A NORTHWARD SHIFT OF THE SOUTHERN WESTERLIES DURING THE ANTARCTIC COLD REVERSAL: EVIDENCE FROM TASMANIA, AUSTRALIA

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ABSTRACT

The Southern Hemisphere Westerlies are one of the most important components of the Earth’s climate system: they are the primary driver of Southern Hemisphere climate, they modulate global ocean circulation patterns, and they are a critical natural driver of atmospheric CO₂ variation. Despite their clear importance, their dynamics in response to rapid changes in climate boundary conditions are poorly understood. Critical to this lack of understanding is (1) an absence of robust proxy-data from the Australian sector of the Southern Hemisphere, which hampers attempts at predictive modelling, and (2) a lack of consensus within the palaeoclimate literature as to how the Southern Westerlies have responded to past periods of rapid climate change. A case in point is the behaviour of the Southern Westerlies during the Antarctic Cold Reversal (ACR; 14,000 – 13,700 years ago), a millennial-scale climate event that punctuated the termination of the Last Ice Age in the Southern Hemisphere. A thorough understanding of how this critical climate component changed during the ACR is hampered by the only available proxy-dataset from the Australian sector of the Southern Hemisphere, which disagrees with records from other regions, and with the leading conceptual understanding of Southern Westerly dynamics. To address this discord, this thesis sought to reconstruct the dynamics of the Southern Westerlies in the Australian sector by developing two robust terrestrial proxy-datasets from Tasmania, Australia, covering the ACR.

The results from this thesis demonstrate that the Southern Westerlies responded to the climatic changes of the ACR as predicted by the leading conceptual understanding of their dynamics, and also revealed that they responded symmetrically across the Southern Hemisphere, coincident with substantial changes in atmospheric CO₂ variation. This thesis supports the hypotheses that the Southern Westerlies are the primary determinant of long-term Tasmanian climate variation and are a critical regulator of long-term global atmospheric CO₂ variation.
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CHAPTER 1: INTRODUCTION

The Earth’s climate is beginning to undergo widespread changes as anthropogenic greenhouse gas emissions drive the atmosphere to warm. To understand how these impending changes will impact us and our environment, we must equip ourselves with the most comprehensive knowledge of the Earth’s climate system so that we can best forecast how it might react to future changes.

The Southern Hemisphere westerly wind belt is one of the most influential components of the global climate system. The latitudinal position and strength of the Southern Westerlies (1) control rainfall variation for much of the sub- and extra-tropical regions of the Southern Hemisphere (Garreaud, 2007), (2) modulate key ocean currents including the global ocean circulation conveyor belt (Kuhlbrodt et al., 2007; Marshall & Speer, 2012), and (3) are a central component of the global carbon cycle (Le Quéré et al., 2009; Anderson et al., 2009). Currently, model predictions of how this wind belt will respond to future climate change are hampered by a lack of consensus between proxy records and conceptual models. Reconciling this dissensus is hampered by a lack of robust proxy data, particularly from the Australian sector. The need to improve our understanding of the dynamics of the Southern Westerlies is now at its most pressing, as a prolonged southerly movement over the past ~60 years has seen long-term declines in average rainfall and increased wildfires across the Southern Hemisphere (Abram et al., 2014; Mariani & Fletcher, 2016; Hendon et al., 2007; Meneghini et al., 2007; Gillett et al., 2006; Reason & Rouault, 2005; Renwick & Thompson, 2006), and any further southward movement will not only enhance these impacts but would also escalate the rate of CO₂ release from the Southern Ocean (Le Quéré et al., 2008), where ~40% of anthropogenic CO₂ emissions are currently sequestered (Frölicher et al., 2015).
The most pertinent way to improve attempts at modelling, address the dissensus between records and to fill the data-gap is to retrieve high-quality palaeoclimate records from key regions under Southern Westerly influence through important periods of past climate change. This thesis aims to achieve this by conducting multi-proxy analyses of Tasmanian lake sediments in order to reconstruct the response of the Southern Westerlies to a millennial-scale climate event, the Antarctic Cold Reversal (ca. 14,700 to 13,00 years ago; Pedro et al. (2016)).

1.1 A Lack of Consensus & Data Gap

While the mechanisms that underpin short-term variation in the position and strength of the Southern Westerlies are reasonably well understood (Abram et al., 2014), our understanding of their variation over longer timescales and in response to rapid climate change is incomplete. This is exemplified by the ongoing discussion surrounding the role of the Southern Westerlies in the termination of the Last Ice Age (Termination I). The leading conceptual models of changes to Southern Westerly dynamics through what is the most recent period of major climatic change in the Earth’s history are supported by a number of terrestrial and marine studies, but remain contradicted by others (Denton et al., 2010; Toggweiler et al., 2006). One of the key proxy records that contradicts these models comes from the southern Australian coast (De Deckker et al., 2012), and is the only Australian empirical record that considers Southern Westerly dynamics through Termination I (Pedro et al., 2016; Clark et al., 2012). Its proxy-based reconstruction of changes in southern Australia through Termination I argues that the Southern Westerlies were positioned poleward of their modern position, closer to Antarctica, through the Antarctic Cold Reversal, where the conceptual models from Denton et al. (2010) and Toggweiler et al. (2006) and the proxy-data they are built upon argue they were positioned equatorward, away from Antarctica. Reconciling this conflict is not only critical to our understanding of the Southern Westerlies more generally, but also to our understanding of global climate dynamics through glacial terminations.
1.2 Thesis Aims & Research Questions

THESIS AIM: This thesis aims to improve our understanding of Southern Westerly Wind dynamics in response to rapid climate change.

This aim will be achieved by retrieving a robust lake sediment proxy-data record of environmental change in Tasmania, Australia, the region with the strongest correlation between Southern Westerly wind strength and rainfall of anywhere across the Southern Hemisphere. The final contention of this thesis will be developed by answering the following research questions:

**RQ 1**: How did the hydroclimate of western Tasmania change through the Antarctic Cold Reversal?

**RQ 2**: How did the hydroclimate of eastern Tasmania change through the Antarctic Cold Reversal?

**RQ 3**: Did the influence of the Southern Westerlies change over Tasmania through the Antarctic Cold Reversal?

**RQ 4**: How did the Southern Westerlies respond to the rapid climate change of the Antarctic Cold Reversal?
CHAPTER 2: BACKGROUND

This chapter will provide the context for this thesis by (1) explaining the research area of palaeoclimatology, (2) explaining the current understanding of Southern Westerly dynamics with a focus on the Antarctic Cold Reversal, and (3) explaining the suitability of Tasmania to address the aim and research questions of this thesis.

2.1 PALAEOCLIMATOLOGY

Climate change of a pace and scale comparable to what the Earth currently faces cannot be found in the short instrumental climate records we possess. As a consequence, we must interrogate the climates of the past to progress our understanding of how the climate changes, the drivers of these changes and how climate change impacts the Earth system if we are to expand our capacity to forecast, adapt to and potentially mitigate future changes in climate (Alverson & Bradley, 2003; Bradley, 2000, 2013).

Palaeoclimatology is the study of the Earth’s climate in the geologic past. Evidence of variation in the Earth’s climate is recorded in a diverse array of natural archives, each with their own advantages and limitations. Physical, biological and chemical properties preserved in such archives are used as proxy-recordings of past climatic conditions. Variation in these properties can provide an insight into changes in past environmental conditions which, given a thorough understanding of the controls of environmental change within any specific archive, can be used to infer the drivers of this change, such as climate (Bradley, 2013). Examples of these natural archives include ice sheets, ocean sediments, lake sediments, trees, cave deposits and corals; and examples of proxies stored within these archives that are used to interpret climate change include stable isotopes, fossil pollen, growth bands, charcoal and sediment geochemistry. This thesis will
utilise two lake sediment archives from Tasmania, Australia and analyse multiple proxies stored within these sediments to develop a robust record of environmental change through the study period.

2.2 **The Southern Hemisphere Westerly Winds**

The Southern Hemisphere westerly wind belt comprises the prevailing winds blowing west-east in the mid-high latitudes of the Southern Hemisphere. They are associated with the influence of the Earth’s rotation at the confluence of the descending air of the Ferrel cell and rising air of the Polar cell (Figure 2-1)(Holden, 2011). The void of continental landmass between 40°S and 60°S permits unimpeded fetch lengths of westerly flow which promotes a remarkably zonally symmetric pattern of circulation that encircles Antarctica, a process that is the fundamental driver of the Antarctic Circumpolar Current (Shulmeister *et al.*, 2004).

![Figure 2-1](image)  
*Figure 2-1* | Simplified schematic of major global atmospheric circulation cells and surface wind patterns. Adapted from Holden (2011).
The position and strength of the Southern Westerly wind belt shifts across multiple timescales. Seasonal to decadal-scale shifts are described by the Southern Annual Mode (SAM); where an equatorward expansion and central weakening of the core (currently ~50 - 55ºS) occurs during negative SAM phases (such as what is observed during the Austral winter), and a poleward contraction and central intensification of the core occurs during positive SAM phases (such as the Austral summer) (Lamy et al., 2010). Over centennial to multi-millennial timescales, their position and strength varies markedly and is predominantly a function of thermal and atmospheric pressure gradients between the equator and the South Pole (Shulmeister et al., 2004). These shifts occur primarily in response to changes in global climate boundary conditions, such as insolation and oceanic thermohaline circulation (Abram et al., 2014; Fletcher & Moreno, 2012; Shulmeister et al., 2004), and exert major influence over terrestrial climates, oceanic currents and the global carbon cycle.

![Map showing the approximate position of the Southern Westerly winds (SWW) and the associated oceanic front, the Subtropical Front (STF) under (a) a poleward contraction, such as a positive SAM index and (b) an equatorward expansion, such as a negative SAM index. Adapted from Bendle (2018).](image)
2.2.1 THE INFLUENCE OF THE SOUTHERN WESTERLIES

The Southern Westerlies exert direct control over the climates of the southern mid-high latitudes but also extend their influence far beyond these regions via their interactions with global ocean circulation patterns and their modulation of atmospheric CO$_2$ concentrations and the global carbon cycle.

2.2.1.1 Southern Hemisphere Terrestrial Climate

The Southern Westerlies are the principle driver of climatic variation for all terrestrial regions in the mid-high southern latitudes. The importance of their position for these regions has been demonstrated over the past ~60 years where stratospheric ozone depletion and increased greenhouse gas concentration have caused a persistent positive trend in the Southern Annular Mode (Thompson & Solomon, 2002, Marshall 2003, Roscoe & Haigh, 2007, Fogt et al., 2009, Jones et al., 2009, Abram et al., 2014). This trend has had profound impacts, including: (1) a substantial and persistent decrease in rainfall for much of southern Australia (Hendon et al., 2007; Meneghini et al., 2007), southern South America (Gillett et al., 2006), western South Africa (Reason & Rouault, 2005) and southern New Zealand (Renwick & Thompson, 2006); (2) increased fire activity in south western South America (Holz & Veblen, 2011) and south west Tasmania (Mariani & Fletcher, 2016) and (3) concurrent cooling and warming of different regions of Antarctica (Ahmed et al., 2013; Bromwich et al., 2013; Gillett et al., 2006; Marshall et al., 2006; Mulvaney et al., 2012; Thompson & Wallace, 2000).

2.2.1.2 Global Ocean Circulation

Changes to the position and strength of the Southern Westerlies have a strong influence on the Atlantic Meridional Overturning Circulation (AMOC) (Kuhlbrodt et al., 2007; Marshall & Speer, 2012), which is the most critical component of the global ocean’s thermohaline circulation and the primary internal controller of climate and climate variability globally (Figure
For example, changes to the strength of the AMOC would have implications for the El Niño–Southern Oscillation (Timmermann et al., 2005), the position of the Intertropical Convergence Zone (Vellinga & Wood, 2002) and sea level in the north Atlantic Ocean (Levermann et al., 2005), and past changes to the AMOC have been shown to substantially contribute to rapid atmospheric temperature change (Clark et al., 2002; Rahmstorf, 2002). The position and strength of the Southern Westerlies partly regulate the strength of the AMOC through two primary mechanisms: (1) they determine wind stress over the Antarctic Circumpolar Current, which governs the exchange of cool deep water between the Southern Ocean and the South Atlantic branch of the AMOC (Figure 2-3a) (Toggweiler & Russell, 2008; Toggweiler & Samuels, 1995, 1993; Marshall & Speer, 2012; Kuhlbrodt et al., 2007; Sijp & England, 2009, 2004) and (2) they modulate the delivery of warm saline water from the India Ocean to the South Atlantic branch via the Agulhas Current off the coast of South Africa (Figure 2-3b) (Bard & Rickaby, 2009; Durgadoo et al., 2013; Biastoch et al., 2009; Sijp & England, 2009).

Figure 2-3 | Simplified diagram of the global ocean circulation conveyor belt. Circled are the zones where the Southern Westerlies exert influence over the Atlantic Meridional Overturning Circulation (AMOC), which is the most critical component of the global ocean circulation conveyor belt. (a) Indicates the area where the Southern Westerlies drive Southern Ocean upwelling that supplies cool deep water to the South Atlantic branch of the
AMOC and (b) indicates the path of the Agulhas Current whose delivery of warm tropical surface waters to the South Atlantic branch of the AMOC is modulated by latitudinal shifts in the Southern Westerlies. Adapted from Rahmstorf (2002).

2.2.1.3 Global Carbon Cycle

The Southern Westerlies are also a substantial component of the global carbon cycle. Their role in governing the exchange of CO$_2$ between the Southern Ocean and the atmosphere has driven substantive changes in Holocene atmospheric CO$_2$ concentrations (Fletcher & Moreno, 2011; Moreno et al., 2010; Saunders et al., 2018), and is hypothesised to be a critical internal climate feedback during late Quaternary glacial terminations (Denton et al., 2010; Toggweiler et al., 2006). Two hypotheses exist to explain the mechanism that drives this process: the dust-delivery hypothesis and the ocean overturning hypothesis.

2.2.1.4 Dust delivery

The position and intensity of the Southern Westerlies has been shown to determine the delivery of continental dust into the oceans across the Southern Hemisphere (Lamy et al., 2014; Li et al., 2008; McGowan & Clark, 2008). The enhanced supply of dust-derived iron (Fe) to the Southern Ocean by the Southern Westerlies during glacial periods has been proposed as a key mechanism to explain the covariance of temperature and CO$_2$ through glacial-interglacial cycles (Martínez-Garcia et al., 2009; Abelmann et al., 2006; Bopp et al., 2003). It is hypothesised that a more equatorward position of the Southern Westerlies increases continental dust delivery and the resulting Fe fertilization of the Southern Ocean stimulates bio-productivity (the *biological pump*), fixing increased amounts of carbon from atmospheric CO$_2$ into the oceanic deep waters (Martin, 1990). However, the contribution of this process to the overall carbon flux between the atmosphere and Southern Ocean is debated. Firstly, the innate complexity of dust processes leads Maher et al. (2010) to question the attribution of the Westerlies as the primary driving mechanism and secondly, others question the relative contribution of the process to CO$_2$ ocean-
atmosphere exchange as compared to the influence of overturning strength, sea-ice coverage and ocean stratification (Fischer et al., 2010; Sigman et al., 2010; Lamy et al., 2014; Menviel et al., 2018).

2.2.1.5 Southern Ocean overturning

The position and strength of the Southern Westerlies has also been shown to regulate CO$_2$ exchanged between the Southern Ocean and the atmosphere, over multiple temporal scales, via their control over the rate of ocean overturning and deep-water upwelling (Anderson et al., 2009; Toggweiler et al., 2006; Fletcher & Moreno, 2011; Le Quéré et al., 2009; Lovenduski et al., 2008; Moreno et al., 2010; Saunders et al., 2018). When the wind belt is positioned more poleward, over the Antarctic Circumpolar Current (ACC), there is increased wind stress on the Southern Ocean surface which enhances the Ekman transport of these top waters, thus enhancing the rate of ocean overturning which then increases deep-water upwelling and the subsequent venting of the carbon that is sequestered in these bottom waters (Figure 2-4a) (Toggweiler et al., 2006; Toggweiler & Samuels, 1995). Conversely, when the Westerlies are positioned equatorward there is substantially less surface wind-stress over the ACC and therefore upwelling rates are heavily reduced, rendering the Southern Ocean a carbon sink as rates of sequestration surpass rates of outgassing (Figure 2-4b) (Toggweiler et al., 2006). This hypothesis has strong empirical support from upwelling-proxy studies in the Southern Ocean (Anderson et al., 2009; Skinner et al., 2010) and the most recent modelling study of CO$_2$ variation over Termination I contends that the rise in CO$_2$ was indeed driven by increased upwelling and not Fe-fertilization induced changes to the Southern Ocean biological pump (Menviel et al., 2018).
Figure 2-4 | Simplified schematic showing (a) modern atmospheric structure and (b) proposed LGM atmospheric structure with the westerly winds of each hemisphere shown schematically by the isotachs. Idealised relative exchange of CO$_2$ between the atmosphere and Southern Ocean under each atmospheric structure is represented as yellow arrows. (a) stronger Southern Westerlies positioned poleward over the ACC leads to a net release of CO$_2$ from the Southern Ocean, (b) weaker Southern Westerlies positioned equatorward away from the ACC leads to a net sequestration of CO$_2$ in the Southern Ocean. Adapted from Toggweiler and Russell (2008).

2.2.2 PAST CHANGES TO THE SOUTHERN WESTERLIES

While there is reasonable consensus on the behaviour of the westerlies in recent Earth history, the nature of past changes to the SWW belt remains highly contested (Fletcher & Moreno, 2012). Interpretations of model outputs, terrestrial proxy-data and marine proxy-data often conflict over how the Southern Westerlies have responded to changes in climate boundary conditions through the late Quaternary. Critically, these conflicts are responsible for the lack of understanding of how the Southern Westerlies respond to changes in the Earth system, and consequently hamper attempts to predict their future response to projected climate changes. The following sections will detail the leading conceptual understanding of how the Southern
Westerlies responded to past climatic change and then review the empirical and model-based evidence.

