGD itself is the fact that the default ‘Statement of Significance’ for most glacial and periglacial sites has been ‘notable example of type’. In principle this implies all features have been evaluated in context and determined to be good representative exemplars of their type, however it is my understanding (from personal involvement with the TGD since its inception) that in practice this statement has generally been applied simply as a default. As such it actually gives no useful information as to which listed features are more excellent and which are more mediocre examples of their class.

During the original project to compile the first version of the TGD (Dixon & Duhig 1996) a georegional approach to systematic assessment of Tasmanian geoheritage was explored – including specifically glacial and periglacial landforms – and a number of georegions were defined, mapped at 1:100,000 scale and used to make an initial gap analysis of the TGD. However this did not result in additional gap-filling listings at the time, and the method has not subsequently been explored further as a means to achieving systematic representation of glacial and periglacial (or other) geoheritage types on the TGD.

Issues arising
Appropriate glacial and periglacial features have never been selected for listing in the TGD on the basis of systematic and comparative assessments of all available data, but have instead been selected in an *ad hoc* (albeit professionally judged) manner. In general it is arguable that a systematic comparative assessment of all known features (which must still be carried out using professional knowledge) is a better basis for selecting a suite of the best available exemplars of each extant assemblage or feature class to be listed as having geoheritage significance at particular levels.

However in the case of the TWWHA it is also arguable that all glacial and periglacial features and assemblages within that region should be listed on the TGD in any case, on the grounds that glacial and periglacial values were one of the key grounds for listing the TWWHA on the UNESCO World Heritage List (DASETT 1989), hence all such features within the TWWHA contribute to this world heritage value. Nonetheless, even if this argument is accepted, there is still value in distinguishing the best listed examples of each class of phenomenon from less well-expressed or more degraded examples, since this allows prioritisation of management attention in situations (e.g., tourism development proposals) where ignorance of comparative values of different sites could lead to un-necessary degradation of more important site. If all known examples of a particular class of phenomenon are listed, better examples can still be distinguished from lesser examples by means of appropriate statements of significance levels or reasons.

Thus it is arguable that the TGD should identify the most significant – or best representative or outstanding – examples of each of the various classes of glacial and periglacial phenomena that it lists. However this expectation is not fulfilled by the TGD as it currently stands. The writer considers that the main obstacle to undertaking more systematic comparative assessments of significance for TWWHA glacial and periglacial phenomena is that there has been no consolidated, comprehensive and consistently classified database or map of the full inventory of known glacial and periglacial features in the TWWHA or Tasmania as a whole, which could have provided a suitable basis for undertaking such comparative assessments by means of systematic searching and analysis. It would be difficult or impossible to carry out comparative assessments across the numerous individual primary data sources, which instead would need to be first consolidated into one comprehensive dataset in any case. Hence the lack of comparative significance assessments of glacial and periglacial phenomena in the TGD to date provides another justification for recommending the development of such a consolidated dataset (see Recommendations Section 5.3.2). Following the development of such a dataset, it is recommended (Section 5.3.5) that a systematic review of site significances be undertaken using the dataset – both for listed and unlisted sites – to identify priorities for additions to or deletions from the TGD.

4.2.7 *Overlaps between listed assemblages*
In a number of cases, differing TGD listings overlap in respect of glacial features, by listing the same features and areas, commonly with no significant additional data being provided by

the multiple listings. An example is the glacial (including glacio-karst) elements in the TGD sites 2542 (Manuka Creek – Blakes Opening – Mt Picton Karst), 2558 (Riveaux – Blakes Glaciokarst) and 2567 (Blakes Opening Glacial / Interglacial sequence).

Issues arising

It is reasonable and expected that some features may fall within more than one TGD site listing in cases where those listings are at different levels in the hierarchy of listing levels identified in Section (4.2.2) above. That is to say, a specific feature listed as a site may overlap with a listing of the broader assemblage of which it is a part, which in turn may overlap with a Predictive Region covering that assemblage and feature.

However, where glacial or periglacial assemblages overlap with other assemblage listings that include some of the same features, the potential exists for some confusion to occur in use and analysis of TGD data. In particular, some analyses would indicate that more features of a particular type have been listed than is actually the case, because some features are being counted twice because they are part of two different assemblage listings.

For many management purposes overlaps such as these are perhaps of little consequence. However the existence of such overlaps may in some cases be evidence of inaccurate assemblage boundary locations (as identified to be a problem in Section 4.2.5 above), and in any case as noted above has the potential to create confusion when analysing TGD data for purposes such as assessing representation adequacy and significance of listed sites (Section 5.3.5).

Consequently, it is recommended in Section (5.3.6) below that in the course of reviewing and editing TGD site boundaries, overlaps between assemblage boundaries should be identified and eliminated.

4.2.8 *Glacio-karst*

Tasmania is the part of Australia most extensively glaciated during the Cenozoic glaciations, and a number of areas affected by glacial processes (erosional or depositional) are underlain by karstified carbonate bedrock. Hence glacio-karst interactions have previously been identified as a distinctive and characteristic element of glacial geomorphic systems in Tasmania, with most known examples occurring within or adjacent the TWWHA (e.g., Kiernan 1989).

Glacio-karst phenomena are mentioned as a component of 14 TGD listings (see Appendix 1, Table 8). In most cases the listings are primarily listings of karst (predictive regions or assemblages), with the existence or possibility of glacio-karst interactions being briefly noted but without specific glacio-karst features being identified (for example, TGD site 2685: Mole Creek Karst). In only five cases are specific features or assemblages listed as glacio-karst features or assemblages *per se*, namely site 2350: Lake Tahune glacio-karstic cirque; 2483: Lake Sydney glacio-karstic lake; 2558: Riveaux – Blakes Glacio-karst; 3073: Mt Anne (North-east ridge) Glacio-karst; and 3244: Eldon Peak Glacio-karst.

In a number of cases specifically glacio-karst listings or karst listings with glacio-karst elements noted overlap with purely glacial listings, creating further examples of the overlap problems referred to in the previous Section (4.2.7) with some glacial features effectively being listed twice or even three times in separate TGD listings. Examples include:

- Overlaps between the glacial and glacio-karst elements of TGD site 2542 (Manuka Creek – Blakes Opening – Mt Picton Karst), 2558 (Riveaux – Blakes Glacio-karst), 2535 (Huon Valley Glacial Systems) and 2567 (Blakes Opening Glacial / Interglacial sequence);
- Site 2538 (Lune Valley Glacial systems) overlaps the glacio-karst elements of 2547 (North Lune and Lune Plains karst), and:
- Site 3072 (Mt Anne Massif Glacial Landforms) overlaps with 3073 (Mt Anne North-east Ridge Glacio-karst) and the glacio-karst elements of 3045 (Weld River Basin Karst & Fluvial Systems)**.**

Issues arising
In principle it is desirable to minimise listing overlaps that involve the same features or assemblages being listed more than once for essentially the same values. Section (4.2.7) above identifies some problems that arise from overlapping listings of the same phenomena. The listing of glacio-karst assemblages on the TGD has created this issue in a small number of cases, for example Site 3072 (Mt Anne Massif Glacial Landforms) and 3073 (Mt Anne North-east Ridge Glaciokarst), both of which are assemblage listings that cover the same glacial features where these are associated with karst.

It is questionable whether this degree of overlap between glacial assemblage listings is warranted; an alternative would be simply to note well-developed glacio-karst as a key value of 3072 (Mt Anne Massif Glacial Landforms).

On the other hand, the separate listing of specific well-expressed glacio-karst features (from a broader glacial assemblage with glacio-karst values noted) seems quite appropriate and in keeping with the purposes of these two differing levels of listing (see sections 4.2.2 and 5.3.4). Thus the separate listing of sites 2350 Lake Tahune glacio-karstic cirque and 2483 Lake Sydney glacio-karstic lake is appropriate as a way of identifying these as particularly well-developed examples of glacio-karstic processes.

As the TGD currently stands, glacio-karst features are listed in the TGD in following ways:

- Karst assemblage listings with brief references to glacio-karst but few details (most glacio-karst references in the TGD are of this type).
- “Glacio-karstic assemblages” listings which in some cases partly or wholly overlap with purely glacial assemblage listings (sites 2558 Riveaux – Blakes Glacio-karst, 3073 Mt Anne (North-east ridge) Glaciokarst, and 3244 Eldon Peak Glaciokarst.).
- Specific glacio-karst feature listings (sites 2350 Lake Tahune glacio-karstic cirque and 2483 Lake Sydney glacio-karstic lake).

Whilst there is arguably some value and only minor redundancy in noting the presence of glacial influences in karst assemblages which overlap with glacial assemblage listings (e.g., site 2538 Lune Valley Glacial systems overlaps 2547 North Lune and Lune Plains karst which notes the glacio-karstic influences), and the separate listing of outstanding specific glacio-karst features seems clearly warranted, the main redundancy in the present listings is the overlap of listed glacial assemblages with listed glacio-karst assemblages (the key examples being site 2558 (Riveaux – Blakes Opening Glacio-karst) which overlaps with 2535 (Huon Valley Glacial Systems), and site 3073 (Mt Anne North-east Ridge Glaciokarst) which overlaps with 3072 (Mt Anne Massif Glacial Landforms).

Although the amount of redundant overlap of this sort in the current TGD is limited, with additional listings of glacial phenomena in future additional redundancies could be created. However it is alternatively arguable that there is sufficient value in identifying particularly well developed glacio-karst assemblages as sub-sets of larger glacial assemblages to maintain this approach, despite the overlap redundancy created by doing so.

It is recommended in Section (5.3.8) that consideration be given to the appropriate protocols for listing glacio-karst assemblages and features on the TGD, and such protocols (which may or may not be a continuation of current practice) be adhered to in future.

Table 5: Summary analysis of gaps in listing of glacial and periglacial features in the Tasmanian Wilderness World Heritage Area (TWWHA) on the Tasmanian Geoconservation Database (TGD). This table summarises data derived from an analysis of actual TGD listings for the TWWHA against the classes of periglacial and glacial features that are defined in Section 3.0 as significant elements of actual or potential glacial and periglacial geodiversity in the TWWHA. The table lists each possible combination of significant temporal, spatial and feature geodiversity classes defined in Section 3.0, and summarises the degree and quality of the representation of each combination in the TGD. The analysis data on which this summary is based is provided in full in Appendix 1, where the data summarised in each cell of this table (below) is listed under the 'cell identifier' obtained by intersecting the alpha-numerical identifiers listed on the table margins to uniquely identify each cell in the table. Note that features are only indicated as listed on the TGD if specified therein; where features are likely to exist within listed areas but are not actually specified in the listings, they are indicated only as possible features with no TGD representation. NOTE the numbers of sites or listings in this table do not sum to the total number of TGD sites analysed since some sites include more than one of the classifications listed, and thus the same sites may be counted under multiple classifications.

Table Key: cell colours highlight representation (listing) of elements of TWWHA glacial and periglacial geodiversity in the TGD as follows:

Represented on TGD (Number of listed sites indicated, but adequacy of representation unspecified)	No TGD representation (features known to or may exist in TWWHA)	No representation on TGD expected (features not expected to exist in TWWHA)

Cell Identifiers		A	B	C	D	E	F	G	H	I	J
		Spatial diversity (glacial / periglacial georegions) (from Table 2)				Temporal diversity (glacial / interglacial phases) (from Table 1)					
	Glacial & periglacial feature and process diversity (landform classes) (from Table 3)	Central Plateau Ice Cap region	Central Plateau and Central Highlands outlet and valley glaciers region	Southwest Quartzite Ranges region	Eastern and Southern Dolerite and Parmeener tabular ranges region	Pre-Maximum Late Tertiary to Mid-Pleistocene glaciations	Maximum Pleistocene Glaciation (Linda Glaciation and correlates)	Other post-Maximum Pleistocene glaciations (not incl. LGM)	Last Glacial Maximum	Present Interglacial (Holocene / Anthropocene)	Unclassified time phase (Cenozoic features, age otherwise uncertain or unspecified)
0	'Predictive regions' for glacial features (neither specific assemblages nor specific features listed)	2	1	2	6		4	3	5		6
1	Areal scouring forms (incl. 'knock & lochan' topography).	Excellent expression of type – within listed areas but not specified	2	Lack of glaciated alpine plateaux; example on Tyndall Ra. but outside TWWHA		Expect completely reworked by maximum glaciation	Expect reworked during Last Glaciation		2	No active glacial processes	Expect LGM examples only
2	Glacial valleys (troughs & other characteristic forms)	1	6	Possible?	1		4	4	6		1
3	Breached watersheds (incl. diffluence cols)	Possible?	1	1	Possible?		1	1	2		Possible?
4	Obstructing rock features (domes, whalebacks, smoothed interfluves, etc)	Possible?					Possible?				Possible?
5	Sculpted rock surfaces (incl. bedrock striations, flutes and grooves)	Likely?	1	1	Likely?		Conceivable albeit less likely than LGM features		1		1
6	Cols	Possible?	Likely	1	1		2	2	2		Possible
7	Cirques	Unlikely	2	3	1		1	1	5		1
8	Valley steps	1	1	1	Possible		Possible				3
9	Roche moutonnées	2	2	Possible			1	1	3		Possible
10	Fractured and gouged surfaces (chattermarks, lunate or crescentic gouged or fractured surfaces)	Possible					Subtle features, pre-LGM examples likely destroyed by weathering or erosion		Possible		Pre-LGM examples likely destroyed by weathering or erosion
11	Residual forms (nunataks, horns, arêtes, gendarmes, cols)	Unlikely due to areal ice-scouring	5	1	1		2	1	7		Likely
12	Other non-streamlined residual erosional forms	Unlikely due to areal ice-scouring	1	Likely			Possible		1		Possible
13	Cirque lakes	Not present due to areal scouring	2	Many examples, but not specified in listings			Expect reworked during Last Glaciation		2		Expect reworked during Last Glaciation
14	Glaciated valley lakes	Not present due to areal scouring	1	Possible	2		1	2	3		Possible
15	Other types of rock basin lakes	2	2	Possible	2		1	Possible	6		Possible
16	Ice-deformed bedrock features ('glacio-tectonic', Kiernan 1996, Table 5.1)	1	1	Possible		Remnants possibly preserved in protected situations	Possible		2		Possible

Glacial & periglacial feature and process diversity (landform classes) (from Table 3)

Cell Identifiers		A	B	C	D	E	F	G	H	I	J
		Spatial diversity (glacial / periglacial georegions) (from Table 2)				**Temporal diversity (glacial / interglacial phases)** (from Table 1)					
		Central Plateau Ice Cap region	Central Plateau and Central Highlands outlet and valley glaciers region	Southwest Quartzite Ranges region	Eastern and Southern Dolerite and Parmeener tabular ranges region	Pre-Maximum Late Tertiary to Mid-Pleistocene glaciations	Maximum Pleistocene Glaciation (Linda Glaciation and correlates)	Other post-Maximum Pleistocene glaciations (not incl. LGM)	Last Glacial Maximum	Present Interglacial (Holocene / Anthropocene)	Unclassified time phase (Cenozoic features, age otherwise uncertain or unspecified)
17	Moraines and glacial deposits (incl. till) generally: numerous sub-types depending on nature of glacial system (lateral & end moraines, hummocky and ground moraines, drumlins, etc)	6	8	3	8	1	8	8	17		2
18	Erratics	Possible	1	1	Possible	Expect completely reworked by maximum glaciation	1	Possible	1		Possible
19	Moraine-dammed lakes		Examples present, not listed		1		1	1	1		Possible
20	Outwash-dammed lakes		Possible	1	Possible		Possible		1		Possible
21	Other lakes barred by glacigenic sediments	1	Possible				Possible		1		Possible
22	Ice-deformed glacial sediment features ('glacio-tectonic', Kiernan 1996, Table 5.1)	1	2	Possible		Possibly preserved in protected situations	Possible		3		Possible
23	Sub-glacial channels cut in bedrock.	Possible				Expect completely reworked by maximum glaciation	Possible				Possible
24	Sub-glacial channels cut in drift.	Possible					Possible				Possible
25	Marginal melt water channels cut in bedrock.	Possible					Possible				Possible
26	Marginal melt water channels cut in drift or composite.	Possible					Possible				Possible
27	Proglacial ('downstream') channels cut in bedrock.	Possible				Remnants possibly preserved in protected situations	Possible				Possible
28	Proglacial ('downstream') channels cut in drift.	Possible					Possible				Possible
29	Ice contact outwash deposits (eskers, kames).	Possible	1	Possible		Expect completely reworked by maximum glaciation	Possible		1		Possible
30	Proglacial ('downstream') or glacio-fluvial deposits (outwash plains or sandurs, outwash deltas, outwash valley terraces, etc)	1	2	2	8	Remnants possibly preserved in protected situations	7	8	6		1
31	Integral glacial landform assemblages (and Parent sites) specified and listed on TGD (but most constituent individual features not specified).	1	4	2	10		10	7	10		3
32	Erosional nivation landforms (nivation cirques or hollows)	Probably present, no examples listed on TGD		1	1	Expect completely reworked by maximum glaciation	Possible			2	Possible
33	Depositional nivation forms (protalus ramparts, boulder tongues)	Possible		1	Possible		Possible			1	Possible
34	Fossil pingos, other ground-ice melt depression forms	Possible					Possible			Holocene permafrost unlikely	Possible
35	Other fossil permafrost features (ice push features, ice-wedge features, others)	1	Possible				Possible		1		Possible
36	Bedrock ice-shatter features (small-scale features, 'frost-shattered')	Likely, no examples listed on TGD					Preservation unlikely due to ongoing bedrock surface weathering		Some possibly preserved, none identified or listed on TGD	Widespread alpine examples in TWWHA, none listed on TGD	Possible (LGM / Holocene)
37	Periglacial erosion tors (mountain-top, break-of-slope, valley-slope)	Expected, not specifically listed on TGD	1	Expected, not specifically listed on TGD			Expect reworked during LGM and Holocene		Some possibly preserved, none identified or listed on TGD	1	Possible (LGM / Holocene)