2.2.2.1 Conceptual Understanding

The leading conceptual models on the behaviour of the Southern Westerly wind belt during glacial terminations hypothesise that the wind belt shifts poleward and experiences central intensification in response to a warming Southern Hemisphere, and then shift equatorward with a central weakening in response to a cooling Southern Hemisphere (Denton et al., 2010; Toggweiler, 2009; Toggweiler et al., 2006). Both the Denton (Figure 2-5) and Toggweiler models (Figure 2-6) contend that changes to the interhemispheric thermal and pressure gradient during periods of changing climate boundary conditions displace the Intertropical Convergence Zone (ITCZ), and consequently the Southern Westerly wind belt. Additionally, a Northern Hemisphere ice sheet volume threshold is also recognised as a necessary precondition to a termination under the Denton model. Both models argue that these initial changes shift the westerlies south towards the “critical latitudes” of the Southern Ocean that have accumulated large amounts of dissolved CO₂ over the course of the glacial period, where wind-driven upwelling has remained low due the equatorward position of the wind belt. Once the wind belt reaches these critical latitudes the CO₂-rich deep waters are overturned at a much higher rate and release large volumes of CO₂ into the atmosphere (Figure 2-6). This creates a strong positive feedback as the increased atmospheric CO₂ concentrations enhance atmospheric warming which displaces the wind belt further south where its core intensifies around Antarctica and releases Southern Ocean CO₂ at a further accelerated rate. Denton and Toggweiler contend that this feedback provides the necessary conditions to shift the Earth from one climate state to another and that the mechanisms forcing the shifts in Southern Westerlies persist for all major climate perturbations (including the ACR) over the last four glacial-interglacial cycles (Denton et al., 2010; Toggweiler, 2009; Toggweiler et al., 2006).
2.2.2.2 Debates from key climate periods

There is both support and contradiction of the Denton and Toggweiler hypotheses from proxy and model-based studies of the Last Glacial Maximum (LGM; ca. 22-18 ka; WAIS Divide Project Members (2015)), where these authors contend the Southern Westerlies were positioned equatorward and experienced a central weakening at their core. Support for an equatorward position is found from both terrestrial and marine proxy-based reconstructions (Moreno et al., 1999; Heusser, 1989; Heusser et al., 2006a; Heusser et al., 2006b; Lamy et al., 1999; Bard & Rickaby, 2009; Gersonde et al., 2005; Nelson et al., 2000; Prell et al., 1980; Gersonde et al., 2003; Shulmeister et al., 2004; Fletcher & Thomas, 2010a; Kohfeld et al., 2013; Moreno et al., 2018b; Whittaker et al., 2011; Anderson et al., 2009; Skinner et al., 2010), and model output interpretations (Williams & Bryan, 2006; Kim et al., 2002; Kim et al., 2003; Drost et al., 2007; Menviel et al., 2018). Conversely, other terrestrial and marine-based proxy reconstructions support a poleward position (Harrison & Dodson, 1993; Markgraf et al., 1992; Markgraf, 1989;...
Williams et al., 2006), as do a number of modelling interpretations (Wyrwoll et al., 2000; Shin et al., 2003; Kitoh et al., 2001; Markgraf, 1993; Wainer et al., 2005). Studies from tropical regions have also contended that the ITZC was displaced towards the Northern Hemisphere during the LGM, which by extension supports the conceptual models from Denton and Toggweiler (Chiang & Bitz, 2005; Zhang & Delworth, 2005; Leduc et al., 2009), given the coupling observed between latitudinal shifts of the ITCZ and the Southern Westerlies (Chiang et al., 2014; Ceppi et al., 2013).

There is also discord within the early Holocene literature as to the position of the Westerlies. In agreement with the Denton and Toggweiler hypotheses several studies directly support a poleward displacement during this period as the pole-equator thermal and pressure gradient weakened (Shulmeister et al., 2004; Lamy et al., 2010; Moreno et al., 2010; Shulmeister, 1999; Villa-Martinez & Moreno, 2007; Moreno, 2004; Moreno et al., 2018a; Saunders et al., 2018). Conversely, others support an equatorward position at this time (Harrison & Dodson, 1993; Dodson, 1998; Veit, 1996; Moros et al., 2009).

**Figure 2-6** | The “Toggweiler model” of the central role of the Southern Westerlies during glacial terminations. (a) the proposed feedback loop that summarises the role of the shifting Southern Westerlies during glacial terminations and (b) schematic diagram showing the hypothesised position of the LGM westerlies and the modern westerlies in relation to the Antarctic Circumpolar Current (ACC). The westerlies are pushed over the threshold region by the proposed feedback loop from part (a). From Toggweiler et al. (2006).
Although there is strong support for the Denton and Toggweiler models within the literature, the sum of the evidence remains equivocal on the behaviour of the Southern Westerlies during both the LGM and the early Holocene. This highlights the necessity to retrieve further high-quality, well-constrained proxy-based records of Southern Westerly dynamics through periods of past climate change. The period between the LGM and the Holocene, Termination I (ca. 18 -11.7 ka; WAIS Divide Project Members (2015)), is marked by a large-scale reorganisation of the Earth’s climate and features a millennial-scale climate fluctuation in the Southern Hemisphere known as the Antarctic Cold Reversal (ca. 14.7 – 13 ka; Pedro et al. (2016)). This period represents the most recent large-scale climatic change in the Southern Hemisphere rendering it a useful analogue to study the dynamics of climate system components, such as the Southern Westerlies. Critically, as with the LGM and the Holocene, there is also a lack of consensus on the behaviour of the Southern Westerlies through this period. As the dynamics of the Southern Westerlies through the Antarctic Cold reversal is the primary focus of this thesis, the following section will provide a thorough interrogation of the current understanding of (1) the nature of and drivers of the Antarctic Cold Reversal and (2) the response of the Southern Westerlies through its duration.

2.3 THE ANTARCTIC COLD REVERSAL

The Antarctic Cold Reversal (ACR) was a millennial scale cold climate event that disrupted Southern Hemisphere warming during Termination I (Pedro et al., 2016). This interval provides a critical insight in to how the Southern Westerlies respond to rapid shifts in climate and is thus an important period for contextualising the current climate trends. Ice core records from Antarctica show that the cooling event persisted for the period ca. 14.7-13 ka before warming resumed in the Southern Hemisphere and full interglacial conditions were reached at ca. 11.7 ka, marking the beginning of the current Holocene epoch (Figure 2-7) (Jouzel et al., 1995; Blunier et al., 1997; Pedro et al., 2011; NGRIP Members, 2004; Rasmussen et al., 2006; WAIS Divide Project Members, 2015; Pedro et al., 2016). The ACR cooling event lagged slightly behind a
broadly contemporaneous Greenland warming event, the Bølling–Allerød (ca 14.7 – 12.7; Buizert et al. (2014), WAIS Divide Project Members, 2015), which was also followed in Greenland by the Younger Dryas cooling event (ca. 12.8 – 11.7 ka; Buizert et al. (2014)), which coincided with the final deglacial warming period in Antarctica (WAIS Divide Project Members, 2015). This asynchrony can be explained via coupled ocean-atmosphere dynamics which result in an anti-phasing of northern and southern hemisphere climatic change through periods of rapid climatic change, the so-called bipolar seesaw (further discussed in section 2.3.1) (Markle et al., 2017; Pedro et al., 2016; Pedro et al., 2018). It is clear that the ACR cooling event was a hemisphere-wide phenomenon in the mid-high latitudes of the Southern Hemisphere (Pedro et al., 2016), which is demonstrated by its presence in proxy records from New Zealand (Newnham et al., 2012; Putnam et al., 2010; Sikes et al., 2013; Vandergoes et al., 2008), Patagonia (Moreno et al., 2018b; Moreno et al., 2015; Pesce & Moreno, 2014; Moreno et al., 2012; Sagredo et al., 2018; Moreno et al., 2009), the South East Pacific Ocean off the coast of Chile (Lamy et al., 2007), the South Atlantic Ocean (Barker et al., 2009), and in the Southern Ocean off the coast of South Australia (Calvo et al., 2007).

2.3.1 THE MECHANISMS OF THE ANTARCTIC COLD REVERSAL

The asynchrony of the millennial-scale climate events that punctuated Termination I (Figure 2-7; the ACR, Bølling–Allerød and Younger Dryas) provide an example of how rapid climate changes are teleconnected between hemispheres during periods of major climatic reorganisation, such as glacial terminations. The thermal (oceanic) bipolar seesaw hypothesis was developed by Broecker (1998) and advanced by Stocker and Johnsen (2003) to explain the asynchrony of these events and it invokes changes in the rate of cross-equatorial ocean heat transfer, in response to perturbations or collapse of the Atlantic Meridional Overturning Circulation (AMOC; Figure 2-3), as the driver Greenland and Antarctic temperature anomalies during millennial-scale climate events.
During glacial terminations the proponents of the thermal bipolar seesaw hypothesise that the AMOC collapses in response to pulses of cool fresh water from melting Northern Hemisphere ice sheets (Stocker & Johnsen, 2003; Broecker, 1998). As a consequence of AMOC collapse, the usual transfer of heat from the South Atlantic to the North Atlantic is diminished and heat accumulates in the Southern Ocean (Crowley, 1992; Barker et al., 2009; Stocker & Johnsen, 2003; Broecker, 1998). During millennial-scale climate events, temperature responses in Antarctica are much less abrupt and lag slightly behind Greenland (Figure 2-7), and Stocker and Johnsen (2003) suggest the presence of a heat reservoir in the Southern Ocean to explain the attenuated Antarctic temperature fluctuations. Indeed, the presence of such a heat reservoir has been furthered by Pedro et al. (2018), who support its role in attenuating Antarctic temperature variation but propose its location to be north of the Antarctic Circumpolar Current (ACC) in the global interior ocean, rather than the Southern Ocean. Further, these authors hypothesise that the time required for the heat reservoir to accumulate enough heat to mix across the ACC and enter the Southern Ocean is the reason for the observed lag of Antarctic warming events following AMOC collapse and Greenland cooling (WAIS Divide Project Members, 2015; Schmittner et al., 2003).

However, the role of the thermal bipolar seesaw in heat transfer during millennial-scale climate events is questioned by Wunsch (2006) and Seager and Battisti (2007) who contend that atmospheric heat transport is the dominant process controlling climate variability during such events. This interpretation includes a central role for the Southern Westerlies as the transfer of heat from the north to the south as the AMOC collapses is thought to involve the coupled southward displacement of the major global atmospheric circulation elements (i.e. Northern Westerlies, ITCZ, Southern Westerlies). As discussed, this mechanism, and in particular the poleward displacement of the Southern Westerlies, is hypothesised to be a critical element of interhemispheric climate change during glacial terminations (Denton et al., 2010; Toggweiler et
Modelling from Pedro et al. (2018) indicates that a poleward shift in the Southern Westerlies would develop within 50 - 100 years following AMOC collapse. Indeed, this result is broadly consistent with proxy evidence of Southern Westerly shifts during last glacial period millennial-scale climate events (Dansgaard-Oeschger events) (Markle et al., 2017). Further empirical support for the displacement of the Southern Westerlies as part of the atmospheric circulation response to AMOC collapse is found through Termination I in New Zealand (Whittaker et al., 2011), Patagonia (Moreno et al., 2018b; Moreno et al., 2015; Moreno et al., 2012) and the Southern Ocean (Anderson et al., 2009; Skinner et al., 2010). However, as these records and the displacement of the Southern Westerlies through Termination I (including the ACR) partly comprise the direct research of this thesis, they will be explored more thoroughly in Section 2.4.

Since the studies of Broecker (1998) and Stocker and Johnsen (2003) the development of higher-resolution more well-dated proxy records (Markle et al., 2017; WAIS Divide Project Members, 2015) and the advancement of models (Pedro et al., 2018) has led to an improved understanding of the mechanisms of millennial climate events, such as the ACR. It now appears that following AMOC perturbation the climate response is propagated rapidly (≤ decadal; Markle et al. (2017)) to the Southern Hemisphere, via changes in atmospheric circulation, but propagation via the thermal (oceanic) bipolar seesaw occurs more slowly (50 – 200 years; Pedro et al. (2018); Markle et al. (2017)). These developments maintain a critical role for the Southern Westerlies in interhemispheric climate change coupling and thus, further illustrate the need to improve our understanding of their dynamics.
Figure 2-7 | Greenland and Antarctic proxy records spanning 19-10 ka, including Termination I (ca. 18-11.7 ka; WAIS Divide Project Members (2015)), the Antarctic Cold Reversal (ACR; ca. 14.7-13 ka; Pedro et al. (2016)), the Bølling–Allerød (B-A; ca. 14.7-12.7 ka; Buizert et al. (2014)) and the Younger Dryas (YD; Buizert et al. (2014)). (a) Greenland average surface air temperature reconstruction average from ice core sites NEEM, GISP2 and NGRIP using δ15N and diffusion methods (Buizert et al., 2014), (b) WAIS Divide (Antarctica) ice core CO2 concentration (WAIS Divide Project Members, 2015) and (c) WAIS Divide (Antarctica) ice core δ18O.

2.3.2 THE ANTARCTIC COLD REVERSAL IN TASMANIA

Currently, there is limited palaeoclimate proxy data to constrain the spatial and temporal extent of the climatic changes of the ACR in Tasmania (Fletcher & Thomas, 2010a). This absence of data is reflected in synthesis studies from Clark et al. (2012) and Pedro et al. (2016) that report only a single dataset from the Australian sector of the Southern Hemisphere; marine sediment core MD03-2611 off the coast of Southern Australia (Calvo et al., 2007). Whilst this record
reveals sea-surface temperature and δ¹⁸O decreases that are consistent with the ACR temperature signal in Antarctic records, it would be imprecise to interpret this data as a proxy for Tasmanian climate as oceanic circulation and atmospheric circulation are known to potentially decouple through time (Toggweiler & Russell, 2008).

Of the studies that were not considered in the syntheses from Clark et al. (2012) and Pedro et al. (2016), mixed signals of ACR conditions in Tasmania are apparent. There is evidence of cooling through the ACR from analysis of fossil pollen assemblages, organic content, charcoal and geochemistry of lake sediments (Beck et al., 2017; Colhoun & Van de Geer, 1986; Fletcher & Thomas, 2010a; Rees & Cwynar, 2010), but the cooling was not substantive enough to induce any detectable glacial re-advancement or lake ice formation (Barrows et al., 2002; Beck et al., 2017; Rees & Cwynar, 2010), such as is reported in the Southern Alps of New Zealand (Putnam et al., 2010). There is scant evidence for changes in hydroclimate; in western Tasmania a decrease in regional lake sediment charcoal influx infers an increase in effective precipitation through the ACR (Fletcher & Moreno, 2012; Fletcher & Moreno, 2011; Mariani & Fletcher, 2016), but no other records exist. A lake sediment record analysed by Mackenzie and Moss (2014) from Hazards Lagoon in eastern Tasmania (Site 2- this study) argues for drier conditions during the ACR through two lines of evidence: (1) elevated charcoal content, and (2) the disappearance of aquatic littoral macrophyte Myriophyllum spp. from the record. However, the interpretations in the Hazards Lagoon record are problematic for the following reasons: (1) the record has poor age constraint; (2) there is no indication of a vegetation response to “drier conditions” in the terrestrial pollen record, and (3) Myriophyllum spp. all but disappears from the record at ca. 15.5 ka, ~900 years before the onset of the ACR (Pedro et al., 2016). Thus, there is no clear and consistent pattern that emerges from the existing Tasmanian proxy data and it is clear that additional well-dated terrestrial climate-proxy data from across Tasmania is required to
definitively constrain the spatial and temporal extend of the ACR in Tasmania (Fletcher & Thomas, 2010a).

2.3.3 THE ACR AS AN ANALOGUE FOR FUTURE CLIMATE CHANGE

As mentioned, there is no consensus on how the Southern Westerlies respond to rapid global-scale climate change. To improve our capacity to forecast how the Southern Westerlies will respond the change the Earth currently faces, this thesis will use the Antarctic Cold Reversal (ACR) as an analogue for future change.

Even though the ACR was a cooling period of climatic change and the current projection show future warming (Stocker et al., 2013), the use of the ACR as an analogue to study changes in Southern Westerlies is justified because: (a) the mechanisms that control Southern Westerly dynamics operate in response to cooling and warming of the atmosphere (Shulmeister et al., 2004; Denton et al., 2010; Toggweiler, 2009), and (b) the ACR is the most recent period of rapid large-scale changes to climate boundary conditions in the Southern Hemisphere and this event is terminated by rapid warming that approaches the rate of change observed today.

2.4 THE RESPONSE OF THE SOUTHERN HEMISPHERE WESTERLIES TO RAPID CLIMATE CHANGE DURING THE ACR

2.4.1 OCEANIC EVIDENCE

The contention from Toggweiler and Denton that during cool phases in the Southern Hemisphere, such as the ACR, the Southern Westerlies shift north away from the Antarctic Circumpolar Current leading to reduced rates of Southern Ocean upwelling is well supported by two marine sediment records. Anderson et al. (2009) find decreases in biogenic opal flux, a proxy for ocean upwelling, in four Southern Ocean sediment cores through the ACR. They then
build on this data by comparing the record with Antarctic CO$_2$ variation over Termination I and part of the last glacial period to demonstrate a coupling between upwelling rates and atmospheric CO$_2$ concentration. A second study from Skinner et al. (2010) also finds strong evidence of reduced Southern Ocean upwelling in the South Atlantic sector through the ACR by demonstrating a pause in the release of $^{14}$C-depleted CO$_2$ from the ocean to the atmosphere, which is indicative of a pause in the rate of deep-water upwelling at their site. Both studies find strong support for the hypothesis that the Southern Westerlies were positioned north, away from the critical latitudes of the Southern Ocean during the ACR.

However, the only proxy-based record that considers the position of the Southern Westerlies through the ACR in the Australian region contradicts the Southern Ocean evidence presented above (De Deckker et al., 2012). This marine sediment record was retrieved from the Murray Canyons off the coast of Southern Australia ($36^\circ43.8'S$, $136^\circ32.9'E$), to the north of Tasmania. Interpretation of the oceanic proxy data from this sediment core argues that the Southern Westerlies were weakened or that they were positioned further south (poleward) during the ACR. De Deckker et al. (2012) reach this conclusion by interpreting presence of the subtropical foraminifera *Globigerinoides ruber* in their record during the ACR as evidence of the presence of the Leeuwin Current, a warm ocean surface current that delivers tropical ocean water from the Indo-Pacific south along Australia’s west coast and along the south coast of Australia. Their argument rests on the contention that penetration of the Leeuwin Current along the south coast of Australia can only occur under reduced Southern Westerly wind conditions (i.e. poleward displacement) and that stronger Southern Westerly wind conditions (i.e. equatorward displacement) act to block the penetration of the Leeuwin Current around Cape Leeuwin and along the south coast. Importantly, the only data available on the role of the Southern Westerlies in Leeuwin Current dynamics, based on modern interannual variations in Leeuwin Current strength and penetration, indicates that during the Austral winter, when the Southern Westerlies
are positioned northward, the strength and penetration of the Leeuwin Current actually increases (Pearce & Pattiaratchi, 1999; Cirano & Middleton, 2004; Feng et al., 2009). The interpretation of Leeuwin Current-Southern Westerly interactions will be further explored in Section 5.6.2.

2.4.2 TERRESTRIAL EVIDENCE

Evidence from terrestrial records across the Southern Hemisphere also show some ambiguity in their interpretation of the dynamics of the Southern Westerlies through the ACR. A number find inconclusive, or conflicting signals in Australia and New Zealand (Rees & Cwynar, 2010; Newnham et al., 2012; Sikes et al., 2013). Others, such as Putnam et al. (2010) and Sagredo et al. (2018), infer the Southern Westerlies were positioned equatorward through the ACR, in line with the Denton and Toggweiler models and upwelling-proxy records from the Southern Ocean, based on evidence of a readvance of glaciers in New Zealand and Patagonia (southern South America). These studies assert that increased effective precipitation derived from strengthened Southern Westerly flow drove glacial advances. These assertions are made despite data revealing that the mass-balances of both the New Zealand and Patagonian glaciers is primarily determined by temperature, not precipitation (Anderson & Mackintosh, 2006; Falaschi et al., 2013). Thus, attributing glacial advances in these regions to increased westerly-derived precipitation (i.e. equatorward positioned westerlies) during the ACR is problematic considering the contemporaneous evidence for cooling in these locations (Vandergoes et al., 2008; Newnham et al., 2012; Moreno et al., 2009).