Cell Identifiers			A	B	C	D	E	F	G	H	I	J
			Spatial diversity (glacial / periglacial georegions) (from Table 2)				**Temporal diversity (glacial / interglacial phases)** (from Table 1)					
			Central Plateau Ice Cap region	Central Plateau and Central Highlands outlet and valley glaciers region	Southwest Quartzite Ranges region	Eastern and Southern Dolerite and Parmeener tabular ranges region	Pre-Maximum Late Tertiary to Mid-Pleistocene glaciations	Maximum Pleistocene Glaciation (Linda Glaciation and correlates)	Other post-Maximum Pleistocene glaciations (not incl. LGM)	Last Glacial Maximum	Present Interglacial (Holocene / Anthropocene)	Unclassified time phase (Cenozoic features, age otherwise uncertain or unspecified)
38	**Feature and process diversity**	Periglacial rock-cut (alti-planation or cryo-planation) surfaces and terraces.	Likely, none specifically listed on TGD					Expect reworked during LGM		Likely, none specifically listed on TGD	Unlikely TWWHA process in Holocene	Possible (LGM)
39		Frost-heave, frost-sorting, patterned ground (in regolith), fjeldmark features	Likely Holocene /active features, possibly some rare preserved LGM features					Expect reworked during LGM and Holocene		Some possible rare preservation of fossil features?	Widespread alpine examples in TWWHA, none listed on TGD	Possible (LGM / Holocene)
40		Rock glaciers, block-fields, block-streams	2	2	Likely, none listed on TGD			Expect reworked during LGM		4	Unlikely TWWHA process in Holocene	Possible (LGM)
41		Talus slopes	1	1	Examples exist, none listed on TGD			Likely examples preserved in some situations		2	Widespread examples in TWWHA, none listed on TGD	Likely examples preserved in some situations
42		Solifluction slope deposits	1	2	1	Examples exist, none specifically listed on TGD	Remnants possibly preserved in protected situations	Likely examples preserved in some situations		3	1	Likely examples preserved in some situations
43		Stratified and/or sorted ice or snow-melt related slope deposits (incl. grèzes litées)	Possible in association with sedimentary rocks, albeit dominant dolerite lithologies unlikely to produce these deposits.		1	1		Possible some examples preserved in some situations		1	Possible, but no recognised Holocene examples	1
44		Colluvial terraces (stone-banked, turf-banked)	Likely	1	Quartzite lithologies not conducive?	2	Expect completely reworked by maximum glaciation	Preservation of examples in protected situations is conceivable			3	Preservation of examples in protected situations is conceivable

5.0 Conclusions and Recommendations

5.1 *Introduction*

Whereas the brief for this project specified that it should be an analysis of gaps in the TGD listing of glacial and periglacial features and systems in the TWWHA, the process of systematically identifying such gaps has resulted in the identification of a number of related issues which effectively mean that an original aim of this project – to identify features to be listed on the TGD to fill identified gaps – cannot be properly achieved until these related issues are first addressed. Hence the related issues are also identified here, and relevant recommendations made.

5.2 *Key Outcomes*

Stated in brief outline, the most important outcomes of this analysis can be stated as follows:

- A number of significant gaps in listings of predictive regions, parent sites and assemblages, and specific landform types for glacial and periglacial geoheritage in the TWWHA have been identified (see lists in Section 4.2.3).

- However there are significant difficulties in selecting specific assemblages and features to list on the TGD in order to fill the identified gaps, most of which arise from the fact that data on known Tasmanian glacial and periglacial landforms is scattered across numerous reports, maps and other documents (many of which still only exist in paper form) which are difficult to consolidate and systematically assess to identify appropriate listings and listing boundaries. This is the case even if a decision were made to list all known relevant features on the TGD, and is an even greater problem if it is considered preferable to list only the best representative examples of each missing landform type. The key difficulties arising include:

    - Records of specific glacial and periglacial features and assemblages in the TWWHA are scattered across numerous references, and are not available as a single consistent and readily analysable dataset;
    - Although there remain gaps in our knowledge of glacial features in the TWWHA, our knowledge of periglacial features and processes in the TWWHA is even more rudimentary – there are many known features that might be periglacial in origin but which have not been studied as yet, and it is highly likely there are other periglacial features present which have not even been speculatively identified as such to date.
    - Even within existing TGD listings, site boundaries and constituent features are poorly and sometimes inaccurately defined. This would probably remain the case for new listings given the fragmented nature of the presently available base data.
    - There is a need to resolve whether to continue using the concept of predictive regions and parent sites for glacial and periglacial listings on the TGD (e.g., if it is decided to continue using predictive regions, then predictive regions

covering all known features could immediately be listed, however there first needs to be a clear decision to do so).

- As a result of these difficulties, no attempt has been made to provide a list of sites which should be added to the TGD in order to plug the various gaps which this analysis has identified. It is arguable that – given the fragmented nature of the existing data - selection of such sites would be *ad hoc* and unsystematic if undertaken at present. Instead, it is recommended that the following projects be undertaken first, in order to provide a greatly improved basis upon which to systematically identify the most appropriate features and assemblages for listing on the TGD:

    - All existing critical data on TWWHA glacial and periglacial landforms should be carefully combined into a digital mapped (GIS) database which defines feature types, boundaries and characteristics as completely and accurately as possible, and which is maintained by DPIPWE with adequate editing and upgrading into the future. This database would complement those which already exist (at various stages of development) for karst, coastal, fluvial and aeolian landforms in Tasmania.
    - More work should be undertaken to improve knowledge of periglacial processes and landforms in the TWWHA (and any relevant data gathered should be added to the recommended comprehensive GIS dataset.
    - Decisions should be made on appropriate usage and definition of predictive region, parent site, assemblage and feature listings in the TGD, and these should be adhered to consistently.

- Following the achievement of these desirable works, it will then be possible to much more systematically and consistently analyse the available data to select the best representative glacial and periglacial features and assemblages in the TWWHA for TGD listing. If an alternative decision is made to list all TWWHA glacial and periglacial landforms on the TGD (because they all contribute to key world heritage values), the improved datasets recommended above are still required in order to be able to accurately define the spatial distribution and boundaries of the specific features which are being listed.

5.3 Recommendations

5.3.1 *Introduction*

This section provides more detail of the critical recommendations arising from this report, which have been referred to in section (5.2) above.

5.3.2 *A consolidated, Tasmania-wide, consistently classified digital (GIS) map and dataset of glacial and periglacial features should be created*

This gap analysis has highlighted the lack of specific detail within most glacial and periglacial site listings in the TGD (section 4.2.4), and has noted that this could potentially raise questions about the appropriateness of the boundaries of some TGD sites (section 4.2.5), and about how appropriate management requirements for listed sites are to be determined in the absence of significant detail within the TGD itself (section 4.2.4). Sections (4.2.3) and (4.2.6) additionally found that there has been no systematic comparative significance assessment applied to glacial or periglacial features in the TWWHA or Tasmania generally (listed and/or unlisted) in order to identify which are better or more mediocre examples of their type than others, and as a result a number of obvious gaps and biases in features and assemblages listed on the TGD can be readily identified. This is an important issue in relation to the TGD, whose purpose (amongst others) is to identify the post important (representative or outstanding) examples of key elements of geodiversity. The generally more *ad hoc* basis on which significant features have to date been identified for listing on the TGD (essentially utilising professional but not necessarily systematic or comprehensive knowledge) is at least partly attributable to the fact that existing data on such features remains scattered across a wide variety of sources including individual reports, papers and maps which are difficult to assimilate in a single analysis. As such it is unlikely to be practical to carry out properly systematic comparative geoheritage significance assessments until all available data on glacial and periglacial landforms in the TWWHA (and Tasmania generally) is consolidated into a single consistent dataset capably of being systematically searched and analysed.

It is noted that currently the only solution to each of these problems would be a time-consuming review of (sometimes numerous and potentially obscure) original data sources – or more realistically an *ad hoc* assessment based simply on the assessors own existing background knowledge and impressions of Tasmanian geomorphology - every time a query is raised about the significance or representativeness of a particular TGD site. This is an unsatisfactory situation since it is time-consuming, and may also lead over time to the same reviews being conducted repeatedly if the results of previous reviews are lost or made redundant by new basic research. However at the same time the TGD itself is arguably not the appropriate place to record detailed information (such as the data supporting significance assessments) since it is better used as a relatively simple and straightforward tool to alert land managers to the presence of significant features that may require management attention.

It is therefore recommended that the appropriate solution is one which has previously been implemented for a range of other geological and landform themes in Tasmania including karst and coastal landform themes (e.g., Kiernan 1995, Sharples 2006). The proposed solution is the extraction of relevant spatial and other geomorphic information about glacial and periglacial landforms, deposits and processes from the broad range of primary data sources, and the creation from these of a consolidated mapped GIS dataset. This can then be used to systematically improve the quality of the TGD itself, as well as containing the detailed information managers need to appropriately manage those sites that are listed on the TGD, but which is beyond the scope of data that could or should be contained within the TGD itself. Such a dataset would serve as a detailed data layer under-pinning the TGD, enabling the confirmation or refinement of appropriate TGD site boundaries and the determination of appropriate management requirements for relevant features within listing boundaries.

Moreover, not only would the creation of such a dataset greatly reduce the need to refer back to the diverse original data sources every time a glacial or periglacial TGD listing triggered a need to review management implications, but it would additionally serve as an invaluable framework and tool for ongoing research (as do equivalent geological, karst, coastal and other similar Tasmanian GIS datasets). In other words, such a consolidated GIS dataset would not need to be justified solely as a tool underpinning the TGD, but rather its existence and maintenance would be justified irrespective of the TGD since it would also underpin a wide range of other research and planning purposes. Ideally, a consolidated glacial and periglacial dataset for Tasmania would be maintained and progressively updated as new research data and mapping become available, so that it remains up to date and suitable both for ongoing use as a research tool, and for repeated querying in order to provide land management information whenever the use of the TGD itself triggers a need for such data.

With the development of GIS systems and the concurrently increasing need to process sufficient data to draw conclusions about appropriate land management and development strategies for large regions (e.g., the whole of Tasmania or the whole of Australia) there has been a global trend in recent decades towards the development of consolidated digital datasets for many information themes. To a large extent this has occurred because of the greatly enhanced potential that GIS offers for a range of data analysis and usage applications that were much more difficult or impossible for data in paper formats, especially where those paper data sources were distributed across a wide range of repositories and formats. Within Tasmania alone, the consolidation of digital geological mapping (Geological Survey, Mineral Resources Tasmania), vegetation mapping (DPIPWE “Tasveg” mapping), karst mapping (Kiernan 1995) and coastal landform mapping (Sharples 2006) and of course geoheritage information (the TGD itself) are just a few amongst numerous examples of this trend. The need for a consolidated GIS-based digital database on Tasmanian glacial and periglacial geomorphology is simply another example of the need for consistent and consolidated natural geodiversity data to facilitate a variety of data applications for which a demand exists.

It is therefore a key recommendation of this gap analysis that:

- A consolidated digital GIS-based dataset on Tasmanian glacial and periglacial landforms and deposits be created and maintained, with a view to facilitating a wide range of purposes including geoheritage assessment and management, geomorphic and palaeo-environment research, education and interpretation (amongst other possible applications).

The initial creation of such a database would be a time consuming process involving the accessing and review of all relevant available data, in its many different forms and sources, and compiling (digitising and geoprocessing) all this into a single consistent dataset. However the advantage is that this process only needs to be undertaken once, after which subsequent editing, upgrades and additions to maintain the currency of the dataset become relatively simpler.

Although the development of such a consolidated dataset would serve a wide range of purposes, from the specific perspective of the TGD and geoheritage management it would greatly improve capacity for at least the following:

- Identification and listing the full range of relevant known phenomena within an area or assemblage (thus facilitating appropriate management of all relevant features within a TGD-listed site polygon);
- Ensuring that TGD polygon boundaries contain all known parts of the phenomena that are of interest;
- Comparison and contrasting of phenomena to identify the best exemplars of particular feature types across assemblages or regions (thus enabling refinement of TGD listings to focus on key representative or outstanding phenomena);
- Analysis of glacial or periglacial systems to identify comprehensive (genetically inter-related) suites of features that should be listed together as assemblages;
- Identification of the best position for TGD polygon boundaries to capture all key features within a site on the basis of available data.

Currently these things can theoretically be done by working through a range of primary references, but it is evident that in practice this has rarely occurred due to time and resource limitations; it would be more likely to be done if the relevant primary information were already consolidated into a single GIS database.

In order to successfully develop such a database, a number of issues will need to be resolved. Although it is beyond the scope of this report to lay out the details of creating such a database, two key issues are worth highlighting as follows:

1. A consolidated dataset requires the development or adoption of a consistent, logical and appropriate classification for the phenomena in question <u>and</u> for the intended uses in question. There are many pitfalls in developing classifications for specific purposes, and these are often not recognised at the outset but may become a significant hindrance to efficient use of data by subsequent users (Sharples *et al.* 2010). It therefore warrants taking the time and making the effort to develop a logical and appropriate classification for such a dataset at the outset, in order to minimise subsequent problematical user issues.

2. In order to be available, maintained and useful in the long term, a dataset must be and must remain actively "*owned"*. That is to say, there must be some group or agency which has acknowledged responsibility for development, maintenance and dissemination of the dataset to users, and which has a means of ensuring ongoing adequate funding

for these purposes. The alternative model whereby a dataset is created with one-off funding but no guarantee of ongoing funding and support, is a recipe for lost and out-of-date datasets which potential users eventually become unable to access; and for subsequent re-invention of wheels as later resurgence in demand results in the recreation of another dataset to serve the same purposes that older but subsequently lost and/or out of date datasets could have served.

5.3.3 *Knowledge and mapping of periglacial features in the TWWHA should be substantially improved*

The glacial and periglacial landforms of the TWWHA were key values for which the region was listed as World Heritage (DASETT 1989, p. 32, 33 and 42). This provides justification for studies to improve our understanding of the nature and significance of those landforms given that this analysis has indicated (Section 4.2.3) that gaps in the representation of TWWHA glacial and periglacial landform classes on the TGD are probably at least partly attributable to gaps in our basic knowledge of those geomorphic systems in the TWWHA.

There is clearly more to be learnt about glacial landforms and deposits in the TWWHA; for example, some more remote glacial landform assemblages such as those in the Spires – Lake Curly – Denison Range area remain little documented. Nonetheless it is also true that most known glacial assemblages in the TWWHA have been subject to some study and mapping. In contrast knowledge of both relict and active periglacial features in the TWWHA is quite rudimentary, consisting mainly of only a few site-specific studies or observations (e.g. Kirkpatrick & Harwood 1980), and little if any regional synthesis of patterns and styles of periglacial processes and landforms in the TWWHA. Indeed in at least one case (TGD site 2487: Moonlight Ridge Periglacial Features) the writer’s own recent field observations raised questions as to whether some of the putative ‘periglacial’ features are in fact attributable to periglacial processes at all.

On the other hand, given the lack of focussed periglacial landform studies to date in the TWWHA, it is likely that some periglacial landform classes exist in the area that have simply been entirely unrecognised to date. As a possible example from the Creekton Rivulet basin adjoining the TWWHA near Hastings, the unexplained landform known as The Duckhole - a small isolated lake completely surrounded by a raised ridge of unconsolidated cobbly and bouldery sediment - has been hypothesised to be potentially a Last Glaciation - age ‘pingo’ formed due to a thick ice lens accumulating at a karst spring outflow (Ian Houshold *pers. comm*.). The presence of Last Glacial - age periglacial landforms produced by permafrost in Tasmania has been suspected previously, but only rarely suggested (Delisle 2001); however if the Duckhole is such a feature it would represent a major class of periglacial feature that is common in northern polar regions but has not previously been recognised in Tasmania. Similarly, Figure 5 to Figure 7 illustrate examples of features in the TWWHA which may be periglacial features, but which are to the writer’s knowledge unstudied and unexplained. Given the small amount of documentation of periglacial phenomena in the TWWHA, features such as this may be merely the tip of a proverbial iceberg.