More robust terrestrial evidence of a northward position through the ACR comes from a New Zealand speleothem study from Whittaker et al. (2011) and on Patagonian lake sediments from Moreno et al. (2018b), Moreno et al. (2015) and Moreno et al. (2012). Whittaker et al. (2011) determine that precipitation amount is the primary control of growth rate and stable isotope ($\delta^{18}O$, $\delta^{13}C$) variation in a stalagmite from Hollywood Cave on the windward side of the New
Zealand Southern Alps (41°57'S, 171°28'E). The Southern Alps intercept westerly zonal flow in a manner commensurate with the central ranges of Tasmania and thus precipitation amount is determined directly by variation in the strength of Southern Westerly flow over the range. The record is anchored by a robust chronology (18 U-series dates) and is of sufficient sample resolution (20-290 year) to interpret millennial-scale climate events, such as the ACR. Indeed, the authors interpret their results as reflecting enhanced precipitation through the ACR and from this infer that the Southern Westerlies were positioned equatorward at this time. Multi-proxy studies of lake sediments from six sites (41-51°S) through Patagonia also present strong evidence for a northward position of the Southern Westerlies through the ACR (Moreno et al., 2018b; Moreno et al., 2015; Moreno et al., 2012). Again, these sites are located on the windward side of a mountain range that intercepts zonal westerly flow, the Andes, and thus precipitation is determined by Southern Westerly strength. The authors interpret higher lake levels (Moreno et al., 2012) and the expansion of hygrophilous (moisture-loving) vegetation and reduced fire-activity (Moreno et al., 2018b; Moreno et al., 2015) as reflecting an increase in precipitation through the ACR. All records possess robust chronologies anchored by numerous 14C dates and are of sufficient sampling resolution to interpret millennial-scale climate events.

Considering all evidence to date, there is mounting support from New Zealand, southern South America and the Southern Ocean for an equatorward position of the Southern Westerlies through the ACR. However, the Australian sector currently prevents any determination of a hemisphere-wide equatorward shift during the ACR, as predicted under the Denton and Toggweiler models, for two reasons: (1) there are no terrestrial proxy records that reconstruct Southern Westerly dynamics through the ACR, and (2) the only oceanic proxy-based reconstruction contradicts other Southern Hemisphere records, arguing the Southern Westerlies were positioned poleward during the ACR. To reconcile this discord and to fill the data gap a terrestrial, high-resolution
proxy record that can unambiguously reconstruct the dynamics of the Southern Westerlies through the ACR in the Australian sector is required.

2.5 The Study Area: Tasmania

Tasmania, Australia has been selected as the study area for this thesis. Tasmania is a small continental island located to the southeast of the Australian mainland between 40-44°S and 144-148°E and is separated from continental Australia by the Bass Strait. Tasmania is the ideal location to study the dynamics of the Southern Westerlies through the Antarctic Cold Reversal (ACR) because (1) Tasmania has the highest correlation between variations in Southern Westerly flow and precipitation anomalies of anywhere in the Southern Hemisphere, which permits past changes in hydroclimate to be confidently interpreted as a response to changes in Southern Westerly flow (Gillett et al., 2006); (2) the orographic effect of the central mountain ranges creates a clear inverse relationship between Southern Westerly flow and precipitation anomalies between western and eastern Tasmania, permitting an unambiguous reconstruction of westerly strength through targeted west-east site selection; (3) Tasmanian lake sediments have been shown to record reliable multiple-proxy responses to changes in climatic conditions (e.g. Colhoun et al. (1999); Beck et al. (2017); Fletcher et al. (2015); Mackenzie and Moss (2014)); and (4) the location of Tasmania in the Australian sector of the Southern Hemisphere within close proximity to the oceanic proxy record of De Deckker et al. (2012) positions it ideally to address firstly, the ACR data gap identified by Clark et al. (2012) and Pedro et al. (2016) and secondly, the discord between the conceptual understanding of Southern Westerly dynamics through Termination I (Denton et al., 2010; Toggweiler et al., 2006) and the findings of De Deckker et al. (2012).
2.5.1 MODERN CLIMATE

Because of Tasmania’s position in the mid-latitudes and the temperature-buffering effect of the surrounding ocean, it has a temperate maritime climate with mild winters and cool summers. The mountain range that bisects the island strongly influences climatic variation between the western and eastern regions through elevation-temperature relationships and through orographic processes acting on the island as the prevailing Southern Westerly winds are intersected by the range (Langford, 1965).

Temperature varies significantly across Tasmania with mountainous regions in the western and central highlands averaging annual temperatures of ~6°C, as compared to ~15°C in coastal and lowland regions (Figure 2-8) (Bureau of Meteorology, 2016). This discrepancy is a product of two main processes: (1) the gradient of near-surface air temperature and altitude (environmental lapse rate) in Tasmania results in a decrease of ~0.6°C with every 100 m of elevation (Nunez, 1988), and (2) the orographic uplift of westerly air masses increases cloud cover on the windward slopes (reducing day-time temperatures) and the dry descending air masses on the leeward slopes forms less cloud cover (increasing day time temperatures) (Langford, 1965).

Rainfall also varies markedly across Tasmania; there is a pronounced west-east rainfall gradient that sees the western regions average annual rainfall of up to 3500 mm, classified as superhumid, and the east average only ~600-700 mm annually, classified as sub-humid (Figure 2-8) (Bureau of Meteorology, 2016; Gentilli, 1972). This gradient is a product of the difference in moisture sources between the west and the east, which stems from the island’s position in the path of the Southern Westerly wind belt and from the orographic influence of the central mountain range. Western and central regions receive all their rainfall from westerly-derived orographic and storm-related precipitation, whereas eastern regions receive most of their rainfall from easterly
Tasman Sea moisture sources; typically easterly lows or tropical intrusions (Gentilli, 1972; Langford, 1965). Because westerly flow also interacts with the easterly-derived moisture sources, the relative strength of zonal westerly flow governs rainfall variability for both western and eastern Tasmania (Garreaud, 2007; Hendon et al., 2007). The mechanism operates as follows: under strengthened westerly flow; rainfall on the west is enhanced by an increase in orographic and storm-related precipitation, and rainfall on the east is reduced as the stronger foehn winds restrict easterly-derived moisture sources from the Tasman Sea reaching the east coast. Under attenuated westerly flow; rainfall on the west is reduced as orographic and storm-related precipitation is abated, while on the East there is an increase in rainfall as weakened foehn winds allow further penetration of easterly moisture sources from the Tasman Sea into the eastern regions (Hendon et al., 2007; Hill et al., 2009). This mechanism allows Tasmania to be

Figure 2-8 | Map of Tasmania showing (a) mean annual precipitation with the 1250 mm isohyet delineating the boundary of the superhumid western region (Gentilli, 1972; Bureau of Meteorology, 2016) and (b) mean annual temperature (Bureau of Meteorology, 2016). Created by Michela Mariani.
divided into clear zones of positive and negative correlation between westerly wind flow and rainfall anomalies (Figure 2-9). This division and the inverse relationship between westerly flow and precipitation between the West and the East comprises part of the rationale that will allow this study to unambiguously reconstruct changes in westerly flow through the ACR.

Figure 2-9 | Map of Tasmania showing the correlation between Southern Westerly wind speed and annual rainfall. The sites in this study are marked as yellow stars. Created by Michela Mariani.

2.5.2 GEOLOGY & SOILS

Tasmania has a complex geology that is broadly characterised by underlying fold-dominated structures in the west and fault-dominated structures in the east (Figure 2-10) (Seymour et al., 2006). Quaternary glaciation and high rainfall have eroded younger rock formations in the west and have left much of the older metamorphosed Precambrian rock exposed. The west also features localised surface exposures of highly mineralised volcanic bedrock deposited within
pyrite and calcite bodies, such as the Mount Read group of volcanics that contain large ore deposits rich in copper, lead, zinc and silver and which have supported a lucrative mining industry for more than a century (Seymour et al., 2006; Solomon et al., 1987). The Mount Read volcanics and Quaternary glacial sediments comprise the surface geology of the Lake Rolleston catchment (Site 1- this study) and will be relevant in the interpretation of proxy-records from this site in Chapter 4.

The geology of eastern Tasmania is dominated by late-Carboniferous sedimentary rocks (termed “Parmeener”) with extensive Jurassic dolerite intrusions (Seymour et al., 2006). Much of the north-east is also underlaid by Devonian granitoids and outcrops of these granites comprise the mountains of Freycinet National Park, the area which Hazards Lagoon (Site 2- this study) is located (Seymour et al., 2006).

As with the contrasting geology and climate of Tasmania, the soils of western and eastern Tasmania are distinctly different (Cotching et al., 2009). The dominant siliceous substrate of western Tasmania is resistant to weathering and thus only forms thin, nutrient-poor soils (Kitchener & Harris, 2013). Deep organic peat soils form where (relatively) productive rainforest has captured the landscape and the cool wet climate restricts decomposition of the organic material they deposit (Di Folco, 2007). The reliance of these organosols on the delivery of organic matter from the vegetation it hosts affects their distribution and level of development; for example, the development of organosols decreases with altitude across western Tasmania as temperature acts to restrict biomass (Bridle & Kirkpatrick, 1997). Further, fire, via its role in restricting the distribution of rainforest, is an important control over the development of organic soils, a process well described by fire-vegetation-soil feedback models (Jackson, 1968; Wood & Bowman, 2012). Eastern Tasmanian soils are primarily determined by their parent material, and are mostly characterised by relatively fertile clay-based soils (Cotching et al., 2009).
2.5.3 MODERN VEGETATION

The modern vegetation of Tasmania is primarily a product of climate, and thus there is stark contrast between the west and east. Geology, topography and a long history of landscape management through the human application of fire have also influenced the overall composition and distribution of Tasmanian vegetation.

2.5.3.1 Western Tasmania

The vegetation of western Tasmania is dominated by cool temperate rainforest, fire promoted buttongrass moorland and wet-sclerophyll forest (a fire-dependent transitional vegetation type between rainforest and moorland) (Figure 2-11). Temperature is the primary determinant of
vegetation distribution in western Tasmania and as such, changes in vegetation distribution follow changes in altitude (Fletcher & Thomas, 2010a; Read & Busby, 1990). Alpine communities prevail above the climatic treeline (~900-1100 m a.s.l) and sub-alpine between ~700 m a.s.l and the treeline (Kirkpatrick, 1982). In alpine and subalpine areas free from fire, forested communities are the climax vegetation and are dominated by coniferous species *Athrotaxis selaginoides*, *A. cupressoides*, *Microstrobos niphophilus*, *Diselma archerii* and *Microcachys tetragona*, as well as the deciduous angiosperm *Nothofagus gunnii* (Kitchener & Harris, 2013). Alpine sedgeland communities also occur and are characterised by members of the Ericaceae, Proteaceae and Asteraceae families and alpine wetlands feature the perennial herb *Astelia alpina* (Kitchener & Harris, 2013).

Below ~700 m a.s.l the climax community is lowland *Nothofagus cunninghamii* rainforest or podocarp rainforest characterised by *Phyllocladus asplenifolius* and *Lagarostrobos franklinii* (Jackson, 1968). Though the amount of rainfall required to support climax rainforest is constant across most areas below ~700 m a.s.l (Jackson, 1983), 41% of lowland western Tasmania is dominated by treeless *Gymnoschoenus sphaerocephalus* (buttongrass) moorland communities (Figure 2-11) (Fletcher & Thomas, 2010b; Kitchener & Harris, 2013). The dominance of buttongrass moorland in areas which are climatically suited to rainforest development is explained by the long-term human application of fire in the landscape (Fletcher & Thomas, 2010b), with high-frequency fire still requirement in the contemporary landscape for these communities to maintain their dominance over rainforest (Jackson, 1968; Wood & Bowman, 2012; Fletcher et al., 2014a).

### 2.5.3.2 Eastern Tasmania

The dominant vegetation types in eastern Tasmanian are dry-sclerophyll forests and woodlands (Figure 2-11) (Kitchener & Harris, 2013). Across the central plateau the transition along the
rainfall gradient from western rainforest/moorland-dominant to eastern dry-sclerophyll dominant is marked by an ecotone of wet-sclerophyll forests and sub-alpine woodlands, dominated by *Eucalyptus spp.* (Colhoun & Shimeld, 2012). Rainfall is the primary determinant of vegetation across eastern Tasmania: wet-sclerophyll *Eucalyptus spp.* forest occurs in the wettest regions; dry-sclerophyll *Eucalyptus spp.* forest and *Eucalyptus spp.* and *Allocasuarina spp.* woodland in drier areas; and in the driest areas lowland grasslands occur, comprising species of *Poa, Thymedea, Austrodanthonia* and *Austrostipa*, which were formally accompanied by a sparse distribution of *Eucalyptus spp.* trees prior to clearance by Europeans (Colhoun & Shimeld, 2012; Kitchener & Harris, 2013).

![Map of Tasmania’s dominant vegetation communities from TAS VEG 3.0](image)

**Figure 2-11** | Map of Tasmania’s dominant vegetation communities from TAS VEG 3.0 (Kitchener & Harris, 2013; DPIPWE, 2018).
2.5.4 VEGETATION AND CLIMATE HISTORY

Climate change was the major driver of Tasmanian vegetation change through the late-Quaternary, with the arrival of humans to the landscape at ca. 39 ka adding a second major control of vegetation distribution (Jackson, 1968; Macphail, 1980; Colhoun & Shimeld, 2012; Cosgrove, 1999; Mariani et al., 2017; Fletcher & Thomas, 2010b).

The Tasmanian climate has changed dramatically throughout the Quaternary, characterised by dramatic variations in temperature over repeated glacial-interglacial cycles (Colhoun et al., 1999). The Last Glacial Maximum (LGM) in Tasmania (ca. 22-18 ka; Petherick et al. (2013)) was characterised by depressed temperatures across the island and restricted glaciation of the western and central ranges (Barrows et al., 2004; Barrows et al., 2002; Colhoun et al., 1994; Mackintosh et al., 2006; Colhoun, 1991). Changes in the vegetation assemblages of western Tasmania reflected changes in temperature, due primarily to the influence western topography has on shifts in the climatic treeline (Fletcher & Thomas, 2010a; Colhoun et al., 1999), with changes in eastern Tasmania most likely reflecting changes in effective precipitation, rather than temperature (Colhoun et al., 1999; Petherick et al., 2013; Colhoun & Shimeld, 2012).

Fossil pollen records from the west reveal that during the LGM there was a reduction in the coverage of rainforest and sclerophyll forest and an expansion of alpine and sub-alpine grassland communities (Colhoun et al., 1999; Colhoun et al., 1994; Macphail, 1979; Colhoun & Shimeld, 2012). Due to the extreme humidity of western Tasmania it is unlikely that precipitation was the limiting factor driving vegetation change through the last glacial period and it is more likely that lower temperature and the human application of fire were the dominant process controlling the vegetation distribution (Colhoun et al., 1999; Fletcher & Thomas, 2010a; Fletcher & Thomas, 2010b; Colhoun & Shimeld, 2012). The termination of the last glacial period in Tasmania (ca. 18-17 ka; Petherick et al. (2013), Mackintosh et al. (2006), Barrows et al. (2002)) saw a region-
wide expansion of the pioneer rainforest tree, *P. aspleniiifolius*, at the expense of alpine and sub-alpine grassland communities across western Tasmania (Colhoun *et al.*, 1999; Colhoun *et al.*, 1994; Macphail, 1979; Colhoun & Shimeld, 2012; Fletcher & Thomas, 2010a). Interestingly, no records from western Tasmania document any pause or reversal in the expansion of rainforest across the deglacial when records from comparable environments across the Southern Hemisphere (New Zealand, Vandergoes *et al.* (2008); Newnham *et al.* (2007); Patagonia, Pesce and Moreno (2014)) record a resurgence in cold-climate taxa contemporaneous with the Antarctic Cold Reversal (ca. 14.7- 13 ka; Pedro *et al.* (2016)).

Eastern Tasmania’s more temperate climate and moderate topography render its vegetation more responsive to changes in moisture availability rather than temperature, and this is reflected in the fossil pollen record (Colhoun *et al.*, 1999; Petherick *et al.*, 2013). Records show much drier conditions prevailed in eastern Tasmania during the LGM along with increased fire activity as Indigenous populations increasingly applied fire to the landscape (Colhoun & Shimeld, 2012; Cosgrove, 1985). Fossil pollen records from eastern Tasmania reveal that vegetation during the LGM featured more arboreal taxa than the west with pollen assemblages indicating a prevalence of *Eucalyptus* spp. dry-sclerophyll forests or woodlands and grassland-steppe communities (Colhoun & Shimeld, 2012; Mackenzie & Moss, 2014; Sigleo & Colhoun, 1981; Colhoun, 1977). Enhanced deposition of dune sands is also observed in eastern Tasmania through the LGM (Duller & Augustinus, 2006; McIntosh *et al.*, 2008), which McIntosh *et al.* (2009) attribute to the drier climate and impact of increased fire on erosion. Following the termination of the glacial period, the deglacial vegetation retained steppe-grassland communities in the dry Midlands (Sigleo & Colhoun, 1981), but other regions such as the Freycinet Peninsula experienced an expansion of dry-sclerophyll communities dominated by *Eucalyptus* spp. and *Allocasuarina* spp. (Mackenzie & Moss, 2014).
CHAPTER 3: METHODS

Developing a robust palaeoenvironmental record from lake sediments requires three main steps: (1) site selection and sediment retrieval, (2) chronology development and (3) proxy-data processing, analysis and interpretation. This chapter outlines the methods used to complete these steps in this thesis and provides justification for their selection. Firstly, it will introduce lake sediments as a palaeoenvironmental archive. Secondly, it will summarise the methods used for each analysis, justify their use, discuss their advantages and limitations and explain the proxy interpretations that will arise from the results.

3.1 LAKE SEDIMENTS AS A PALAEOENVIRONMENTAL ARCHIVE

Lakes accumulate sediment from their surrounding catchment and these sediments can provide continuous records of environmental change occurring both within the lake, in its catchment and beyond (Figure 3-1) (Smol et al., 2002). These sediments are comprised of material from two sources: allochthonous material, that originates from outside of the lake, and autochthonous material that is produced within the lake. Both these lacustrine materials can contain a number of proxy-types that record environmental change at and around the lake (Bradley, 2013). Because many processes can be controlling change in these proxy records, the most robust environmental reconstructions involve a multi-proxy analysis so to minimise the chance of misinterpretation of the records (e.g. Fletcher et al. (2014b), Mariani et al. (2018), Moreno et al. (2018b)). Such an approach has been adopted in this thesis.