Such large knowledge gaps make it particularly problematical to systematically and confidently identify periglacial features and assemblages of significant representative and

Figure 5: The scalloped lee side of this ridge crest (lower LHS) in the Anne River gorge area of the TWWHA is suggestive of periglacial nivation hollows, however field investigations are needed to confirm or refute this possibility. The view beyond these features looks northwards over undoubted glacial and periglacial terrain at Schnells Ridge and the Mt Anne Massif beyond (Kiernan 1990b). Photo by Chris Sharples (2014).

Figure 6: A series of large but subtle terraces with short steep risers are evident in this north-facing view of Gallagher Plateau (TWWHA). All the risers face eastwards (leeward to the prevailing dominant westerly weather direction). These could possibly be bedrock features but to the writers' knowledge have not been investigated and are equally likely be periglacial solifluction lobes or similar features, possibly of Last Glacial age. Photo by Chris Sharples (2014).

Figure 7: Hummocky and terraced forms on moorland organic soil slopes such as these examples above Schooner Cove in Port Davey are relatively common in the TWWHA but to the writers knowledge have not been systematically investigated or explained to date. Whilst one possible explanation is that these are the result of organic soil creep during the Holocene, another is that they are Pleistocene periglacial terrace forms preserved by a Holocene organic soil mantle. Investigation of the stratigraphy and subsurface structure of these features could distinguish between these alternatives (e.g., utilising steel soil probes and limited pit excavations). Photo by Chris Sharples (2009).

outstanding geoheritage value, and the consequence is that existing listing of periglacial TWWHA features and assemblages on the TGD is very limited and *ad hoc* in nature, as has been noted in Section (4.2.3) above. Consequently – and although knowledge of glacial phenomena in the TWWHA would also benefit from additional work – this analysis has highlighted lack of knowledge of periglacial landforms as a key major data gap in understanding the geoheritage of the region. Indeed, given the greater past focus on glacial landform studies in Tasmania relative to periglacial features; it is likely that at the present time a greater focus on furthering knowledge of periglacial landforms in the TWWHA would be more fruitful in terms of the amount of new knowledge that might be generated.

It is therefore recommended that:

- As resources permit, priority should be given to studies, mapping and inventory work in the TWWHA to improve knowledge of periglacial landforms and processes in the region, both relict (Last Glacial age) and presently active. Such studies should aim to improve understanding of the diversity of periglacial landforms and processes in the area, their spatial (including altitudinal) distribution, and the degree to which relict periglacial features can be differentiated from present-day periglacial processes.

5.3.4 *The purpose of listing sites at differing levels should be defined and adhered to consistently*

This analysis has noted (Section 4.2.2) that glacial and periglacial listings on the TGD can be readily grouped into four 'levels' or categories of listing, namely 'Predictive Regions', 'Parent Sites', 'Assemblages' and (individual) 'Features'. Following the discussion in Section (4.2.2) it is recommended that:

The purposes of the four levels of listing be reviewed:

- Table 6 below provides suggested definitions and purposes for each level. A decision should be made as to whether it is useful to recognise and use all four, or only some, of these levels in the TGD.

- As opportunity and resources permit, existing TGD listings should be reviewed, edited and removed or added to in order to ensure that the differing levels of listing to be used in the TGD are indeed being used consistently in accordance with their agreed purposes.

  For example, if the use of predictive regions for glacial (or periglacial) geodiversity is to be continued, then these regions should in virtue of their purpose be extended to cover all known areas in which glacial (or periglacial) features may exist on current knowledge.

  Note that any review of the appropriateness of existing assemblage and feature listing levels will depend on the existence of an adequate base dataset for making such judgements (see recommendation Section 5.3.2), and would ideally be an integral part of a broader review of the significance and representativeness of listings as recommended in Section (5.3.5) below.

- Assuming these recommendations are adopted, any subsequent nominations of new TGD listings should conform with these purposes for each level or category of listing.

It is additionally implicit that equivalent listing levels and purposes will be apply to other TGD listing themes beyond the glacial and periglacial phenomena considered in this analysis, which therefore will in due course require equivalent review.

Table 6: Recommended purposes of different listing levels (or types) for Glacial and Periglacial phenomena within the Tasmanian Geoconservation Database.

Listing level (type)	Definition	Purpose
Predictive regions	Region in which glacial or periglacial features are known or thought likely to exist; but no particular features or assemblages are identified in the predictive region listing. Do not constitute significant listings in themselves, nor imply that any significant features must necessarily be present.	A means of alerting planners and managers to the possibility significant features may be present in an area (and hence should be considered in planning management processes affecting the predictive region). As such, predictive regions for any given geodiversity theme (e.g., glacial or periglacial) should arguably be defined to cover all areas in which representatives of the theme could be present.
Parent sites	Umbrella site listing covering multiple sub-listings, which may themselves be feature or assemblage listings. Essentially a high-level "Assemblage" listing.	A means of identifying broader assemblages having common values that are themselves composed of multiple sub-assemblages which individually warrant listing as separate distinctive assemblages.
Assemblages	Functionally integrated assemblages of features (e.g., a complete erosional to depositional glacial system) which are considered to have geoheritage significance *as an assemblage.* Generally with only a few or in some cases no specific features within the assemblage being identified in the listing. Individual constituent features should ideally be specified by a listing boundary that can be overlain on a suitable mapped dataset specifying all known specific features within the assemblage, as recommended in Section (5.3.2), rather than by attempting to specify all features in the TGD itself. It is conceivable that cases may exist where no individual constituent feature is sufficiently significant to warrant a specific feature listing, but taken as a whole the entire assemblage of such features constitute a significant system worth listing.	A means of identifying inter-related geomorphic systems whose overall geoheritage values might be diminished by damage to individual parts.

Features	Individual features of high geoheritage value, irrespective of the broader integrated values of any assemblage they form part of.	Individual features considered sufficiently significant as to be worth listing (and managing) in their own right. Generally should be outstanding or ideal representative exemplars of their class.

5.3.5 *The significance and representativeness of sites should be systematically assessed when a consolidated dataset is available*

As noted in Sections (4.2.3) and (4.2.6), the glacial and periglacial sites currently listed on the TGD were selected on the basis of professional geomorphic knowledge, but in a nonetheless *ad hoc* rather than systematic fashion. All listed sites have been classed as being of 'representative' significance; however this has mostly been applied as a default category rather than being based on the results of a systematic and consistent comparative assessment across all known comparable features.

For the purposes of a geoheritage database, the ability to identify the best representative (or outstanding) examples of particular classes of geodiversity is arguably fundamental. The fact that existing TGD listings of glacial and periglacial features are based on the knowledge of a range of professionals with good knowledge of TWWHA geomorphology ensures that most if not all the features listed are at least good examples of their type. Nonetheless the analysis in Section (4.2.3) has also demonstrated that there are obvious gaps in listings, with a number of key features and assemblages that arguably should be listed not having been so. Moreover, as discussed in Section (4.2.6) there is no assurance that any features or assemblages that have been listed on the TGD are actually the best exemplars of their type in the TWWHA (or Tasmania as a whole). These limitations have arisen from the non-systematic *ad hoc* process by which the existing listings were compiled, and demonstrates how phenomena that are clearly important can nevertheless quite easily "fall through the gaps" if a significance assessment is conducted in a non-systematic, non-consistent and non-comparative fashion.

This report argues that a properly systematic comparative assessment of glacial and periglacial geoheritage in the TWWHA will not be possible until all relevant data has been assembled into a single consistent classified dataset (see Section 5.3.2); under the current state of affairs, with the basic geomorphic data needed for such an assessment only available in a distributed form across a large number of individual reports, papers and other records, it is simply too difficult to undertake a proper comparative assessment. Hence the only feasible approach to compiling glacial and periglacial listings into the TGD to date has been the *ad hoc* approach.