3.1.1 PROXY RECORDS ENTRAINED IN LAKE SEDIMENTS

The multi-proxy analyses conducted on the lake sediments in this thesis will allow a comprehensive reconstruction of environmental change in western and eastern Tasmania through
the Antarctic Cold Reversal (ACR; ca. 14.7 – 13 ka Pedro et al. (2016)). Analysis of sediment geochemistry will provide a record of changing lake conditions and catchment weathering and erosion regimes, analysis of fossil pollen and palynomorph assemblages will provide a record of changes to aquatic and terrestrial biota and analysis of sedimentary charcoal will provide a record of changes in fire activity. Interpreted together, these results will provide a record of environmental change across Tasmania through the ACR that can be assessed against potential drivers, such as changes in hydroclimate or temperature.

![Figure 3-1](image)

**Figure 3-1** | Lake schematic showing examples of proxy-sources within the lake and its catchment.

### 3.2 Site selection

To address the research questions outlined in *Section 1.2*, this study focusses on two sites that met the following criteria:
(1) The sediments within the selected wetland/lake sites would provide a continuous and datable record of environmental change that extends through the ACR.

(2) The sites are located in regions with a clear relationship between the changes in Southern Westerly dynamics and climate.

Considering these criteria, the following sites were selected:

**Site 1- Lake Rolleston:** this site is located in the zone of highest positive Southern Westerly-rainfall correlation in Tasmania (Figure 2-9), indicating a high potential for this site to record evidence of Southern Westerly-driven climatic change. Lake Rolleston is a glacially carved lake basin located on the northern edge of the Tyndall Ranges in western Tasmania (41°55'17"S, 145°37'29"E). Outflow from the lake is bound by moraines that were emplaced ca. 18 – 16 kyr (Barrows et al., 2002), indicating a high probability of securing the ACR.

**Site 2- Hazards Lagoon:** this site is located in the zone of highest negative Southern Westerly-rainfall correlation in Tasmania (Figure 2-9). Hazards Lagoon is located on the Freycinet Peninsula on the eastern coast of Tasmania (42°10'20"S, 148°17'21"E). This site was the focus of a previous low-resolution (millennial-scale) study that recorded initiation of the lagoon at ca. 21 ka (Mackenzie and Moss (2014), indicating that the site contains the ACR.

By selecting sites that display strong anti-phased relationships between hydroclimate and changes in Southern Westerly flow, this thesis is able to minimise any ambiguity in attributing *past* changes in hydroclimate at these sites to changes in westerly flow because it relies on a well-described physical processes that is fixed through time: (1) the orographic effect of the central mountain range over westerly derived precipitation and (2) the modulation of easterly moisture incursions by westerly wind strength. By explicitly targeting two sites, this study addresses the limitations
inherent in single-site studies. Further, the study design (multiple sites and multiple proxies) addresses issues of non-stationarity of the main driver of change at the sites through time (i.e. the possibility that different drivers of change become important at various points in time) that can confound the interpretation of palaeoclimate proxy data (Gallant et al., 2013).

3.3 SEDIMENT RETRIEVAL

The characteristics of lake sediment sequences vary greatly based on (1) the origin of the sediment, (2) the processes that transport it, (3) its transit path through the water body and (4) the manner in which it is incorporated into the lake bed (Glew et al., 2001). Sediment sequences can also vary greatly within a lake. Sediment accumulation is influenced by a process known as sediment focussing, whereby the slope of a lake bed is the most important factor in determining where sediment accumulates without further disturbance (Blais & Kalff, 1995). This process thus determines that the sediment accumulation zone is formed in the deepest part of a lake basin, where sediment would have accumulated systemically through time, with younger sediment overlaying older sediment (Blais & Kalff, 1995). To reconstruct millennial-scale periods of environmental change such as the ACR, it is critical to retrieve a continuous high-resolution record and thus, it is important to recover core samples from the sediment accumulation zone (Glew et al., 2001).

3.3.1 LAKE ROLLESTON

Coring of Lake Rolleston was undertaken in 2015 by members of the University of Melbourne Palaeoecology Laboratory, prior to this student’s enrolment. The sediment accumulation zone of Lake Rolleston was determined by locating the deepest part of the lake through bathymetric survey using a hand-held depth sounder. A core sample of the sediment was taken using a Nesje
coring system attached to a tripod on a floating platform (Figure 3-2). The Nesje coring system (Nesje, 1992) is a cable-operated piston coring device designed for retrieval of long cores in deep lakes (Figure 3-3). Piston corers such as Livingstone (Livingstone, 1955) and Nesje corers are advantageous because the piston creates a vacuum seal inside the chamber which counters the frictional forces that are a common cause of sediment draw-down in other coring systems, such as open barrel type systems (Glew et al., 2001).

![Figure 3-2 | Coring platform on Lake Rolleston with the Nesje coring system attached to a tripod and winch. Photo: Michela Mariani 2015.](image)

**3.3.1.1 Methodology**

The operation of the Nesje corer involved (1) attaching an aluminium chamber to the core head and lowering the corer 20-50 cm into the lake bed using the winch and tripod, (2) fixing the piston in place via a cable attached to the platform, (3) hammering the core head through the lake bed, pushing the aluminium chamber around the piston and creating a vacuum seal to collect the sediment (Figure 3-3), and (4) winching the full chamber and core head back up to the platform once bedrock was reached.
3.3.1.2 Justification

The Nesje system was selected over the Livingstone as the preferred piston-type coring system because its cable and percussion-hammer method overcome the depth and mechanical strength limitations of the driving rod method used in the Livingstone. The limitations of the Nesje, namely its weight (~400 kg) and the compaction of surface sediments due to percussion hammering, where not restrictive in this case because Lake Rolleston was accessible by driving and the temporal focus of this study did not require in-tact surface sediments.

![Diagram of the Nesje piston coring device](image)

**Figure 3-3** Schematic of the Nesje piston coring device (Nesje, 1992) The method used in this thesis utilised a tripod and winch to raise the percussion hammer (*weight*), rather than a jack as show here. An aluminium sampling tube was also used in place of the PVC tube shown here.

3.3.2 HAZARDS LAGOON

The sediment accumulation zone of Hazards Lagoon was determined by locating the thickest sequence of sediment by physical probing. A core sample of the sediment was taken in 2017 using a Livingstone coring system from on top of a semi-submerged wooden platform (Figure 3-4). The Livingstone coring system (Livingstone, 1955) relies on the same piston-coring
principles as the Nesje system but uses driving rods to drive the core head and chamber into the lake bed, rather than a percussion hammer and winch. This was adequate to access the sediment at Hazards Lagoon because of the shallow water depth. This also makes the system much more light-weight and transportable, with the only true disadvantage being the requirement of repeated drives pushed by hand rather than the single percussion hammer driven sample of the Nesje.

3.3.2.1 Methodology

The operation of the Livingstone corer involved (1) driving the core head and chamber into the sediment with the piston secured independently by cable and clamp, (2) extruding the sample from the chamber, (3) driving the core head and chamber to the basal depth of the previous sample with the piston locked to the bottom of the core chamber, (4) unlocking the piston and driving the core chamber around the piston to create the vacuum seal and recover the next section, (5) repeating steps 2 and 3 until bedrock is reached or frictional forces prevent further drives.

3.3.2.2 Justification

The use of simpler coring systems such a Russian D-section are common in swamps and wetlands such as Hazards Lagoon and such a method was used in a the previous of this site by Mackenzie and Moss (2014). However, the Livingstone system was selected for this site based on (1) its capacity to recover a greater sediment volume with each drive, due to a larger chamber, and (2) its capacity to recover sediment from deeper in the sediment profile than the Russian D-section, because the penetration of these corers is limited when multiple drive rods are required.
3.3.3 SEDIMENT HANDLING AND SUB-SAMPLING

Cores were transported to the University of Melbourne to be sub-sampled for analysis. Cores were split in half longitudinally using a GEOTEK core splitter prior to sub-sampling and half archived under refrigeration. The Lake Rolleston core (TAS1504 N1) was sub-sampled at 0.5 cm intervals and Hazards Lagoon (TAS1704) at 1 cm intervals. Sample intervals were selected to maximise the sample resolution while maintaining enough sediment volume in each sub-sample for multi-proxy analysis and archiving. Sub-samples were stored in sealed sterile sample bags until required for analysis.
Figure 3-5 | Selected stages of the sub-sampling process: (a) Hazards Lagoon core TAS1704 prior to sub-sampling, (b & c) sub-sampling at 1 cm increments and (d) storage in sealed sterile bags.

3.4 CHRONOLOGY

For any record of past environmental change to be useful, it must be supported by a robust chronology. Understanding the timing and duration of environmental change can be just as informative as identifying the change itself (Björck & Wohlfarth, 2002). Indeed, robust age controls and sophisticated age-depth modelling are critical for this project as they will allow the timing and duration of environmental change at each site to be compared with other regional and global records, which will facilitate inference on the drivers of the observed change (e.g. climate).

3.4.1 RADIOCARBON DATING

Radiocarbon dating was the chosen dating method for both Lake Rolleston and Hazards Lagoon. Radiocarbon dating relies on the principle that all living organisms incorporate radioactive carbon isotope $^{14}$C from $^{14}$CO$_2$ into their tissue in equilibrium with the atmosphere until their death, at which time these isotopes begin to decay within the tissue at a known rate (Libby, 1955; Björck & Wohlfarth, 2002). Because we know this rate, a half-life of 5730±40 years
(Godwin, 1962), it is possible to measure the amount of $^{14}$C decay that has occurred by comparing its concentration to the known stable isotope $^{12}$C. From this, we can calculate an age of death for the material up to a limit of $\sim$60,000 years (Björck & Wohlfarth, 2002). As most lake sediments contain ample organic material, radiocarbon dating is the most widely used technique in palaeolimnology (Björck & Wohlfarth, 2002; Lowe et al., 2015; Cohen, 2003). While Tasmanian lake sediments contain few organic macrofossils, a preferred material for radiocarbon dating of lake sediments, the use of bulk organic sediment samples for radiocarbon dating has been used successfully by many studies in Tasmania (e.g. Fletcher et al. (2018a); Mariani et al. (2018); Beck et al. (2017); Stahle et al. (2016); Rees and Cwynar (2010)).

### 3.4.1.1 Methodology

Radiocarbon analysis was performed on six bulk organic sediment samples at the Australian Nuclear Science and Technology Organisation (ANSTO) for Lake Rolleston and on six bulk organic sediment samples at Direct AMS USA for Hazards Lagoon. All samples were analysed using Accelerated Mass Spectrometry (AMS) with the following methodology:

1. Removal of rootlets and other visible contaminants.

2. *Acid-Alkali-Acid* chemical pre-treatment to remove remaining contaminated carbon (Gupta & Polach, 1985; Hatté et al., 2001).

3. Combustion and graphitisation of sample to produce solid, pure carbon. (Björck & Wohlfarth, 2002).

4. Measurement of the amount of $^{12}$C, $^{13}$C and $^{14}$C within the sample by AMS method (Björck & Wohlfarth, 2002).
3.4.1.2 Calibration

The age returned from radiocarbon analysis, the *radiocarbon age*, is impacted by changes in the atmospheric production rate of $^{14}$C through time, in response to cosmic ray fluctuation (Björck & Wohlfarth, 2002; Lowe *et al*., 2015). To correct for the discrepancy between a true age and the radiocarbon age, ages are calibrated to curves that have been constructed using dendrochronology (tree-ring analysis) on radiocarbon dated wood, thus, allowing a correction between radiocarbon years and calendar years. The latest calibration curve for the Southern Hemisphere is SHCal13 (Hogg *et al*., 2013) and was used calibrate radiocarbon ages in this study.

3.4.2 ADVANTAGES AND LIMITATIONS

Radiocarbon dating of lake sediments using the AMS method is advantageous because (1) it can be conducted on small amounts of organic material (~0.1 grams) (Direct AMS, 2018), (2) it can be utilised on sediments ~500 – 60,000 years old (Chappell, 1978; Lowe *et al*., 2015), (3) sample preparation is simple, (4) accuracy and methods continue to develop (Björck & Wohlfarth, 2002) and (5) updated calibration curves can be applied to old dates (Hogg *et al*., 2013).

However, radiocarbon dating does have notable limitations: (1) dates can be influenced by contamination from younger or older carbon if pre-treatment fails to remove all contaminants (Gupta & Polach, 1985; Hatté *et al*., 2001), (2) reservoir effects (lower within-lake $^{14}$C/$^{12}$C than the atmosphere) can influence error (Björck & Wohlfarth, 2002), and (3) radiocarbon uncertainties are higher than some other dating methods (e.g. Uranium series, luminescence) and error approximation methods can differ between laboratories (Björck & Wohlfarth, 2002; Lowe *et al*., 2015).
3.4.3 AGE-DEPTH MODELLING

Because dating samples is expensive and time-consuming, dating of every sample in a sediment sequence is not feasible. Therefore, to assign ages for all sample depths it is necessary to create an age-depth model which interpolates ages to all samples based on the known ages and statistical methods. This thesis uses Bayesian age-depth modelling in the Bacon V. 2.2 software package for R (Blaauw & Christen, 2011; R Core Development Team, 2017).

Bacon age-depth modelling uses Bayesian statistics and a priori information (such as accumulation rates and rejection of age reversals) to inform the error ranges in the model (Blaauw & Christen, 2013; Blaauw & Heegaard, 2012). The model runs thousands of iterations of sampling probability to estimate accumulation rates through the core in years/cm (depositional time) and uses student t-test distributions to determine outliers (Blaauw & Christen, 2011, 2013). This then creates age and error estimates for each depth interval between radiocarbon ages (Blaauw & Christen, 2011, 2013).

While age-depth modelling as a broader method can be problematic due to overfitting, underestimating of age uncertainties and some models producing age reversals (Blaauw & Heegaard, 2012; Björck & Wohlfarth, 2002), it remains the preeminent technique for developing chronologies in natural archives and interpolating ages for non-dated sections.

3.4.4 INTERPRETING ENVIRONMENTAL CHANGE FROM SEDIMENT ACCUMULATION RATES

The calculation of depositional time as part of the Bayesian age-depth can reveal changes to the rate of sediment accumulation throughout the record. Inferences of changing environmental conditions can be drawn from these changes because the rate of sediment accumulation in lakes is often determined by the rate of erosion in the catchment, especially in small-moderately sized
lakes with steep basins and catchment slopes, like Lake Rolleston, where it is well documented that sediment influx is determined by the amount of runoff and precipitation (Eden & Page, 1998; Page et al., 1994; Rees et al., 2015). However, the calculation of depositional time is influenced by the intensity and location of dating horizons, thus, changes in depositional time may reflect dating intensity as well as actual changes in sediment accumulation. Consequently, depositional time will be used as supporting evidence for interpretations of more robust proxy records, such as \( \mu \)XRF geochemistry.

### 3.5 \( \mu \) X-RAY FLUORESCENCE SCANNING

Micro X-ray fluorescence (\( \mu \)XRF) scanning of sediment cores is a non-destructive method of geochemical analysis. \( \mu \)XRF scanning of sediment cores provide semi-quantitative measurements of down-core elemental variations, typically for elements with atomic numbers between 13(Aluminium) – 92 (Uranium) (Croudace & Rothwell, 2015). \( \mu \)XRF scanners recognise different elements by stimulating the surface of the sediment with an x-ray band delivery of either irradiated primary protons or accelerated electrons, which then generates secondary x-rays whose energies are characteristic of the elements present on the surface (Boyle, 2002; Croudace & Rothwell, 2015). From these measurements, data are provided as elemental counts per second (Croudace & Rothwell, 2015; Croudace et al., 2006).

#### 3.5.1 METHODOLOGY

\( \mu \)XRF scanning of cores TAS1504 N1 (Lake Rolleston) and TAS1704 (Hazards Lagoon) were conducted using an ITRAX \( \mu \)XRF core scanner (Figure 3-6; Croudace et al. (2006)) at the Australian Nuclear Science and Technology Organisation (ANSTO). Cores were scanned at a resolution of 200 µm for 29 elements plus scattering coherence and incoherence, which provide estimates of water content (Croudace & Rothwell, 2015; Croudace et al., 2006). Because lake
sediments have high organic and water content and their chemical composition can vary substantially down core, it is recommended that counts be normalised to an internal standard (Croudace & Rothwell, 2015; Croudace et al., 2006; Boyle, 2002). The most common method is to normalise counts to total thousand count per spectrum (kcps) (Croudace & Rothwell, 2015) and this method has been adopted in this thesis.

Figure 3-6 | ITRAX µXRF core scanner (Croudace et al., 2006).

3.5.2 ADVANTAGES AND LIMITATIONS

Although µXRF scanning analysis is not fully quantitative and has poorer detection limits than solution-based geochemical analysis (Boyle, 2002), it is a preferable method for many palaeolimnological studies because (1) most elements of interests occur in concentrations well above µXRF detection limits (Boyle, 2002), (2) analysis is non-destructive, (3) analysis can be very high resolution (Croudace & Rothwell, 2015) and (4) relative element trends can provide sufficient information to interpret environmental change through time, particularly with the support of other proxies (e.g. (Moreno et al., 2015; Haberzettl et al., 2007; Mariani et al., 2018; Kylander et al., 2011; Augustinus et al., 2011; Saunders et al., 2018)).
3.5.3 INTERPRETING ENVIRONMENTAL CHANGE FROM µXRF DATA

Geochemical analysis of lake sediments can provide powerful proxy evidence of changes in catchment processes, such as weathering and erosion, and within-lake processes, such as lake levels and evaporative conditions (Boyle, 2002). Due to the complexity of responses lake sediments have to changing catchment and within-lake processes (Schnurrenberger et al., 2003), interpretations of environmental change using sediment geochemistry is most effective when multiple geochemical properties are considered and when interpretations are supported by biological proxy data, such as pollen and charcoal (Mackereth, 1966; Engstrom & Wright Jr, 1984; Boyle, 2002; Davies et al., 2015). Several studies have successfully applied this approach to lake sediments to reconstruct environmental change in Tasmania (Beck et al., 2017; Mariani et al., 2018; Rees et al., 2015; Fletcher et al., 2014b) and such an approach has been adopted in this thesis.

Provided below is an outline of the proxy interpretations of the µXRF data that will be used in Chapter 5 of this thesis.

- Changes to the elemental profiles of organic and terrigenous elements will provide indications of changes in sediment provenance and rates of erosion (to be supported by changes in depositional time) (Boyle, 2002).

- Changes to ratios of elements sensitive to chemical weathering will provide indications of changing weathering regimes (Davies et al., 2015; Clift et al., 2014).

- Changes to profiles of authigenic (within-lake) carbonate-indicating elements will provide indications of changing evaporative conditions and lake levels (Davies et al., 2015; Cohen, 2003; Kylander et al., 2011)
• Changes to the profiles of organic-indicating elements (Bromine; Br) and terrigenous-indicating elements (e.g. Titanium; Ti) will provide indications of changes to lake productivity and light conditions (Mariani et al., 2018). Br forms strong covalent bonds with organic molecules (Gilfedder et al., 2011) and has been found to covary with sediment total organic content in a number of studies (Kalugin et al., 2013; Kalugin et al., 2007; Phedorin et al., 2000; Gilfedder et al., 2011; Zolitschka & Negendank, 1996). Ti is a geochemically stable terrigenous element (Boës et al., 2011).