For this and several other reasons, the compilation of a single comprehensive consolidated GIS dataset that consolidates all relevant available information about Tasmanian (including TWWHA) glacial and periglacial phenomena is a key recommendation of this analysis (see Section 5.3.2 above). Assuming this recommendation is adopted and implemented, it is further recommended that the currently *ad hoc* nature of glacial and periglacial listings in the TGD be remedied by:

- Subsequent to preparation of a consolidated digital (GIS) dataset on Tasmanian glacial and periglacial phenomena, that dataset should be used to undertake a comparative geoheritage assessment in order to systematically identify a full suite of best representative examples of glacial and periglacial assemblages and individual specific features across the temporal periods and spatial regions over which the diversity of such features is distributed in the TWWHA.

The application of such an analysis would depend on a further decision alluded to in Section (4.2.6), namely:

- A decision should be made as to whether all known glacial and periglacial features in the TWWHA should be listed on the TGD (on the grounds that they all contribute to key world heritage values for which the area was inscribed on the UNESCO World Heritage list); or whether the TGD should only list the best representative or outstanding examples of each assemblage and feature class that occurs within the TWWHA.

In the former case, the recommended systematic comparative assessment would allow features and assemblages listed on the TWWHA to be differentiated according to their priority for management consideration. In the latter case the systematic analysis would enable a comprehensive suite of the most significant TWWHA representative and outstanding glacial and periglacial sites to be selected for listing on the TGD. Such an analysis should identify priorities for additions to or deletions from the TGD, and should enhance the representativeness of TGD listings whilst minimising the degree of both gaps and biases within TGD listings.

5.3.6 *Site boundaries and constituent features should be systematically defined by reference to a consolidated dataset when available*

The preceding sections 4.2.4 and 4.2.5 have noted problems that may arise in the use of the TGD as a management tool because of the lack of details in glacial and periglacial assemblage and parent site listings in regard to the specific locations and nature of the particular features constituting each listing, and to the correct locations of overall assemblage boundaries. To a lesser extent similar ambiguities may exist for specific feature listings. Section (4.2.7) has similarly noted that some glacial assemblage boundaries overlap, which effectively means that the same features (or parts of assemblages) are listed twice on the TGD, in differing listings. This may create confusion in analysing TGD data, and in some cases may also be further evidence of inaccuracies and ambiguities in existing TGD assemblage polygon boundaries.

This limitation means that some polygon boundaries for listed assemblages are wrong; for example some incorrectly exclude relevant landforms. It also means that it may not necessarily be obvious which actual features within a listing polygon are the features to which the listing refers. There will typically be non-glacial or non-periglacial features within any listed polygons, which do not require the same management approaches as the actual glacial or periglacial features to which the listing refers, however a non-specialist will not necessarily be able to discern the difference.

Currently this limitation can only be dealt with by a time-consuming process of referring back to the (potentially numerous and scattered) data sources on which listings are based. However, if recommendation (5.3.2) above is adopted and a single consolidated digital (GIS) dataset mapping all known glacial and periglacial features in the TWWHA is created, then these problems can be readily resolved. Assuming such a dataset is created, then it is recommended that the following subsequent actions should be undertaken:

- At the earliest possible opportunity, the boundaries of TGD glacial and periglacial listing polygons (at all levels but especially assemblages and parent sites) should be reviewed and corrected where necessary by comparison with the mapped data on the actual location and extent of relevant features.

- Overlapping assemblage boundaries of a given type (glacial or periglacial) should be identified and rationalised to eliminate overlaps where-ever possible, by merging or splitting assemblage listings as necessary to create mutually-exclusive polygon boundaries.

- On an ongoing basis, whenever specific information about the relevant features comprising each TGD listing (polygon) is needed (e.g., for management purposes), this should be obtained from the consolidated dataset. Ideally, the consolidated dataset should be formally identified as the data under-pinning glacial and periglacial listings on the TGD, and should be searchable via the same online portals as the TGD itself (e.g., it should be available on the DPIPWE Natural Values Atlas, and perhaps on the LIST).

5.3.7 *Interim glacial and periglacial sites for TGD listing in advance of a consolidated data set becoming available*

The preceding recommendations which aim to improve the value, usefulness and comprehensiveness of glacial and periglacial site listing information in the TGD (Sections 5.3.4 – 5.3.6) are based on the proposition that it will first be necessary to create a systematically consolidated and mapped dataset on glacial and periglacial phenomena in Tasmania (Section 5.3.2), and ideally to acquire more fundamental information on Tasmanian periglacial phenomena (Section 5.3.3).

However it will undoubtedly take some time to create the comprehensive dataset required to facilitate a more systematic and justifiable approach to identifying significant glacial and periglacial geoheritage. In the meantime, the analysis of biases and gaps in the listing of sites on the TGD (Section 4.2.3) has revealed a number of obvious gaps in listed predictive regions which should arguably be listed in virtue of the purpose of predictive regions (which is simply to identify regions potentially containing features of particular types, without judging their significance; see Section 5.3.4 above). These are listed in Table 7 below. On the other hand no unlisted assemblages or specific features are recommended for listing, on the grounds that doing so would contradict the primary recommendation that a comprehensive representative suite of significant assemblages and features should be selected on the basis of a systematic assessment of a comprehensive dataset when this becomes available.

Nonetheless it is recognised that specific *ad hoc* nominations may arise from time to time – particularly when identified in the course of focussed studies - that clearly warrant listing on their own merits.

Table 7: TWWHA glacial and periglacial regions, assemblages and features considered likely to warrant TGD listing irrespective of systematic assessments outlined in previous recommendations.

Listing level (type)	Recommended new listings	Notes / rationales
Predictive regions	All known glacial regions not already covered by predictive regions; includes: • Mt Humboldt – Spires – Lake Curly – Denison Range glaciated region; • Gallagher Plateau (leeward side); • Hamilton Range – Wilmot Range glaciated regions • Mt Maconochie, Companion Range • Part Hartz Mountains – Adamson's Peak glaciated region • Lake Eucryphia area (Mt Norold region): likely glacial lake. • Other areas listed as assemblages but not predictive regions (see Section 4.2.3)	No assessment of site significance implied; purpose is simply to identify areas where significant features could be present. Thus should cover all known glacial regions for consistency.
	Consider predictive periglacial regions for Maximum Glaciation, Last Glacial Maximum and present-day periods?	Existing understanding may not be sufficient to clearly define periglacial predictive regions. Glacial Maximum periglacial regions might conceivably cover whole of Tasmania outside glacial regions to sea-level; present day periglacial regions sometimes defined as all areas above 1000m but unclear if this adequately captures all present day periglacial phenomena?
Parent sites	None specifically recommended at this time.	Should be based on consideration of listed features and assemblages.

Assemblages	Many unlisted assemblages are likely to qualify for listing but are currently difficult to assess the geoheritage value of without a consolidated database for comparative assessment. It is recommended that identification and boundary definition of TWWHA glacial and periglacial assemblages warranting listing on the TGD be conducted when a suitable consolidated GIS dataset is available.	Should be based on assessment of data consolidated into GIS dataset as per Recommendation (5.3.2) and (5.3.5).
	However recommend listing of any periglacial assemblages assessed as significant by focussed studies as per Recommendation (5.3.3), or any glacial assemblages identified by focussed assessments as warranting listing.	Exceptions apply for any assemblages subject to focussed assessment in advance of a consolidated dataset becoming available.
Specific features	None specifically recommended at this time. However it is recognised that specific *ad hoc* nominations may arise from time to time that clearly warrant listing on their own merits.	In the absence of a systematic assessment (as recommended in Section 5.3.5), it is problematic to suggest specific unlisted features that ought to be listed on the TGD, since this would involve the same *ad hoc* assessment style that has resulted in the gaps and biases in the listing of specific features on the TGD to date.

5.3.8 *Protocols for listing glacio-karst features and assemblages*

Section (4.2.8) above identified that the listing of glacio-karst assemblages which overlap with broader glacial assemblages of which they are a part effectively creates overlapping glacial assemblage listing on the TGD which effectively result in the same features (within the areas of overlap being listed twice on the TGD. Since redundant overlaps between assemblages of the same type of features should ideally be avoided (Section 4.2.7), there would appear to be a case for eliminating such overlapping assemblages, and simply listing one glacial assemblage, with the presence within it of glacio-karst noted as a value, and any outstanding specific glacio-karstic features listed as separate specific feature listings.

On the other hand however, it is arguable that the existing protocol of sufficiently well-developed glacio-karst landform assemblages being listed as stand-alone assemblages is useful as a way of highlighting these distinctive systems despite the (relatively limited) redundancy such overlaps create in the TGD.