3.6 PALYNOLOGY

Palynology is the analysis of fossil pollen grains, spores and other microfossils (non-pollen palynomorphs) entrained in sediment records. It is widely used in palaeoecology and palaeoclimatology to determine the response of plants or aquatic biota to past environmental change (Van Geel, 2002; Faegri et al., 1989; Bennett & Willis, 2002) and relies on the basic principle that the relative composition of pollen grains in the sediment is somewhat proportional to the relative composition of vegetation in the landscape (Erdtman, 1943). However, the relationship between the assemblages of pollen that are preserved in sediments and the actual assemblage of vegetation in the landscape is much more complex (Faegri et al., 1989; Bennett & Willis, 2002) and measures to address this limitation when interpreting the pollen record will be discussed in Section 3.6.2 and 3.6.3. Plants and aquatic algae produce pollen and spores as part of their reproductive cycles and the outer layer of these grains is highly resistant to degradation in anoxic conditions, such as those found in lake depositional environments (Bennett & Willis, 2002; Faegri et al., 1989). Pollen grains and spores from different plant and algae taxa are diverse in their shape, size and texture and this allows the plant or algae of origin to be identified once the grains and spores have been isolated from the sediment sample (Faegri et al., 1989; Bennett & Willis, 2002; Van Geel, 2002).
3.6.1 METHODOLOGY

Processing for pollen and spore analysis followed standard methods from Faegri et al. (1989). Sample resolution for Lake Rolleston was every 3 cm (average of 193 years) based on having an even spread through the core. Sample resolution for Hazards Lagoon varied through the core because at the time of processing an age-depth model had been developed and thus, the location of the ACR in the core was known and could be targeted for higher resolution. Samples were taken every 1 cm (average of 125 years) between ca. 16 – 13.1 ka and every 2-3 cm either side of this age range. All samples were processed at the University of Melbourne using 0.5 cc of sediment. Pollen grains and spores were isolated from the sediment and prepared for microscopic analysis using the following procedure (Faegri et al., 1989):

1. **Hot Potassium Hydroxide (KOH) treatment**
   
   Samples are mixed with 5 ml 10% KOH and immersed in 90ºC water bath for 20 minutes to digest any humic material.

2. **Sieving**

   Samples are sieved with a 100 μm mesh to remove coarse material.

3. **Spike**

   A known number of exotic pollen grains (*Lycopodium spp.*) is added to each sample and dissolved in 5 ml 10% Hydrochloric acid (HCl) to allow calculation of pollen, spore and charcoal accumulation rates.
4. **Hot Hydrofluoric acid (HF) treatment**

   Samples are mixed with 5 ml 48% HF and immersed in a 90°C water bath for 20 minutes to dissolve siliceous matter.

5. **Acetolysis**

   Samples are dehydrated with glacial acetic acid (CH₃COOH) before being treated with an acetolysis mixture of 9-parts acetic anhydrite ((CH₃CO)₂O) and 1-part sulfuric acid (H₂SO₄) for three minutes. This process removes any organic material not digested by KOH treatment and darkens pollen grains to aid identification.

6. **Microscope slide mounting**

   Processed samples are then cleaned with ethanol and mixed with ~0.5 ml of glycerol and left overnight so that the ethanol can evaporate. Pollen slides are then prepared by mounting the glycerol-sample mix under a glass cover slip and sealing with nail polish.

Most identification and counting were completed at 400x magnification using a ZEISS AX10 light microscope with bright field objective. Each sample was counted until 300 terrestrial grains were identified, which is typical of most palaeoecological studies. Identification was determined using the personal reference collection of Mike Macphail, the University of Melbourne Palaeoecology collection and the Newcastle Pollen collection (Hopf *et al.*, 2002).

### 3.6.2 ADVANTAGES AND LIMITATIONS

Pollen grains and spores entrained in lake sediments are an extremely useful proxy for environmental reconstructions because (1) pollen and spores are highly abundant in the environment and are well preserved in many lakes and water bodies (Faegri *et al.*, 1989; Bennett & Willis, 2002), and (2) many different plant taxa can be identified from the morphology of their pollen which, when combined with knowledge of the plant’s ecology, can provide valuable insights into the terrestrial biological responses to environmental change in a lake catchment (Bennett & Willis, 2002; Lowe *et al.*, 2015). There are however several limitations to palynological analysis: (1) not all taxa can be identified down to the same taxonomic level,
which can be problematic when ecologies within a plant group vary greatly. For example, *Eucalyptus spp.* are only identifiable to a genus level and the ecology between the ~700 species can differ distinctly (Jacobs, 1955). (2) Pollen assemblages in sediments are not equivalent to catchment vegetation assemblages (Faegri *et al.*, 1989; Bennett & Willis, 2002; Fletcher & Thomas, 2007; Macphail, 1979; Kershaw, 1979; Kershaw *et al.*, 1994). This is due to effect that different pollen production rates, dispersal vectors (i.e. wind, water, animals) and grain morphology between taxa have on the deposition of pollen into lakes and water bodies (Faegri *et al.*, 1989; Bennett & Willis, 2002). To address this limitation, modern pollen-vegetation relationships and the over- or under-representation of different taxa in the modern pollen rain will be used to inform interpretations of fossil pollen spectra at Lake Rolleston (Fletcher & Thomas, 2007) and Hazards Lagoon (D'Costa & Kershaw, 1997; Kershaw *et al.*, 1994).

### 3.6.3 **INTERPRETING ENVIRONMENTAL CHANGE FROM PALYNOLOGY**

The utility of fossil pollen assemblages to reconstruct past changes to terrestrial vegetation assemblages has been demonstrated by a number of studies in western Tasmania (Colhoun *et al.*, 1999; Fletcher & Thomas, 2007; Fletcher, 2009; Stahle *et al.*, 2016; Hopf *et al.*, 2000; Mariani *et al.*, 2018; Beck *et al.*, 2017) and eastern Tasmania (Macphail & Jackson, 1978; Thomas & Kirkpatrick, 1996; Jones *et al.*, 2017; Mackenzie & Moss, 2014). This thesis will infer both terrestrial and aquatic environmental change by interpreting changes in the abundance and accumulation rates of fossil pollen and spores as a response to environment change. These interpretations will be based on the known ecologies of plant and aquatic algae taxa, the level of representation of each taxa in the pollen rain (Fletcher & Thomas, 2007; Macphail, 1979; Kershaw *et al.*, 1994) and the modern pollen-vegetation climate relationships observed in western Tasmania (Fletcher & Thomas, 2007) and southeast Australia (D'Costa & Kershaw, 1997; Kershaw *et al.*, 1994).
3.7 CHARCOAL

Analysis of charcoal entrained in lake sediments can be used to interpret past fire activity (Whitlock & Larsen, 2002). Fire in a landscape is determined by fuel, climate and ignition sources (Murphy et al., 2013; McWethy et al., 2013; Bradstock, 2010). Indeed, climate can regulate fire activity in the landscape directly by drying fuels and increasing the frequency of favourable fire weather (Mariani & Fletcher, 2016; Whitlock et al., 2007) and/or indirectly by changing the composition of flammable and less-flammable vegetation in the landscape (Pausas & Paula, 2012). Sedimentary charcoal is comprised of the partly combusted plant material left in the landscape following fire that has been transported by air or water into the lake. Primary charcoal is charcoal deposited immediately following a fire event (Whitlock & Larsen, 2002; Gardner & Whitlock, 2001) and secondary charcoal is charcoal deposited in the lake from a previous fire event, often after residing the landscape for an extended period of time (Blong & Gillespie, 1978; Ohlson & Tryterud, 2000). The particle sizes of sedimentary charcoal have been used as an indicator of distance travelled by the particle, based on the premise that smaller particles can be transported aloft further from the fire (Clark & Patterson, 1997; Whitlock & Larsen, 2002; Scott, 2010). However, this interpretation may not apply in all settings as all particle sizes float well in water (Nichols et al., 2000) and can transported long distances via river networks (Scott, 2010), and particle size can also be a reflection of fuel type (Fletcher et al., 2014b).

3.7.1 METHODOLOGY

The sediments from Lake Rolleston and Hazards Lagoon were analysed for both microscopic (<125 µm) and macroscopic charcoal (>125 µm). Microscopic charcoal was processed and counted as part of pollen analysis and macroscopic charcoal was processed and analysed according to the methods of Whitlock and Larsen (2002). Samples of 1.25 cc of sediment were
taken at 0.5 cm increments for Lake Rolleston (average resolution 30 years per sample) and 1 cm increments for Hazards Lagoon (average resolution 105 years per sample). Processing followed these steps:

1. Full digestion of 1.25 cc of sediment in either sodium hypochlorite (NaOCl; *bleach*) or hydrogen peroxide (H₂O₂) if organic content is high.

2. Digested samples are sieved using 250 µm and 125 µm meshes to separate smaller and larger fractions.

Counting was conducted using an Olympus SZ51 dissecting microscope with charcoal particles suspended in water inside a petri dish and 250 µm and 125 µm counts summed to check for consistency between size fractions (Figure 3-8b).

![Figure 3-8](image.jpg)

**Figure 3-8** Images of (a) macroscopic charcoal sample from Hazards Lagoon containing 3852 individual pieces, and (b) macroscopic charcoal sample under 3x magnification.

### 3.7.2 ADVANTAGES AND LIMITATIONS

There are several limitations for the use of charcoal to reconstruct past fire activity: (1) there is no practical way to differentiate between primary and secondary charcoal (Whitlock & Larsen, 2002), (2) the taphonomy (nature of the journey from source to deposit) of sedimentary charcoal
particles may influence results (e.g. deposition of large secondary particles may provide false indication of fire) (Whitlock & Larsen, 2002), (3) the reason for different sized practices is open to interpretation (e.g. Clark and Patterson (1997), Whitlock and Larsen (2002); Scott (2010); Fletcher et al. (2014a)) and (4) only fire occurrence, not intensity or magnitude can be inferred for sedimentary charcoal (Higuera et al., 2007). Despite these caveats, sedimentary charcoal analysis provides useful information on past changes in catchment fire activity that can used in conjunction with pollen analysis to illuminate past vegetation-fire-climate dynamics.

3.7.3 INTERPRETING ENVIRONMENTAL CHANGE FROM CHARCOAL

In western Tasmania, sedimentary charcoal records have been used to infer past changes in hydroclimate (Mariani & Fletcher, 2016; Fletcher & Moreno, 2011; Fletcher et al., 2018a) and vegetation dynamics (Fletcher et al., 2014b; Fletcher et al., 2014a). Similarly, sedimentary charcoal has also been used to infer changes in hydroclimate in eastern Tasmania (Mackenzie & Moss, 2014; Jones et al., 2017). However, these eastern Tasmanian records only consider microscopic, not macroscopic charcoal and, thus, their inferences rely on much less robust datasets. This thesis will examine the results of both microscopic and macroscopic sedimentary charcoal in conjunction with the results of pollen analysis to reconstruct vegetation-fire dynamics through the ACR and infer the drivers of environmental change.

3.8 STATISTICAL ANALYSIS

3.8.1 ACCUMULATION RATE CALCULATIONS

Constructing an age-depth model allows for the calculation of sediment accumulation rates. From this rate, proxy-data can be converted from counts per sample to accumulation rates, which helps to account for the influence of variable sedimentation rates on proxy-data trends.
3.8.1.1 Depositional time

Sedimentation rates are presented as depositional time in this thesis and were calculated as years per cm using the results of the age-depth modelling produced with Bacon V. 2.2 in R (Blaauw & Christen, 2013).

3.8.1.2 Pollen, spores and microscopic charcoal

The addition of a known quantity of exotic Lycopodium spp. spores into each pollen sample allows accumulation rates for pollen, spores and microscopic charcoal to be calculated using the formula below:

\[
\text{Accumulation rate (objects cm}^{-2}\text{ year}^{-1}) = \frac{\text{objects counted}}{\text{Lycopodium spores counted}} \times \frac{\text{Lycopodium spores per tablet}}{\text{sediment volume (cm}^3\text{)}} / \frac{\text{years per sample}}{\text{years per sample}}
\]

3.8.1.3 Macroscopic charcoal

Macroscopic charcoal accumulation rates (CHAR) were calculated using the formula below:

\[
\text{Charcoal accumulation rate (pieces cm}^{-2}\text{ year}^{-1}) = \frac{\text{pieces counted}}{\text{sediment volume (cm}^3\text{)}} / \frac{\text{years per sample}}{\text{years per sample}}
\]

3.8.2 CLUSTER ANALYSIS

Stratigraphically constrained cluster analyses were performed on the terrestrial pollen data from Lake Rolleston and Hazards Lagoon using the CONISS (constrained sum of squares) method in Tilia pollen diagramming software (Grimm, 1991; Grimm, 1987). The CONISS cluster analysis groups similar data using Euclidian distance dissimilarity metrics while maintaining the
stratigraphy of the dataset (Grimm, 1987; Birks et al., 2012). This analysis permits the identification of significant shifts in pollen assemblages through time (with significance of zones determined using the broken-stick model of variance) and these shifts form the basis of the pollen zones used to described changes in the terrestrial pollen data through time (Bennett, 1996; Birks et al., 2012).

3.8.3 ORDINATION ANALYSIS

Ordination analysis was performed on the terrestrial pollen and μXRF elemental data from Lake Rolleston and Hazards Lagoon using PC-ORD statistical software (McCune & Mefford, 1999). Ordination analyses are used to reveal relationships between multivariate data and summarise these relationships in two-dimensional space so that the main compositional trends in the dataset are highlighted (Birks et al., 2012). Many ordination techniques are available for multivariate data and Principal Component Analysis (PCA) and Detrended Correspondence Analysis (DCA) were selected for this thesis.

3.8.3.1 Principal Component Analysis (PCA)

PCA uses multiple linear regression to interpret trends in the dataset in multidimensional space (McCune & Mefford, 1999; Birks et al., 2012). PCA provides axis scores by using Euclidian distances between data points and measures the variance explained by each axis using eigenvalues (Birks et al., 2012; McCune & Mefford, 1999). Because PCA assumes a normal distribution and the fact that μXRF data are typically skewed, the data were relativised to the standard deviate prior to analysis. PCA was selected as the ordination analysis for the μXRF data at Lake Rolleston and Hazards Lagoon and the terrestrial pollen data at Hazards Lagoon based on the principle that PCA is more appropriate for datasets with short axis gradients (<2.5 standard deviations) (Birks et al., 2012; McCune & Mefford, 1999). Lake Rolleston and Hazards Lagoon...
lagoon \( \mu XRF \) elements with axis correlations >0.5 \( r^2 \) and Hazards Lagoon terrestrial pollen taxa with axis correlations >0.4 \( r^2 \) were plotted on ordination biplots.

### 3.8.3.2 Detrended Correspondence Analysis (DCA)

DCA uses chi-squared distances to interpret trends in the dataset and assumes a unimodal distribution, rather than a normal distribution like PCA (McCune & Mefford, 1999; Birks et al., 2012). This makes it more appropriate for datasets with greater variance (axis gradients >2.5 standard deviations), which are common amongst ecological data (McCune & Mefford, 1999; Birks et al., 2012). Indeed, the Lake Rolleston terrestrial pollen dataset had long axis gradients, owing to the large variability within the dataset. The data were square root transformed to induce normality and rare taxa down-weighted prior to analysis to mitigate the influence of outliers. Pollen taxa with axis correlations >0.3 \( r^2 \) were plotted on an ordination biplot.
CHAPTER 4: RESULTS

4.1 LAKE ROLLESTON

![Figure 4-1 | Lake Rolleston, looking southeast. Photo: Michael Fletcher](image)

4.1.1 SITE DESCRIPTION

Lake Rolleston (41°55'17"S, 145°37'29"E) is a glacial lake located on the northern flank of the Tyndall Ranges in western Tasmania. The lake lies within the superhumid zone in an area that has a strong positive relationship between enhanced Southern Westerly flow and rainfall (Figure 2-9). The lake sits at an elevation of 560 m a.s.l, receives 3187 mm of rainfall per year and has a mean annual temperature of 10.2 °C (Figure 2-8). Lake Rolleston has a maximum depth of 42 m and is divided into two main basins (B1 and B2) by a subaqueous mound of rocky material located in the centre of the lake (Figure 4-2). The lake is fed by outflows from Lake Huntley and Saddle Lake to the south and south-west as well as runoff from the catchment slopes (Figure 4-2a). The lake has a single outflow via the Anthony River which flows north into the artificial lake, Lake Plimsoll (Figure 4-2a).
Figure 4-2 | Location and site characteristics of Lake Rolleston, red star shows coring location. (A) Aerial photo showing catchment drainage (DPIPWE, 2018), (B) Oblique Google Earth image (Google Earth, 2018), (C) Vegetation groups surrounding Lake Rolleston as defined by TasVeg 3.0 (DPIPWE, 2018; Kitchener & Harris, 2013), and (D) Geologic map (1:25,000) of the catchment (Calver, 2016). Note change in orientation in panel B.
The vegetation of the catchment is split into two distinct types; rainforest communities dominate the catchment of the southern basin (B2), while non-forest communities (principally moorland and wet scrub) dominate the catchment of the northern basin (B1) (Figure 4-2c). The rainforest communities within the catchment of B2 are dominated by *Athrotaxis selaginoides* rainforest and *Nothofagus-Atherosperma* rainforest, with a fringe of *Leptospermum* and *Eucalyptus nitida* forest separating the rainforest from the non-forest communities (Kitchener & Harris, 2013; DPIPWE, 2018). The non-forest communities that surround B1 are dominated by *Gymnoschoenus sphaerocephalus* with *Leptospermum* and *Melaleuca* species present in a taller stratum in some areas (Figure 4-2c) (Kitchener & Harris, 2013; DPIPWE, 2018). The geology surrounding Lake Rolleston is composed of three main groups: (1) Quaternary glacial deposits, (2) Owen group Cambrian sandstones and other sedimentary conglomerates, and (3) Mt. Read group Cambrian volcanics (Figure 4-2d). The Mt. Read volcanic rocks present on the eastern side of the Lake Rolleston catchment have been the subject of mineral exploration for the high content of valuable metals, such as lead, zinc and silver (Turnbull & Base 2002; Seymour *et al.*, 2006).

### 4.1.2 SEDIMENT RECOVERY

Core TAS1504 N1 was recovered from the southern basin (B2) of Lake Rolleston in 2015 (Figure 4-2). Radiocarbon, µXRF geochemical, palynological and charcoal analysis were performed on the bottom 93 cm.

### 4.1.3 CORE & CHRONOLOGY

#### 4.1.3.1 Chronology

The results of radiocarbon analysis for TAS1504 N1 are presented in Table 1. Six radiocarbon ages were returned from six bulk sediment samples and ranged in stratigraphic order between an upper age of 9470 radiocarbon years before present (\(^{14}\text{C} \text{ yr BP}\)) and a basal age of 13,395 \(^{14}\text{C} \text{ yr BP}\).
BP. All ages were calibrated to calendar years before present (cal yr BP; BP=1950CE) using Southern Hemisphere calibration curve SHcal13 (Hogg et al., 2013). Bayesian age-depth modelling results of TAS1504 N1 were used to interpolate calendar ages to each sample depth and the model is presented in (Figure 4-4).