The two alternative approaches to listing glacio-karst on the TGD can be contrasted as follows:

Current listing protocol	**Alternative listing protocol**
Karst assemblage listings with brief references to glacio-karst but few details.	Karst assemblage listings with brief references to glacio-karst but few details.
“Glacio-karstic assemblages” listings (which in some cases partly or wholly overlap with purely glacial assemblage listings).	Glacial assemblage listings with glacio-karstic phenomena noted as a key value (but not separately listed as an overlapping polygon).
Specific (generally outstanding) glacio-karst feature listings.	Specific (generally outstanding) glacio-karst feature listings.

It is recommended that consideration be given to the relative merits of these contrasting protocols and a decision be made as to whether to continue the current protocol or adopt the alternative instead.

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Appendix 1: TGD analysis data

This appendix (Table 8) summarises information on all glacial or periglacial phenomena partly or wholly within the TWWHA that were listed on the TGD as at 2012. This data provides the basis for the gap analysis, and in particular for the analysis provided in Table 5.

Table 8: Key characteristics of TWWHA glacial and periglacial geomorphic features listed on the Tasmanian Geoconservation Database. Total no. of listed sites, assemblages or regions: 85

TGD Site ID	Listed TGD site name	Classes (as per Table 5, listed by cell identifiers)	Condition	Notes
2348	Frenchmans Cap – Cliff	11C, 11H, 11F (Residual glacial headwall)	Good	Part of 2363
2349	Frenchmans Cap Summit Nivation Cirque	32C, 32I, 33C, 33I (Active nivation cirque)	Mostly good (minor foot traffic degradation of associated sediments)	
2350	Lake Tahune Glacio-karstic Cirque	7C, 7H (cirque only listed; likely partly karstic depression with glacial erosion)	Good (no landform degradation reported)	Glacio-karst (primarily karst listing with glacial influences identified); part of 2363
2353	Redan Hill Erratics	18C, 18F (dolerite erratics on quartzite hill)	Significant disturbance (?)	
2354	Stonehaven Creek Glacial sediments	17B, 17H, 30B, 30H (specific till and glacio-fluvial outwash deposit site)	Mostly good (some degradation from road-making)	
2363	Frenchmans Cap Glacial area	31C, 31F, 31H (Assemblage only listed, no specified landforms)	Good	
2374	West Coast Range (Glaciated Terrain)	31C, 31F, 31G, 31H (Parent site only; specific assemblages and features not listed)	N/A	
2483	Lake Sydney glacio-karstic lake	15D, 15H (Lake only listed, basin is partly karstic)	Good	Glacio-karst (primarily karst listing with glacial influences identified)
2485	Wargata Mina (Judds Cavern) Karst System	31D, 31F (glacially-influenced karst development, specific glacial features not specified)	Good	Glacio-karst (primarily karst listing with glacial influences identified)
2486	The Boomerang solifluction steps	44D, 44I (assemblage of active solifluction terraces)	Good (no degradation recorded)	
2487	Moonlight Ridge Periglacial features	44D, 44I (assemblage of active solifluction terraces)	Mostly Good (slight degradation recorded)	
2535	Huon Valley Glacial Systems	31D, 31F, 31G, 17D, 17F, 17G, 30D, 30F, 30G (glacial and glacio-fluvial sediments noted, specific features not specified)	Mostly Good (minor degradation in places)	
2536	Picton Valley Glacial Systems	31D, 31F, 31G, 17D, 17F, 17G, 30D, 30F, 30G (glacial and glacio-fluvial sediments, specific features not specified)	Moderate (significant degradation in places)	
2537	Lower Weld Valley Glacial Site	31D, 31F, 31G, 17D, 17F, 17G, 30D, 30F, 30G (glacial and glacio-fluvial sediments, specific features not specified)	Mostly Good (minor degradation in places)	
2538	Lune Valley glacial systems	0D, 0F, 0G, 0H (Listed as assemblage but arguably better regarded as a predictive region on current evidence)	Mostly good (minor degradation due to road-making and logging)	Moraines, glacial deposits and glacio-fluvial deposits have been reported but not properly confirmed to date; site is best considered a 'predictive region' rather than a confirmed assemblage on basis of existing evidence.
2539	D'Entrecasteaux and Catamaran Valleys Glacial Systems	0D, 0J, 31D, 31J (Predictive region, Likely integral assemblages, no specific features mentioned)	N/A	
2542	Manuka Creek – Blakes Opening – Mt Picton Karst	17D, 17F, 17G, 30D, 30F, 30G (karst mantled with probable tills and outwash; inferred glacio-karst interaction)	Good (no degradation recorded)	Glacio-karst (primarily karst listing with glacial influences identified)
2543	Hastings – Upper Creekton Rivulet Karst	17D, 17F, 17G, 30D, 30F, 30G, 43D, 43H (Karst system with possible Glacio-karst interaction; includes likely periglacial sediments in Wolfhole – grèzes litées)	Mostly Good (minor degradation due to roading, cave tourism and logging in parts)	Glacio-karst (primarily karst listing with glacial influences identified)
2544	Picton River Karst	0D, 0J (predictive region for glacio-karst interactions; no specific features identified)	N/A	Predictive glacio-karst (primarily karst listing with possible glacial influences)
2547	North Lune and Lune Plains Karst	0D, 0J (predictive region for glacio-karst interactions; no specific features identified)	N/A	Predictive glacio-karst (primarily karst listing with possible glacial influences)

2553	Exit Cave – D'Entrecasteaux Valley Karst area	30D, 30G, 30H (Glacio-fluvial deposits recorded: important controls on karst development)	Mostly Good (slight degradation recorded)	Glacio-karst (primarily karst listing with glacial influences identified)
2558	Riveaux – Blakes Glaciokarst	17D, 17F, 17G, 30D, 30F, 30G (karst mantled with probable tills and outwash; inferred glacio-karst interaction)	Mostly Good? (some degradation noted?)	Glacio-karst (primarily karst listing with glacial influences identified).
2567	Blakes Opening Glacial / Interglacial Sequence	30D, 30H (Last Glacial outwash / Interglacial fluvial sediment sequence)	Good (no artificial disturbance)	
2498	Double Lagoon Ground Moraine	17A, 17H, 22A, 22H (Moraines with ice-push features)	Unknown	
2499	Lake Ada Ground Moraine	17A, 17H (extensive ground moraine)	Unknown	
2500	Pine Lake Glacis	40A, 40H (Block stream with ice matrix assisting movement)	Good (no degradation)	
2504	Great Western Tiers Escarpment	12B, 12H (Glacially-eroded tectonic escarpment) 42B, 42H (Solifluction slope deposits)	Mostly Good (variable degradation in parts)	
2508	Liffey – Poatina Glacial Areas	0A, 0H, 0F (Predictive site only; specific assemblages and features not listed)	N/A	
2656	Mt Geryon – Acropolis Glacial Geomorphology	11B,11H (Assemblage of spectacular glacial erosion forms)	Good (no degradation)	
2658	Chalice Lake Rock Basin	15A, 15H (rock basin lake from ice cap erosion)	Good (no degradation)	
2660	Forth Valley Glacial Trough	2B, 2H, 2F, 2G (classic glacial trough)	Good within TWWHA, Moderate outside TWWHA (no degradation in TWWHA, part extending out of TWWHA partly disturbed by Hydro works incl. roads and excavations)	
2661	Jacksons Creek Drainage	40B, 40H (drainage through 'scree' of inferred periglacial origin filling glacial valley floor)	Unknown	
2662	Julian Lakes Dead Ice Topography	17A, 17H, 21A, 21H (area of hummocky terrain and residual glacial lakes)	Good (no degradation)	
2663	Junction Lake Glacial valley Step	8A, 8J (Glacially excavated valley step)	Good (no degradation)	
2664	Labyrinth Glaciated Terrain	1B, 1H, 9B, 9H, 15B, 15H (glaciated plateau)	Good (no degradation of glacial features)	
2665	Lake Adelaide Glacial Rock Basin Lake	15B, 15H, 17B, 17H, 18B, 18H (rock basin lake landform assemblage)	Good (no degradation)	
2666	Lake Explorer Rock Basin Lake	15A, 15H, 17A, 17H, 9A, 9H (local feature assemblage)	Good (no degradation)	
2667	Lake Helios Glacial Striae	5B, 5H (rare feature)	Good (no degradation)	Rare feature – glacial striae preserved on dolerite
2668	Lake Leonis Pressure Release Chasm	11B, 11H (deglaciation bedrock feature – classed as 'residual' form)	Unknown	
2669	Lees Plains Glacial Valley Profile	2B, 2J (Classic U-shaped glacial valley)	Good (no degradation of form)	
2670	Lobster Rivulet Ice Spillover Area	17A, 17H, 30A, 30H (ice cap edge spillover deposits on Western Tiers)	Mostly good	
2671	Massif Mountain Geomorphology	7B, 7H (Recorded as 'summit cirque'; geomorphic process origin unclear from listing)	Good (no degradation)	
2672	Moses Creek Stepped Valley	8B, 8J, 16B, 16H, 22B, 22H (Glacial stepped valley with deformation till and bedrock deformation)	Unknown	