4.1.3.2 Sediment accumulation

The rate of sediment accumulation in core TAS1504 N1 was low for the period ca.15, 800 cal yr BP (hereon ca. 15.8 kyr) to 14.7 kyr (Figure 4-3). The sedimentation rate increases steadily from ca.14.7 ka before elevating rapidly at ca.14 ka and reaching peak levels at ca.13.6 ka, followed by a decline through to ca.13 ka where it returns to a low rate. The low rate persists until ca.12.2 ka when the rate elevates to moderately-high levels which are maintained for the remainder of the record.

Figure 4-3 | Sediment accumulation rate for Lake Rolleston core TAS1504 N1 presented as depositional time (years per cm of accumulation) on an inverted y-axis and optical image of the core retrieved from ITRAX core scanning.

Table 1 | Radiocarbon dating results for Lake Rolleston core TAS1504 N1 along with median calibrated ages calculated in Bayesian age-depth software Bacon V. 2.2 (Blaauw & Christen, 2011) using SHcal13 (Hogg et al., 2013).

<table>
<thead>
<tr>
<th>Lab code</th>
<th>Sample depth (cm)</th>
<th>Material dated</th>
<th>Fraction of modern pMC</th>
<th>Radiocarbon age 1σ error yr BP</th>
<th>Median age (cal yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OZW238</td>
<td>5.5</td>
<td>Bulk sediment</td>
<td>30.76</td>
<td>9470</td>
<td>10673.6</td>
</tr>
<tr>
<td>OZW239</td>
<td>29.5</td>
<td>Bulk sediment</td>
<td>28.42</td>
<td>10105</td>
<td>11700.2</td>
</tr>
<tr>
<td>OZW240</td>
<td>53.5</td>
<td>Bulk sediment</td>
<td>22.77</td>
<td>11890</td>
<td>13560.2</td>
</tr>
<tr>
<td>OZW241</td>
<td>65</td>
<td>Bulk sediment</td>
<td>23.20</td>
<td>11735</td>
<td>13818</td>
</tr>
<tr>
<td>OZW242</td>
<td>77</td>
<td>Bulk sediment</td>
<td>20.86</td>
<td>12590</td>
<td>14840.6</td>
</tr>
<tr>
<td>OZW243</td>
<td>89</td>
<td>Bulk sediment</td>
<td>18.87</td>
<td>13395</td>
<td>15991.6</td>
</tr>
</tbody>
</table>
4.1.4 GEOCHEMISTRY

A total of 1793 measurements of 29 elements and scattering incoherence and coherence were recorded by µXRF scanning of Lake Rolleston core TAS1504 N1. Profiles of selected elements and elemental ratios are presented in Figure 4-6. Principal Component Analysis (PCA) results of elemental and scattering incoherence/coherence (Inc/Coh; reflecting sediment water content) data are presented as an ordination biplot in Figure 4-5.
4.1.4.1 Principal Component Analysis

PCA of the geochemical data reveals that axis 1 explains 26% of the variance in the dataset and axis 2 explains 17% (Figure 4-5). Elements with a strong positive correlation ($r^2 >0.5$) with axis 1 are Cr, Rb, Fe, Co, Pb, Ar, Zn, Si, K, Ti and Ce, and elements with strong negative associations ($r^2 <0.5$) are Br and the Inc/Coh scattering ratio. PCA axis 1 scores (PCA 1) are presented alongside selected elemental profiles in Figure 4-6.

Figure 4-5 | PCA ordination biplot of Lake Rolleston core TAS1504 N1 μXRF geochemistry showing elements with axis correlations ($r^2$) >0.5. Grey diamonds represent samples. Red arrows represent the relationships between elements (and Incoherence/Coherence (Inc/Coh)) and the PCA axes; arrow size reflects the strength of the correlation and arrow direction the direction of the correlation. All data were adjusted to the standard deviate prior to analysis.
4.1.4.2 ca.16 – 14.7 kyr

The period ca.16 – 14.7 kyr shows a slight and gradual decline in the detrital elements Ti, K, Ar and Co as well as PCA 1. Pb and Fe decline more markedly through this period and Zn is more variable but records minimum values at ca.14.7 kyr. Br, an indicator of sediment organic content (Gilfedder et al., 2011), remains at low levels and Inc/Coh, also an indicator of organic content (Croudace & Rothwell, 2015), increases marginally. The ratios of Ca/Ti and S/Ti, indicators of authigenic carbonate minerals (Kylander et al., 2011), steadily increase and reach peak values at ca. 14.7 kyr. Fe remains high through this period but is also variable.

4.1.4.3 ca.14.7 – 13.5 kyr

The period between ca.14.7 – ca.13.5 kyr is marked by elevated values in PCA 1 and the detrital elements Ti, K, Ar, and Zn and two sharp peaks at ca. 14.7 and 13.6 ka. These peaks are concomitant with equally sharp declines in organic indicators Br and Inc/Coh. Ca/Ti and S/Ti also decline abruptly at ca. 14.7 ka and maintain minimum values through the period. The decline in Pb from the previous period is interrupted by an increase to almost peak values and Fe continues to decline.

4.1.4.4 ca.13.5 – 10.5 kyr

The period between ca.13.5 – 10.5 kyr is characterised by minimal values in detrital elements Ti, K, Co, Pb, Zn, and Ar as well as Fe, and PCA 1. Organic indicators Br and Inc/Coh increase steadily to peak values and Ca/Ti and S/Ti increase, reaching peak values at ca.10.5 kyr.
Figure 4-6 | µXRF geochemistry results for Lake Rolleston. Profiles of selected elements are presented as normalised values in counts/thousand counts per spectrum (c/kcps) with an 11-point weighted average in colour. PCA axis 1 analysis results are presented as axis scores (PCA 1). Ca/Ti and S/Ti are presented as ratios and indicators of authigenic carbonate precipitation (higher values = increased precipitation) (Kylander et al., 2011). Incoherence/Coherence (Inc/Coh) is presented as a ratio and an indicator of organic content (higher values= higher organic content) (Croudace & Rothwell, 2015).
4.1.5 PALYNOLOGY

A total of 32 samples were analysed for pollen, spores and microscopic charcoal. A total of 11,453 pollen grains and spores were identified and counted from a total of 70 different taxa; results are summarised as a pollen diagram in Figure 4-8 with pollen as percentages of the terrestrial sum and algae spores and charcoal as accumulation rates. CONISS analysis revealed three pollen zones within the terrestrial pollen record: Zone LR 1 - ca.16.4 – 15.6 kyr; Zone LR 2 - 15.6 – 17.8 kyr; and Zone LR 3 - 11.8 – 10.5 kyr (Figure 4-8). Detrended correspondence analysis (DCA) was completed on the terrestrial pollen dataset and ordination scores from axes 1 (DCA 1) and 2 (DCA 2) are plotted on the percentage pollen diagram in Figure 4-8.

4.1.5.1 Detrended Correspondence Analysis

Figure 4-7 presents correlations between pollen taxa and the two most significant ordination axes as an ordination biplot. DCA axis 1 explains 33% of the variance in the terrestrial pollen dataset and DCA axis 2 explains 12%. The following taxa had positive correlations with axis 1: Poaceae ($r^2 0.768$), *Tasmannia lanceolata* ($r^2 0.485$), *Nothofagus gunnii* ($r^2 0.449$), *Monotoca* spp. ($r^2 0.391$) and Cupressaceae ($r^2 0.303$); and those with negative correlations were *Bauera rubioides* ($r^2 0.583$), *N. cunninghamii* ($r^2 0.635$), *Microstrobos* ($r^2 0.637$) and *Leptospermum* spp. ($r^2 0.357$). Cupressaceae also displayed a weak positive correlation with axis 2 ($r^2 0.334$) and *Phyllocladus aspleniiifolius* displayed a strong negative correlation ($r^2 0.901$).

The ordination space in Figure 4-7 is organised by CONISS-determined pollen zones that correspond to variation in pollen assemblages through time. Zone LR 1 is associated with Cupressaceae, Poaceae, *Microstrobos spp.*, *N. gunnii* and *Tasmannia lanceolata* fossil pollen.
Zone LR 2 is strongly associated with *P. aspleniofolius*. Zone LR 3 is associated with *N. cunninghamii* and *Bauera rubioides*.

![Detrended Correspondence Analysis (DCA) ordination biplot for the Lake Rolleston (LR) terrestrial pollen dataset.](image)

**Figure 4-7** | Detrended Correspondence Analysis (DCA) ordination biplot for the Lake Rolleston (LR) terrestrial pollen dataset. Samples are grouped by colour to show CONISS-determined pollen zones (corresponding time periods found in legend). The proportion of variance in the terrestrial pollen dataset explained by each axis is shown as a percentage. The strength of the correlation between important taxa and the ordination axes are shown as $r^2$ values, with the corresponding axis and direction of correlation indicated by the direction of each arrow. Data were square root transformed and rare species down-weighted prior to analysis.

4.1.5.2 Zone LR 1- ca.16.4 – 15.6 kyr

This zone is characterised by high abundances of Cupressaceae (40-61% of the terrestrial pollen sum) and *Nothofagus gunnii* (5-21%) and peak proportions of grasses & herbs (33% declining to 15%). This proportion includes peak values of Poaceae (14%), Asteraceae (7%), Amaranthaceae (4%) and Apiaceae (1%). DCA 1 experiences a slight increase at the onset of this zone before declining in two steps and DCA 2 declines more steadily throughout. Microscopic charcoal record minimum values at ca.16.4 kyr, before increasing to moderate values by ca.15.6 kyr.
4.1.5.3 Zone LR 2- ca.15.6 – 11.8 kyr

This zone is characterised by increased abundance of *P. aspleniifolius* (18-44%) and *N. cunninghamii* (11-27%) at the expense of: (1) Cupressaceae and *N. gunnii*, that both decline to minimum values of 2% and 1%; and (2) grasses & herbs that decline steadily to values of ~14%, with key taxa Poaceae, Asteraceae and Amaranthaceae all declining. However, this trend in Poaceae and Asteraceae is temporarily reversed between ca.14.4 – 13 kyr with abundances of both taxa increasing from 3% to 7%. This is at the expense of *P. aspleniifolius*, which declines from 40% to 25%, before recovering after ca.13 kyr. DCA 1 continues a steady decline through this zone but does experiences a positive excursion at ca. 14.7 kyr and DCA 2 becomes more variable displaying several peaks and troughs but maintaining overall low values. Microscopic charcoal values remain steady through the first half of this zone before a two-step peak in values occurs at ca.13.7 and 13.5 ka, followed by a decline at ca.12.4 kyr.

4.1.5.4 Zone LR 3- ca.11.8 –10.5 kyr

This zone is characterised by a major decline in *P. aspleniifolius*, falling to just 3%. The abundance of *N. cunninghamii* pollen increases to peak values (50%), as does *Eucryphia* (3%). Several moorland-type taxa reach peak abundance including Cyperaceae, Ericaceae, *Monotoca spp.*, *Agastachys spp.* and *Leptospermum/Baeckea spp.*, as well as several sclerophyll forest-type taxa including *Allocasuarina spp.*, *Pomaderris apetala.*, and *Bauera rubioides*. DCA 1 shows some variability through this zone but maintains overall low values and DCA 2 increases markedly and reaches peak values. Microscopic charcoal values increase and become more variable through this zone.
Figure 4-1 | Percentage pollen diagram showing all taxa present in the Lake Rolleston record with >1% abundance. The y-axis is plotted according to age. Note changes in x-axes scales. Pollen zones are delineated by red dashed lines. Microscopic CHAR (charcoal accumulation rate) is presented as particles cm$^{-2}$ yr$^{-1}$. Percentage trees & shrubs is represented in green and percentage grasses & herbs in yellow. DCA axis scores estimate trends in the pollen data: axis 1 33% variance and axis 2 12% variance.
4.1.6 CHARCOAL

A total of 171 samples from Lake Rolleston core TAS1504 N1 were analysed for macroscopic charcoal. Charcoal accumulation rates (CHAR) are very low (>0.01 pieces cm$^{-2}$ year$^{-1}$) for the period ca.15.6 –14.9 kyr before increasing to moderately low levels (0.01-0.1 pieces cm$^{-2}$ year$^{-1}$) for the period ca.14.9 –13.9 kyr (Figure 4-9). CHAR then increase markedly from ca.13.9 ka with several peaks (>0.4 pieces cm$^{-2}$ year$^{-1}$) occurring and moderately high values (0.1-0.4 pieces cm$^{-2}$ year$^{-1}$) are maintained until ca.12.9 ka. Lower values then persist until ca.11.8 ka with two peaks punctuating this low trend at ca.12.2 ka. CHAR then increase after ca.11.8 ka and become more variable.

Figure 4-9 | Macroscopic charcoal results from Lake Rolleston core TAS1504 N1 B presented as Charcoal Accumulation Rates (CHAR) (pieces cm$^{-2}$ year$^{-1}$).
4.2 HAZARDS LAGOON

Figure 4-10 | Hazards Lagoon, looking southwest towards Mt. Freycinet and Mt. Graham. Photo: Michael Fletcher.

4.2.1 SITE DESCRIPTION

Hazards Lagoon (42°10'20"S, 148°17'21"E) is a freshwater wetland located within the Freycinet National Park, eastern Tasmania. The site has a strong negative relationship between enhanced westerly wind flow and rainfall (Figure 2-9). The wetland sits at 1.8 m a.s.l, receives 715 mm of rainfall per year and has a mean annual temperature of 12.8 °C (Figure 2-8). The wetland is primarily recharged by precipitation and runoff from Mt. Freycinet and Mt. Graham to the south and when full flows out through Hazards Beach into Promise Bay (Figure 4-11d) (Mackenzie & Moss, 2014).

The vegetation surrounding Hazards Lagoon is dominated by of a mix of *Eucalyptus* forest and woodland with large communities of *Allocasuarina verticillata* woodland and *Leptospermum glaucescens* heathland present on the slopes to the north and northeast. *Acacia longifolia* scrub fringes the dunes of Hazards Beach and coastal heathland is present behind the dunes of Wineglass Bay (Figure 4-11c) (Kitchener & Harris, 2013; DPIPWE, 2018).
Figure 4.11 | Location and site characteristics of Hazards Lagoon, red star shows coring location. (A) Aerial photo (DPIPWE, 2018), (B) Oblique Google Earth image (Google Earth, 2018), (C) Vegetation groups surrounding Hazards Lagoon as defined by TasVeg 3.0 (DPIPWE, 2018; Kitchener & Harris, 2013), and (D) Geologic map (1:250,000) of Freycinet Peninsula (Calver, 2016).
Hazards Lagoon sits on Quaternary sand, gravels and mud within the Wineglass Bay tombolo system, which is constrained by Devonian granitic outcrops that comprise The Hazards to the north and Mt. Freycinet and Mt. Graham to the south (Figure 4-11d) (Seymour et al., 2006; Calver, 2016; Everard, 2001).

4.2.2 SEDIMENT RECOVERY

Core TAS1704 was recovered from Hazards Lagoon in 2017, approximately 50 m from the north-western edge (Figure 4-11). Radiocarbon, μXRF geochemical, palynological and charcoal analysis were performed on the 78 to 139 cm section of the core.

4.2.3 CORE & CHRONOLOGY

4.2.3.1 Chronology

The results of radiocarbon analysis for TAS1704 are presented in Table 2. Six radiocarbon ages were returned from six bulk sediment samples and were in stratigraphic order, with an upper age of 7751 radiocarbon years before present ($^{14}$C yr BP) and a basal age of 16,765 $^{14}$C yr BP. All ages were calibrated to calendar years before present (cal yr BP; BP=1950CE) using Southern Hemisphere calibration curve SHcal13 (Hogg et al., 2013). Bayesian age-depth modelling results of TAS1704 were used to interpolate calendar ages to each sample depth and the model is presented in Figure 4-12.
Table 2 | Radiocarbon dating results for Hazards Lagoon core TAS1704 along with median calibrated ages calculated in Bayesian age-depth software Bacon V.2.2 (Blaauw & Christen, 2011) using SHcal13 (Hogg et al., 2013). All samples were run at Direct AMS (USA).

<table>
<thead>
<tr>
<th>Lab code</th>
<th>Sample depth (cm)</th>
<th>Material dated</th>
<th>Fraction of modern pMC</th>
<th>Radiocarbon age yr BP</th>
<th>Median age (cal yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-AMS 028345</td>
<td>70</td>
<td>Bulk sediment</td>
<td>38.100</td>
<td>7751</td>
<td>8477.7</td>
</tr>
<tr>
<td>D-AMS 028346</td>
<td>89</td>
<td>Bulk sediment</td>
<td>25.360</td>
<td>11021</td>
<td>12830.6</td>
</tr>
<tr>
<td>D-AMS 028347</td>
<td>103</td>
<td>Bulk sediment</td>
<td>20.820</td>
<td>12606</td>
<td>14889.3</td>
</tr>
<tr>
<td>D-AMS 028348</td>
<td>116</td>
<td>Bulk sediment</td>
<td>18.57</td>
<td>13525</td>
<td>16258.9</td>
</tr>
<tr>
<td>D-AMS 028349</td>
<td>136</td>
<td>Bulk sediment</td>
<td>16.34</td>
<td>14550</td>
<td>17732.8</td>
</tr>
<tr>
<td>D-AMS 028350</td>
<td>193</td>
<td>Bulk sediment</td>
<td>12.405</td>
<td>16765</td>
<td>20275.1</td>
</tr>
</tbody>
</table>

Figure 4-12 | Age-depth model for core TAS1704 from Hazards Lagoon. Main panel shows the age-depth model with six radiocarbon dates and their probability distributions marked in blue. The dotted red line marks the weighted mean age and the dashed grey lines mark the 95% confidence intervals and black shading marks 1000 iterations of the Bayesian statistic. The upper-left panel shows the iteration history. The upper-middle panel shows the prior and posterior of the accumulation rate in yr/cm. The upper-right panel shows the prior and posterior of the memory. The model was developed in Bacon V. 2.2 (Blaauw & Christen, 2011).
4.2.3.2 Sediment accumulation

The rate of sediment accumulation in core TAS1704 was high at the beginning of the record and decreases gradually until ca.12.3 cal yr BP (hereon ca. 15.8 ka). From ca 12.3 ka sediment accumulation decreases more markedly, followed by an increase at ca.11.6 ka and then a decrease to minimum levels at ca.10.6 ka (Figure 4-13).

![Depositional time](image)

**Figure 4-13** | Sediment accumulation rate for Hazards Lagoon core TAS1704 presented as depositional time (years per cm of accumulation) and optical image of the core retrieved from ITRAX core scanning.

4.2.4 GEOCHEMISTRY

A total of 850 measurements of 29 elements and scattering incoherence and coherence were recorded by µXRF scanning of the Hazards Lagoon core. Profiles of selected elements and elemental ratios are presented in Figure 4-15. Principal Component Analysis (PCA) results of elemental and scattering incoherence/coherence (Inc/Coh) data are presented as an ordination biplot in Figure 4-14.

4.2.4.1 Principal Component Analysis

PCA analysis of the µXRF geochemical data revealed that axis 1 explains 54% of the variance in the dataset and axis 2 explains 6% (Figure 4-14). Elements with a strong positive correlation ($r^2>0.5$) with axis 1 are Ni, Ca, Sr, Cl, S, and Br as well as the Inc/Coh ratio.
Elements with a strong negative correlation with axis 1 are Ti, K, Rb, Fe, Si, Co, Ar, and Pb. Mn had a strong negative correlation with axis 2 ($r^2 = 0.58$). PCA axis 1 scores (PCA 1) are presented alongside elemental profiles, elemental ratios and the Inc/Coh ratio in Figure 4-15.

4.2.4.2 ca.18 – 16.4 kyr

The period ca.18 –16.4 kyr is characterised by elevated values of detrital elements Ti, K, and Fe that begin to decline steadily from ca.16.6 ka (Figure 4-15). PCA 1 and Inc/Coh are anti-phased with the detrital elements throughout the record and record minimum values through this period before a slight increase at ca.16.6 ka. Organic indicator Br (Gilfedder et al., 2011) increases steadily through the period from minimum values at ca.18 ka to peak values at ca.16.7 ka, followed by a decline and recovery at ca.16.5 ka. Ca and Sr remain low and Mn records mostly moderate values. Ca/Ti and Sr/Ti display very low values.

4.2.4.3 ca.16.4 – 14.7 kyr

This period is marked by abrupt declines in the detrital elements Ti, K and Fe that are synchronous with equally abrupt increases in PCA 1 and Inc/Coh. Br remains high through this period with some variation and Ca and Sr increase gradually to moderate values. Mn declines to minimum values at ca. 16.5 ka before recovering to moderate values at ca.15 ka. Ca/Ti and Sr/Ti values increase moderately through this period.

4.2.4.4 ca.14.7 – 13 kyr

This period is characterised by elevated values of Ca/Ti and Sr/Ti, occurring with two peaks at ca.14.1 and 13.4 ka, before declining to moderately high values between ca.13.3 and 13 ka. Fe also experiences two positive excursions at ca.14.1 and 13.4 ka but otherwise remains low. Br is variable through this period and experiences two negative excursions at ca.14.7 ka and ca.14.5 – 13.9 kyr. Ca, Sr and Mn increase but are interrupted by negative excursions at
ca.13.4 ka, reaching peak values at ca.13.2 ka. Ti and K remain low through this period and PCA 1 and Inc/Coh remain high.

### 4.2.4.5 ca.13–10.5 kyr

Through this period Ca/Ti and Sr/Ti remain at moderately high values with slight elevations at ca.11.3 ka. Fe is variable with a notable increase at ca.11.3 ka, in-phase with Ca/Ti and Sr/Ti. Ca, Sr and Mn remain high except for at ca.11.3 ka when they experience slight negative excursion. Br is moderately high through and experiences a positive excursion ca.11.5 ka, while PCA 1 and Inc/Coh remain high and Ti and K low.

![PCA ordination biplot of Hazards Lagoon μXRF geochemistry showing elements with axis correlations ($r^2 > 0.5$). Grey diamonds represent samples. Red arrows represent the relationships between elements (and Incoherence/Cohereence (Inc/Coh)) and the PCA axes with arrow size reflecting the strength of the correlation and arrow direction indicating the direction of correlation. All data were adjusted to the standard deviate prior to analysis.](image)

**Figure 4-14** | PCA ordination biplot of Hazards Lagoon μXRF geochemistry showing elements with axis correlations ($r^2 > 0.5$). Grey diamonds represent samples. Red arrows represent the relationships between elements (and Incoherence/Cohereence (Inc/Coh)) and the PCA axes with arrow size reflecting the strength of the correlation and arrow direction indicating the direction of correlation. All data were adjusted to the standard deviate prior to analysis.
Figure 4-15 | μXRF geochemistry results for Hazards Lagoon. Profiles of major elements are presented as normalised values of counts/thousand counts per spectrum (c/kcps) with a 5-point weighted average in colour. PCA axis 1 results are presented as axis scores (PCA 1). Incoherence/Coherence (Inc/Coh) is presented as a ratio and is an indicator of organic content (higher values = higher organic content) (Croudace & Rothwell, 2015). Ca/Ti and Sr/Ti are presented as ratios and are indicators of authigenic carbonate precipitation (higher values = more precipitation) (Kylander et al., 2011).
4.2.5 PALYNOLOGY

A total of 37 samples were analysed for pollen, spores and microscopic charcoal. A total of 307,713 pollen grains and spores were identified and counted from a total of 61 different taxa; results are summarised as a pollen diagram in Figure 4-17 with pollen as percentages of the terrestrial sum and algae spores and charcoal as accumulation rates. CONISS analysis revealed three pollen zones within the terrestrial pollen record and the third zone was partitioned into 3 sub-zones: Zone HL 1- ca.17.9 – 16.5 kyr; Zone HL 2- ca.16.5 – 14.9 kyr; Zone HL 3a- ca.14.9 – 13.9 kyr; Zone HL 3b- ca.13.9 – 12 kyr; and Zone HL3c- ca.12 – 10.5 kyr (Figure 4-17). Principal Component Analysis (PCA) was completed on the terrestrial pollen dataset and ordination scores from axes 1 (PCA 1) and 2 (PCA 2) are plotted in the pollen diagram in Figure 4-17.

4.2.5.1 Principal Component Analysis

Figure 4-16 presents correlations between terrestrial pollen taxa and the two most significant ordination axes as an ordination biplot. PCA axis 1 explains 39% of the variance in the dataset and PCA axis 2 explains 13%. The following taxa had positive correlations with axis 1: *Amperea xiphoclada* (*r^2* = 0.613) and *Pomaderris apetala* (*r^2* = 0.549); and Poaceae (*r^2* = 0.652), Asteraceae (*r^2* = 0.639), Amaranthaceae (*r^2* = 0.425) and *Tubulifloridites pleistocenicus* (*r^2* = 0.414) had negative correlations with axis 1; *Allocasuarina spp.* (*r^2* = 0.45) was positively correlated to axis 2; and *Eucalyptus spp.* was negatively correlation to axis 2 (*r^2* = 0.592).

The ordination space in Figure 4-17 is organised by CONISS-determined pollen zones that correspond to variation in pollen assemblages through time. Zone HL 1 is associated with Poaceae, Asteraceae, and Amaranthaceae fossil pollen. Zone HL 2 is associated with
*Tubulifloridites pleistocenicus* and *Eucalyptus spp.* Zones HL 3a, b and c are associated with *Allocasuarina* spp., *Amperea xiphoclada*, *Pomaderris apetala* and *Eucalyptus spp.*

**Figure 4-16** | Principal Components Analysis (PCA) ordination biplot of the Hazards Lagoon terrestrial pollen dataset. Samples are grouped by colour to show CONISS-identified pollen zones (corresponding time periods found in the legend). The proportion of variance in the terrestrial pollen dataset explained by each axis is shown as a percentage. The strength of the correlation between important taxa and the ordination axes are shown as $r^2$ values, with the corresponding axis and direction of correlation indicated by the direction of each arrow. Data were square root transformed prior to analysis.

**4.2.5.2 Zone HL 1- ca.17.9 – 16.5 kyr**

This zone is characterised by a steady increase in trees & shrubs (38- 63%) at the expense of grasses & herbs (37- 6%) (Figure 4-17). This trend is primarily driven by an increase in *Eucalyptus spp.* (19- 52%) and decreases in Poaceae (26- 9%), Asteraceae (15- 6%) and Amaranthaceae (5- 2%). Aquatic macrophyte abundance remains high through the zone (between 70 and 90%) and is comprised of the relative abundances of *Isoëtes spp.* and *Myriophyllum spp.*, which show anti-phased oscillations through the zone. *Botryococcus spp.*
steadily increases through the zone, reaching peak values, and microscopic charcoal remains low.

4.2.5.3 Zone HL 2- ca.16.5 –14.9 kyr

The terrestrial record in this zone is characterised by a slight increase in the dominance of trees & shrubs over grasses & herbs (63- 68%). The proportion of *Eucalyptus* spp. and other Myrtaceous taxa remains high until ca.15.3 ka, when their abundance declines synchronous with an increase in *Allocasuarina* spp. (2- 8%) and *Amperea xiphoclada* (<1- 2%). Microscopic charcoal increases at the onset of this zone, remains high for ca. 1000 years and spikes at ca.15.4 ka before declining substantially, synchronous with the decline in *Eucalyptus* spp. and Myrtaceous taxa. The aquatic record shows an abrupt decline in *Isoëtes* spp. (60- 3%) and a gradual decline in *Myriophyllum* (58- 2%). Sedges & rushes increase through with Cyperaceae peaking at 33% before declining concomitant with an increase in Restionaceae from (2- 7%). *Botryococcus* spp. decline step-wise through this zone and are anti-phased with increases in *Zygnema* spp. spores, which appear abruptly in the record at ca. 16.5 ka.

4.2.5.4 Zone HL 3a- ca.14.9 –13.9 kyr

This zone is characterised by further increases in the abundance of *Allocasuarina* spp. (9%), *Amperea xiphoclada* (6%) and *Pomaderris apetala* (2%) at the expense of *Eucalyptus* spp. (52- 43%) and other Myrtaceous taxa. Poaceae (17%), Amaranthaceae (3%) and *Plantago* spp. (4%) also increase moderately through the zone. Restionaceae and Cyperaceae maintain high abundance as aquatic macrophytes and open-water aquatic algae all but disappear from the record. Microscopic charcoal increases steadily from moderate to moderate-high levels.
4.2.5.5 Zone HL 3b- ca.13.9 – 12 kyr

This zone is characterised by a resurgence in *Eucalyptus spp.* (68%), increased Cupressaceae (7%), slight decreases and then increases in *Amperea xiphoclada* and *Pomaderris apetala* and declines in * Allocasuarina spp.* (2%), Poaceae (4%) and Amaranthaceae (<1%). Microscopic charcoal increases markedly for the first half of the zone before declining to low levels. Restionaceae (~4%) and Cyperaceae (~7%) maintain slightly lower abundances than the previous zone.

4.2.5.6 Zone HL3c- ca.12 – 10.5 kyr

This zone sees a marked rise in *Allocasuarina spp.* (2- 20%) and high abundances of *Amperea xiphoclada* (5%) and *Pomaderris apetala* (5%). This is synchronous with declines in *Eucalyptus spp.* (56- 41%) and Cupressaceae (7- <1%). Relatively low charcoal values are recorded at the onset of the zone before a large peak at ca.11.2 ka and then a decline to moderate values. In the aquatic record there is a slight increase in *Botryococcus spp.*, while Cyperaceae maintains moderate values and Restionaceae increases to peak abundance (8%).
Figure 4-17 | Percentage pollen diagram showing all taxa present in the Hazards Lagoon record with >1% abundance. The y-axis is plotted according to age. Note changes in x-axes scales. Pollen zones are delineated by red dashed lines and sub-zones by grey. Microscopic charcoal and algal spores are presented as accumulation rates (pieces/cysts cm\(^{-2}\) yr\(^{-1}\)). Percentage trees & shrubs is represented in green and percentage grasses & herbs in yellow. Percentage aquatic macrophytes is presented in dark blue. Summed accumulation rates of open-water algal spores are presented in light blue. PCA axis scores estimate trends in the pollen data: axis 1 39% variance and axis 2 13% variance.
4.2.6 **CHARCOAL**

A total of 86 samples from Hazards Lagoon core TAS1704 were analysed for macroscopic charcoal. Charcoal accumulation rates (CHAR) maintain low values (<0.5 pieces cm$^{-2}$ year$^{-1}$) from ca.18.5 – 16.3 kyr before increasing to moderate values (0.05-0.75 pieces cm$^{-2}$ year$^{-1}$) from ca.16.3 – 15 kyr (Figure 4-18). There is a peak at ca.14.8 ka, followed by a decline, an anomalously high peak (single sample; 10.6 pieces cm$^{-2}$ year$^{-1}$) at ca.14.2 ka, followed again by a decline and then a sustained peak between ca.13.3 – 13 kyr. CHAR then remain low from ca.12.9 – 10.5 kyr.

![Figure 4-18](image)

**Figure 4-18**| Macroscopic charcoal results from Hazards Lagoon core TAS1704 presented as Charcoal Accumulation Rates (CHAR) (pieces cm$^{-2}$ year$^{-1}$). Note y-axis break from 2 to 5.
CHAPTER 5: DISCUSSION

This chapter will discuss the results obtained by this thesis and carefully examine their effectiveness in addressing the research questions, as outlined in Chapter 1:

**RQ 1:** How did the hydroclimate of western Tasmania change through the Antarctic Cold Reversal?

**RQ 2:** How did the hydroclimate of eastern Tasmania change through the Antarctic Cold Reversal?

**RQ 3:** Did the influence of the Southern Westerlies change over Tasmania through the Antarctic Cold Reversal?

**RQ 4:** How did the Southern Westerlies respond to the rapid climate change of the Antarctic Cold Reversal?

These questions will be addressed by (1) interpreting the multi-proxy data from Lake Rolleston and Hazards Lagoon to infer the nature and drivers of environmental change at each site through the Antarctic Cold Reversal (ACR), (2) considering these records collectively to reconstruct the influence of the Southern Westerlies over Tasmania through the ACR, and (3) placing this reconstruction within the context of existing regional empirical records to elucidate the response of the Southern Westerlies the rapid climate change of the ACR. Finally, this chapter will close by discussing the implications of the findings for our understanding of regional Southern Hemisphere climate dynamics, global climate dynamics and the climate mechanisms of Termination I.
5.1 ENVIRONMENTAL CHANGE AT LAKE ROLLESTON

The palaeoenvironmental reconstruction at Lake Rolleston reveals substantial change in terrestrial vegetation, catchment processes and within-lake conditions through Termination I. This section will discuss these changes through three defined periods: (1) the early deglacial, defined as the period ca. 16.5 – 14.7 ka based on a synthesis of proxy-records of Termination I in Australia (Petherick et al., 2013), (2) the Antarctic Cold Reversal (ACR), defined as ca. 14.7 – 13 ka based on composite Antarctic ice core records (Pedro et al., 2016), and (3) the late deglacial and Holocene, defined as ca. 13 – 10.5 ka and which encompasses the late deglaciation period immediately following the conclusion of the ACR and the initial ca. 1,500 years of the Holocene, based on the Australian proxy-record synthesis (Petherick et al., 2013) and Antarctic ice core records (WAIS Divide Project Members, 2015).

5.1.1 EARLY DEGLACIAL- CA. 16.5 – 14.7 kyr

5.1.1.1 Vegetation change

Results of fossil pollen analysis reveal a transition from herb-dominated vegetation through Cupressaceae-Notofagus gunnii rainforest, to a Phyllocladus aspleniifolius- rainforest through the early deglacial period. Initial high abundances of Poaceae and Asteraceae indicate that alpine grassland communities were established at Lake Rolleston at 16.5 cal ka (Figure 5-1). While the Lake Rolleston pollen record from this thesis does not extend beyond 16.5 cal ka, data from the nearby Lake Selina (4 km north, 510 m a.s.l) indicate the dominance of alpine grass and herb taxa during the Last Glacial Maximum (LGM; ca. 22 – 18 ka, Petherick et al. (2013)) and through the early deglacial (Colhoun et al., 1999). During the LGM the ascendency of grass and herb pollen over arboreal pollen in western Tasmanian records is interpreted as a reflection of a substantial temperature depression limiting the distribution of trees to lower altitudes, resulting in an open alpine environment across the landscape (Colhoun, 1996; Colhoun et al., 1999;
Colhoun & Van de Geer, 1986; Van de Geer et al., 1989; Colhoun, 1985; Fletcher & Thomas, 2010a). Indeed, Colhoun (1996) suggests that the altitudinal treeline across western Tasmania was near sea level at this time, well below Lake Rolleston (current day 560 m a.s.l).

![Figure 5-1](image)

**Figure 5-1** | Selected terrestrial pollen percentages from Lake Rolleston. The Antarctic Cold Reversal (ACR) is marked in blue and the Holocene (H) is delineated by the dashed black line.

Poaceae and Asteraceae abundances then decline for the remainder of the early deglacial as Cupressaceae and *N. gunnii* ascend in the record, followed by *P. aspleniifolius* (Figure 5-1). Cupressaceae and *N. gunnii* rise to proportions indicative of a localised presence between 16 and 15 cal kyr (Fletcher & Thomas, 2007), and alpine/sub-alpine shrub *Microstrobos spp.* reaches peak values (Figure 4-8). In modern western Tasmania these taxa occur as cool-climate alpine or
sub-alpine rainforest communities (Kirkpatrick, 1982; Jarman & Brown, 1983; Kitchener & Harris, 2013) and their distribution is controlled primarily by temperature and fire activity (Jackson, 1968; Bowman & Jackson, 1981; Kirkpatrick, 1982; Fletcher & Thomas, 2010a; Fletcher & Thomas, 2010b). Their presence at Lake Rolleston in the absence of fire through the early deglacial (Figure 5-2) suggests they expanded upslope in the catchment in response to increasing temperatures and a concomitant rising treeline (Fletcher & Thomas, 2010a; Colhoun, 1996). Through this period, the abundance of lowland rainforest species *N. cunninghamii* and *P. aspleniifolius* (Jarman & Brown, 1983) also increased from a virtually absent, to reach a combined ~20% of the terrestrial pollen sum. However, these species are prolific pollen dispersers and are commonly over-represented in the pollen rain, especially at alpine and sub-alpine sites, and as consequence local presence can only be assumed at proportions of >40% and >9 respectively (Fletcher & Thomas, 2007; Macphail, 1979). Their presence in the record likely reflects expansion of lowland rainforest at lower altitude sites in the region up until 15.5 ka, when *P. aspleniifolius* surpasses 8% and local establishment can be assumed, whereas *N. cunninghamii* values remain at background levels. *P. aspleniifolius* is a pioneering rainforest species and prefers cooler conditions than *N. cunninghamii* (Read & Busby, 1990), which explains the early local establishment prior to *N. cunninghamii* and further supports the inference that temperature is the dominant factor controlling vegetation at Lake Rolleston through this time.

Interestingly, the charcoal record indicates almost no fire activity at Lake Rolleston through this period (Figure 5-2) despite regional charcoal records reflecting a substantial increase in biomass burning from 16.5 ka onwards (Fletcher et al 2018, unpublished). This may reflect the location of the coring site for TAS1504 N1 in the southern Lake Rolleston basin; the southern basin (B2; Figure 4-2) is surrounded by rainforest that is hyper fire-sensitive and which has a low fuel flammability, whereas sites that record an increase in burning are all sites occupied by
flammable fire-promoting vegetation (moorland) (Pyrke & Marsden-Smedley, 2005; Kitchener & Harris, 2013)(Fletcher, unpublished).