2673	Mt Rogoona Nunatak	11B, 11H, 41B, 41H (Last Glacial nunatak and associated scree)	Good (no degradation)	
2674	Narcissus Valley Fluted Moraines	17B, 17H (extensive moraine complex)	Good (no degradation)	
2675	Nells Bluff Slab Topple	16A, 16H, 35A, 35H (very large slab topple)	Good	Likely produced by a combination of glacial-over-riding and ice-push processes
2676	Toad Rock tor (Mt Pelion East)	37B, 37I (Sandstone tor attributed partly to frost action)	Good (no recorded degradation)	
2677	Walls of Jerusalem Last Glacial Ice window	40A, 40H, 41A, 41H, 42A, 42H, 9A, 9F, 9G (Last Glacial periglacial features in ice-free window; over-ridden features during earlier glaciations)	Good (no degradation)	
2684	Central Plateau Terrain	31A, 31F, 31G,31H (cited only as 'ice-cap glaciated terrain')	Good	
2685	Mole Creek Karst	31B, 31F, 31G, 31H (glacio-karst assemblage: listed as 'glaciated' karst, no details in TGD)	Partly degraded (condition variable)	Glacio-karstic features relatively well known, but not described in site listing.
2695	Moses Creek Deformation Till	22B, 22H (ice-deformed glacial sediment site)	Good (no degradation recorded)	
2696 (2697)	Pillinger Bog end moraine (& consequent disrupted fluvial drainage)	17B, 17H (Last Glacial end moraine)	Good (No degradation recorded)	
2697	Wurragarra Creek Glacially Disrupted Drainage	Strictly, fluvial features consequent upon moraine in listing 2696 above.	Good (no degradation recorded)	Fluvial feature consequent upon moraine listed as 2696.
2698	Upper Mersey Overridden Valley walls	3B, 3H (glacially over-ridden escarpment)	Good (No degradation recorded)	
2699	Chapter Lake Hanging Valley	2A, 2H (characteristic type of glacial valley)	Good (no degradation)	
2701	Talinah Lagoon End Moraine Complex	17A, 17H (Extensive hummocky end moraine complex)	Good (no degradation)	
2708	Cuvier Valley Moraine Complex	17B, 17H (Moraine complex)	Good (No degradation)	
2709	Cynthia Bay moraines (Thule-Baffin end-moraines)	17B, 17H (Thule-Baffin end-moraines)	Partly degraded (surficial disturbance by roads and buildings in parts)	
2710	Lake Rufus Glacial Trough	2B, 2H, 2G,14B,14H,14G (Classic glacial trough in Permian rocks)	Good (no degradation)	
2711	Lake St Clair Glacial trough	2B, 2F, 2G, 2H, (glacial trough occupied by Lake St. Clair)	Mostly good (minor degradation through dam works)	
2712	Mt Rufus Solifluction Terraces	42B, 42I, 44B, 44I (Assemblage of 'solifluction' terraces)	Mostly good (minor foot traffic degradation)	
2713	Mt King William I Dilation Trench	11B, 11H (post-glacial unloading bedrock feature)	Good (no degradation)	Classified as 'residual bedrock feature' for lack of better classification options; glacio-tectonic bedrock feature option not appropriate as it's a response to removal of ice, not to ice itself)
2714	Mt Olympus rock glaciers	40B, 40H (inactive rock glaciers)	Good (no degradation)	
2715	Narcissus Valley ?Esker	29B, 29H (possible esker)	Good	Not demonstrated to be an esker
2716	Upper Franklin Valley glacial features	2B, 2H, 9B, 9H, 17B, 17H, 31B, 31H (glacial valley erosional & depositional assemblage, some feature types specified)	Good (no known degradation)	
2717	Surprise Valley Glacial trough	2B, 2F (classic glacial trough)	Mostly good (Lyell Highway road excavations & fill)	
2718	Mt Olympus cirques	7B, 7H, 13B, 13H (Examples of moraine-dammed and rock-basin cirques)	Good (no degradation)	
2722	Florentine Valley Glacial Areas	31D, 31F (Whole assemblages cited, no specific features listed)	Mostly good (partly degraded by road-works)	

2787	Southwest Tasmania Glacial Areas	0C, 0D, 0F, 0G, 0H, 0J (Southwest Tas predictive region; specific features or assemblages not listed)	N/A	TGD polygons do not include all known areas of SW glaciation, e.g., Denison Range, Spires – Mt Curly areas not included.
2788	Western Arthur Range Glaciated Terrain	31C, 31F, 31G, 31H, 7C, 7H, 3C, 3F, 3G, 3H, 6C, 6F, 6G, 6H, 8C, 8J, 17C, 17F, 17G, 17H, 30C, 30F, 30G, 30H (assemblage, some specific landform types (but not sites) specified)	Good (no degradation)	
2802	Champ Cliff Limestone and karst	30C, 30J (Glacio-fluvial outwash sediments perched on limestone cliff top)	Mostly good (minor degradation)	
2523	Warners Landing Perched Lake Sediments and Karst	17C, 17E (possible Tertiary-age tills preserved in karst depression)	Good (no recorded degradation)	Identification as pre-Pleistocene till is speculative; possibly glacio-fluvial, possibly neither; requires more study.
2884	Hannant Inlet Pre-Last Glacial Sediments and Fossil wood	42C, 42H, 43C, 43J (low altitude cold climate sediments of uncertain Pleistocene age)	Good (exposed by coastal erosion)	TGD listing requires updating with recent dating and palynological results.
2918	Mt La Perouse Nivation Site	32D, 32I (Nivation site with striated pavement)	Good (no degradation)	
2942	Cradle Mountain Glacial Features	31B, 31H, 11B, 11H, 1B, 1H, 13B, 13H, 17B, 17H, 30B, 30H (assemblage, some specific landform types (but not sites) specified)	Mostly good (minor degradation associated with infrastructure)	
2953	Central Highlands Cenozoic Glacial Area	0A, 0B, 0J (Predictive Region)	N/A	
3034	Snowy Range Glacial Systems	17D, 17H, 17J, 31D, 31H, 31J (whole assemblage implied by polygon boundary although not by database description; only tills specifically mentioned)	Good in highland areas; unknown (some degradation possible) in valley floor areas.	TGD polygon appears to cover full glacial assemblage incl. highland features, but database description refers only to distal valley features and specifies only tills.
3035	Mt Weld Karst	31D, 31J (Glacio-karst interaction cited as 'possible', assemblage implied; no specific features identified)	Unknown (minor disturbances, condition of putative features unknown)	
3045	Weld River Basin Karst & Fluvial Systems	0D, 0H, 0J (predictive region for glacio-karst; specific features not listed)	N/A	Glacio-karst (primarily karst listing with glacial influences identified)
3071	Mt Wedge – Boyd River Glacial area	7C, 7J, 17C, 17J, 31C, 31J (assemblage: cirque and 'glacial deposits' cited in listing)	Unknown	
3072	Mt Anne Massif Glacial Landforms	31D, 31F, 31G, 31H (Whole multiphase glacial assemblage listed, most features not specified in listing but includes: 2D, 6D, 7D, 11D, 14D, 15D, 17D, 19D; 2F, 6F, 7F, 11F, 14F, 15F, 17F, 19F; 2G, 6G, 7G, 11G, 14G, 15G, 17G, 19G; 2H, 6H, 7H, 11H, 14H, 15H, 17H, 19H)	Mostly Good (minor degradation associated with Scotts Peak Road & walking tracks)	
3073	Mt Anne (North-east ridge) Glaciokarst	31D, 31H (Whole glacio-karst assemblage listed, but only a couple of features specifically noted e.g., Lake Timk: 14D, 14H)	Mostly Good (only minor degradation due to caving activities)	Glacio-karst (primarily karst listing with glacial influences identified)
3074	Mt Curly Glaciated Surface	5C, 5J (Glacially-smoothed and striated rock surfaces)	Good (no degradation)	
3088	Lake Pedder (the original)	20C, 20J (outwash-dammed lake)	Poor (inundated)	
3244	Eldon Peak Glaciokarst	31B, 31H (Check listing for details)	Good (pristine)	Glacio-karst (primarily karst listing with glacial influences noted)