Figure 5-2 | Charcoal results from Lake Rolleston presented as charcoal accumulation rates (CHAR). The Antarctic Cold Reversal (ACR) is marked in blue and the Holocene (H) is delineated by the dashed black line.

5.1.1.2 Weathering and erosion

Analysis of sediment geochemistry and sediment influx from the early deglacial period reveal declining rates of catchment weathering and erosion (Figure 5-3). Rates of chemical weathering are influenced by changes to temperature, humidity and physical erosion (West et al., 2005). Wetter and warmer climates cause stronger chemical weathering (West et al., 2005; Gabet et al., 2006), and proxy evidence of past weathering regimes can be used to infer past climate conditions (Clift et al., 2014; Hu et al., 2012; Heymann et al., 2013).

Changes to the ratio of K/Rb within sedimentary records can be used to infer past changes to chemical weathering rates within a catchment (Clift et al., 2014; Hu et al., 2012; Jin et al., 2006;
Das et al., 2006). Potassium (K) is more soluble than Rubidium (Rb) and thus fractionates at a greater rate than Rb under increased humid conditions and enhanced weathering (Shaw, 1968; Nesbitt & Young, 1982; Hu et al., 2012; Jin et al., 2006). The ratio of K/Rb is low at Lake Rolleston through the beginning of early deglacial, indicating the rate of chemical weathering was low. This inference is further supported by declines in the µXRF profiles of trace elements lead (Pb) and Zinc (Zn) through this period. Because of the high content of these trace elements in the catchment bedrock, changes to their presence in the sediment through time is interpreted as reflecting changes to the rate at which they are weathered and leached from the rock into the lake (Boyle, 2002; Jin et al., 2006).

The K/Rb and trace element data indicate that the rate of chemical weathering at Lake Rolleston was low and declining through the early deglacial period despite increasing regional temperature (Figure 5-3) (Fletcher & Thomas, 2010a; Calvo et al., 2007; WAIS Divide Project Members, 2015). Thus, low rates of chemical weathering must be a reflection of either (1) reduced precipitation and/or (2) increased physical erosion (West et al., 2005; Gabet et al., 2006).

Erosion of soils that cover bedrock decreases the supply of mineral reactants to the rock surface and causes weathering to become increasingly climate (temperature and moisture) limited (West et al., 2005; White & Blum, 1995). This thesis uses the presence of Titanium (Ti) as an indication of catchment erosion (Metcalfe et al., 2010; Corella et al., 2012; Gigué-Covex et al., 2011; Moreno et al., 2007; Rees et al., 2015) in addition to the rate of sediment influx (depositional time) (Eden & Page, 1998; Page et al., 1994; Rees et al., 2015). By combining fluctuations in sedimentary Ti with changes in depositional time, the limitations of depositional time (see Methods: Section 3.4.4) can be accounted for and a robust record of catchment erosion can be inferred. Together, the Ti and depositional time records reveal that catchment erosion was low and decreased slightly through the early deglacial (Figure 5-3), which is interpreted as a reflection of low runoff. This in itself indicates that precipitation was low at Lake Rolleston.
during the early deglacial, but the low rates of erosion combined with evidence of increasing temperatures discussed above means that the most plausible explanation of the observed reduced rates of chemical weathering is also low precipitation.

5.1.1.3 Lake level & evaporative conditions

Analysis of sediment geochemistry reveals increasing precipitation of evaporative carbonate minerals within Lake Rolleston through the early deglacial period. Precipitation of evaporative carbonate minerals in fresh-water lakes increases (decreases) with more (less) evaporative conditions and lower (higher) lake levels (Cohen, 2003; Kelts & Hsü, 1978; Haberzettl et al., 2005). The type of evaporative minerals that are precipitated in the water column are dependent on initial water chemistry, which is related to the underlying catchment geology (Eugster & Hardie, 1978). At Lake Rolleston, calcium carbonate (CaCO₃) and gypsum minerals (CaSO₄) exist as weathering products from calcite and pyrite bodies within the Mt. Read volcanics (Figure 4-2) (Solomon et al., 1987; Calver, 2016; Seymour et al., 2006; Ritsema & Groenenberg, 1993). The authigenic (within lake) deposition of these evaporative minerals into the sediment is tracked using µXRF profiles of Calcium (Ca) and Sulphur (S), normalised to allogenic (outside of lake) Ti to accounted for any allogenic sources of these elements in the sediment (Kylander et al., 2011). The presence of authigenic Ca and S increases from moderate to high levels through the early deglacial period at Lake Rolleston, indicating an increase in evaporative conditions and lower lake levels (Cohen, 2003; Kylander et al., 2011).

The multi-proxy evidence of environmental change from the early deglacial period (ca 16.5 – 14.7 ka) at Lake Rolleston reveals an expansion of warm-climate rainforest, reduced rates of weathering and erosion, increased evaporative lake conditions and declining lake levels. This indicates a warming climate with declining precipitation during the early deglacial.
Figure 5.3 | Selected Lake Rolleston μXRF geochemistry results, sediment accumulation rate and rainforest pollen percentage. μXRF elemental profiles are presented as counts/ thousand counts per spectrum (c/kcps) with an 11-point weighted average in black, and the sediment accumulation rate is presented as depositional time on an inverted y-axis. The Antarctic Cold Reversal (ACR) is marked in blue and the Holocene (H) is delineated by the dashed black line.

5.1.2 ANARCTIC COLD REVERSAL - CA. 14.7 – 13 kyr

5.1.2.1 Vegetation change

A reverse in the trends from the early deglacial sees Asteraceae, Poaceae and N. gunnii pollen increase through the ACR, which indicates a re-expansion of cool climate vegetation during this time at the expense of lowland rainforest (namely P. asplenifolius) (Figure 5-1). These trends indicate that the deglacial warming trend that drove the expansion of rainforest upslope was
reversed during the ACR, resulting in a lowering of the treeline. This inferred shift toward cooler temperatures during the ACR is entirely consistent with modelling studies (Pedro et al., 2016), and low-resolution temperature-proxy records from western Tasmania (Fletcher & Thomas, 2010a), as well as proxy records from the southern Australian coast (Calvo et al., 2007) and further afield in mid-latitude New Zealand (Newnham et al., 2007; Vandergoes et al., 2008; Putnam et al., 2010).

Interestingly, fire activity increases for the first time in the record through the second half of the ACR (ca. 13.8 – 13 kyr) (Figure 5-2). This is in contrast with regional fire trends that see a decline in fire activity through the ACR, a trend that is consistent with wetter conditions in western Tasmania systems (Mariani & Fletcher, 2016). The influx of charcoal particles through the ACR at Lake Rolleston coincides with a dramatic increase in sediment influx (depositional time) (Figure 5-1, 5-2). As charcoal accumulation rates are calculated using the same methods as depositional time, they too are affected by the impact of inconsistent dating intensities on the age-depth model for core TAS1504 N1. The influx of charcoal particles coeval with the dramatic increase in sediment flux indicates the charcoal peak may be reflecting increased erosion of secondary charcoal particles that were deposited within the catchment slopes during previous episodes of fire activity, rather than be representative of increased burning through the ACR.

5.1.2.2 Weathering and erosion

Analysis of sediment geochemistry and sediment influx indicates that the Lake Rolleston catchment experienced enhanced weathering and erosion during the ACR. A marked increase in the K/Rb ratio is interpreted as an increased rate of chemical weathering through this period (Figure 5-3). This interpretation is supported by the increased presence of trace elements Pb and Zn in the sediment, as their release from rocks on the catchments slopes is directly determined by the rate of weathering. Increased rates of erosion through this period are inferred from peak
Ti values and higher sediment influx. Erosion of the soil mantling catchment rocks would have also reduced the supply of reactants to the rock surface and, thus, moderated the rate of weathering, rendering it more climate sensitive (West et al., 2005; White & Blum, 1995). Interestingly, the reduction in temperature inferred from this and regional studies during the ACR (Pedro et al., 2016; Fletcher & Thomas, 2010a; Calvo et al., 2007), might be expected to reduce the rate of weathering, contrasting with the evidence presented here. The evidence for increased rates of weathering and erosion synchronous with reduced temperatures during the ACR at Lake Rolleston can be reconciled via an increase in precipitation. Indeed, an interpretation of increased precipitation is also consistent with the peak values of Ti and higher sediment flux that reflect increased runoff at Lake Rolleston during the ACR.

5.1.2.3 Lake level & evaporative conditions

Results of geochemical analyses also reveal a decrease in the presence of evaporative minerals in the Lake Rolleston sediments during the ACR. Ratios of Ca/Ti and S/Ti both decline markedly at ca. 14.7ka and remain depressed for the duration of this period. The reduction in these ratios reflects a decline in the precipitation of evaporative minerals within Lake Rolleston, which is interpreted at a response to reduced evaporative conditions and higher lake levels and thus, provides support for the inference that precipitation increased during the ACR.

5.1.3 LATE DEGLACIAL- CA. 13 – 11.7 & HOLOCENE- 11.7 – 10.5 kyr

5.1.3.1 Vegetation change

Pollen analysis results indicate an expansion of lowland rainforest during the late deglacial at Lake Rolleston and a subsequent transition to N. cunninghamii-dominated rainforest at the onset of the Holocene (ca. 11.7 ka) (Figure 5-1). Following the conclusion of the ACR, P. aspleniiifolius increases at the expense of Poaceae and Asteraceae, and lowland rainforest shrub Bauera rubioides increases markedly (Figure 5-1). These trends are consistent with other
evidence of regional warming and upslope expansion of lowland rainforest vegetation (Colhoun et al., 1999; Colhoun, 1996; Macphail, 1979; Fletcher et al., 2018b). Thus, the pollen sequence here is interpreted as a response to temperature change. The decline of *P. aslepidiifolius* from peak to negligible values at 11.8ka is also a ubiquitous trend across the region (Beck et al., 2017; Mariani et al., 2017; Stahle et al., 2016; Fletcher et al., 2018b), as more thermophilus taxa, *N. cunninghamii* and *B. rubioides* (Read & Busby, 1990), assume dominance of the rainforest vegetation under the Holocene temperature regime (WAIS Divide Project Members, 2015).

5.1.3.2 Weathering and erosion

Rates of weathering and erosion in the Lake Rolleston catchment declined following the conclusion of the ACR (Figure 5-3). As mentioned, warming temperatures would have a positive effect on chemical weathering, yet rates fell, as indicated by the decline in K/Rb and Pb and Zn profiles. Erosion of terrigenous material, represented by Ti, declined in the late deglacial, as did the overall influx of sediment. The observed decrease in weathering and erosion despite increasing temperature provides evidence for a reduction in precipitation and runoff in the catchment declined following the ACR.

There is an increase in overall sediment influx following the onset of the Holocene, however the terrigenous contribution (Ti) remains low (Figure 5-3). Chemical weathering rates (K/Rb) increase marginally, likely in response to the warmer temperatures, but the presence of Pb and Zn remains low. This geochemical signature differs markedly from the pre-Holocene sediments and reflects a change in the provenance of material being deposited in the lake. The marked increase in the µXRF profile of Bromine (Br) reflects an increase in organic matter content being delivered into the lake from the surrounding catchment. The likely province of the organic material is the organic soils that develop under rainforest vegetation in Tasmania and which captured the landscape at the onset of the Holocene (Bridle & Kirkpatrick, 1997): the upslope
temperature-driven expansion of lowland rainforest was accompanied by the development of thick organic peat soils that covered the Pb and Zn-bearing bedrock, shielding it from weathering. This material would have then become the primary source of sediment input, accounting for the increase in sedimentary Br.

5.1.3.3 Lake level & evaporative conditions

The ratios of Ca/Ti and S/Ti both increase consistently following the ACR, indicating a period of enhanced precipitation of evaporative carbonate minerals in the water column. This indicates a period of enhanced evaporative conditions and declining lake levels, supporting the contention that precipitation declined following the ACR. The onset of the Holocene at ca. 11.7 ka (Petherick et al., 2013; WAIS Divide Project Members, 2015) is marked by a decline in the precipitation of evaporative carbonate minerals and thus a period of higher lake levels and reduced evaporative conditions is inferred. The multi-proxy evidence from the late deglacial and early Holocene at Lake Rolleston is indicative of a warming climate with reduced precipitation following the ACR.

5.2 Climatic Interpretations at Lake Rolleston

Overall, the proxy-data at Lake Rolleston through Termination I indicates that changes in temperature drove changes in vegetation whilst changes to the hydroclimate provoked strong responses in rates of weathering and erosion and from within-lake conditions. Fossil pollen revealed a temperature-driven succession of vegetation from alpine grassland and herbfields through to lowland rainforest that was briefly interrupted by a reversal during the ACR. μXRF geochemical evidence, supported by depositional time, indicated the highest rates of chemical weathering and physical erosion occurred in response to increased precipitation during the ACR, and that this increase in precipitation also drove higher lake levels and reduced evaporative
conditions. Together, these lines of proxy evidence provide explicit support for the hypothesis that Lake Rolleston became wetter during the ACR

5.3 ENVIRONMENTAL CHANGE AT HAZARDS LAGOON

The palaeoenvironmental reconstruction at Hazards Lagoon reveals the terrestrial and aquatic environments changed substantially through Termination I. This section will discuss changes to both the these environments through three defined periods: (1) the early deglacial, defined as the period ca. 18 – 15 ka based on a synthesis of proxy-records of Termination I in Australia (Petherick et al., 2013), (2) the Antarctic Cold Reversal (ACR), defined as ca. 15 – 13 ka based on composite Antarctic ice core records (Pedro et al., 2016) and accounting for radiocarbon errors that may have impacted the Hazards Lagoon chronology, and (3) the late deglacial and Holocene, defined as ca. 13 – 10.5 ka and which encompasses the late deglaciation period immediately following the conclusion of the ACR and the initial ca. 1,500 years of the Holocene (Petherick et al., 2013).

5.3.1 EARLY DEGLACIAL - CA 18 – 15 kyr

5.3.1.1 Terrestrial record

The early deglacial period (ca. 18 – 15 kyr) at Hazards Lagoon was characterised by a shift in the dominant vegetation from a grassland steppe community to Eucalyptus spp. forest. Eucalyptus spp. values indicate a local presence (>20%) (Macphail, 1979; Dodson, 1998) by 17.8 ka and a continued increase at the expense of grasses and herbs until becoming most dominant pollen taxon by ca.16.2 ka (Figure 4-17). Similar trends are also recorded in other south east Australian pollen records spanning the early deglacial period (ca. 18 – 15 kyr) (Williams et al., 2006; Builth et al., 2008; Harle et al., 2004), including from Lake Tiberias and Pipe Clay Lagoon in eastern Tasmania (Macphail & Jackson, 1978; Colhoun, 1977), and in the
existing low-resolution pollen record from Hazards Lagoon (Mackenzie & Moss, 2014). Although rising deglacial temperature would have had some influence over vegetation succession, increased moisture was the primary factor that drove the expansion of *Eucalyptus* spp. dominated communities across the east of Tasmania (Colhoun *et al*., 1999; Petherick *et al*., 2013). Indeed, Macphail (1979) estimated the LGM altitudinal treeline in eastern Tasmania to be located at ca. 400 m a.s.l (relative to modern sea level), well above the altitude of Hazards Lagoon. Increasing moisture availability through the early deglacial period at Hazards Lagoon is also reflected in compositional changes within the arboreal vegetation: *Eucalyptus* spp. gradually increase their dominance over the dry-tolerant *Allocasuarina* spp., represented as a ratio of abundance in (Figure 5-4), as the climate became wetter through the early deglacial. The relative expansion of *Eucalyptus* spp. over *Allocasuarina* spp. has been used in multiple records from temperate southeast Australia to infer increases in effective precipitation (Builth *et al*., 2008; Williams & Bryan, 2006; Harle *et al*., 2004). These inferences are supported empirically by an analysis of modern pollen spectra and climate variables across southeast Australia that find *Eucalyptus* spp. dominant over *Allocasuarina* spp. in wetter regions, with *Allocasuarina* spp. increasing in importance as rainfall decreases (D'Costa & Kershaw, 1997; Kershaw *et al*., 1994). In this record, *Eucalyptus* spp. increase at the expense of *Allocasuarina* continuously through the early deglacial until ca. 15.2 ka, when there is an increase in the dry-tolerant taxa (*Allocasuarina* spp. and *Amperea xiphoclada*) that indicates a reduction in effective precipitation at this time (Figure 5-4).

Fire activity at Hazards Lagoon appears to be positively related to *Eucalyptus* pollen content, suggesting that fires at this site are fuel-limited at this site. *Eucalyptus* species have highly flammable foliage and are well-adapted to fire. In contrast, *Allocasuarina* spp. are both fire-sensitive and have a low flammability (Pyrke & Marsden-Smedley, 2005). Fire activity remains low until 16.4 ka, when it increases to moderate levels ca. 200 years after *Eucalyptus* spp.
reaches peak values, supporting the inference that available fuel controls fire activity (Figure 5-4).

![Figure 5-4](image)

**Figure 5-4** | Summary plot of terrestrial environmental change at Hazards Lagoon. Macroscopic charcoal accumulation rates are presented as pieces cm$^{-2}$ year$^{-1}$ and a single outlier sample presented in grey on a broken y-axis. *Allocasuarina spp.* and *Eucalyptus spp.* are shown as a ratio and other taxa as percentage values.

### 5.3.1.2 Aquatic record

Major changes to the aquatic environment are also evident at Hazards Lagoon through the early deglacial period (ca. 18 – 15 ka). Prior to ca. 16.3 ka, when the terrestrial environment was
dominated by grassland steppe communities and productivity was low, the dominance of inorganic elements such as Ti, K, and Fe in the sediment and low organic-indicating Br suggest the water body resembled a clear open water lagoon (Figure 5-5). This is supported by the high abundance of open-water aquatic macrophyte *Isoetes spp.*, which prefers a sandy substrate and high light penetration (Chappuis *et al.*, 2015; Harle *et al.*, 1999; Colhoun *et al.*, 1991). As the terrestrial ecosystem began to transition into *Eucalyptus spp.* forest and woodland, the organic matter entering the lagoon (Figure 5-5; *Br*) increased and terrigenous inputs (Figure 5-5; *Ti*) decreased. This change in trophic conditions would have decreased light penetration through the water column (Mariani *et al.*, 2018), favouring *Myriophyllum spp.* over *Isoëtes spp.* (Colhoun *et al.*, 1991). As *Myriophyllum spp.* increased its dominance over *Isoëtes spp.* and *Eucalyptus spp.* continued to expand, organic matter built up to point where a transition from open-water lagoon to open-water wetland occurred between ca. 16.3 – 16.5 ka (Cadd *et al.*, 2018). This is marked by abrupt declines in sediment Ti and *Isoëtes spp.*, and the increase in colonial (free-swimming) algae *Botryococcus spp.*, which is common in dystrophic open water environments (Guy-Ohlson, 1992; Komárek & Marvan, 1992).

As organic material continued to infill the wetland from 16.5 ka, the emergent sedges Cyperaceae and Restionaceae gradually expand into the littoral area and the presence of *Myriophyllum spp.* declines to moderate levels. *Botryococcus spp.* also decline to moderate levels by ca. 15.5 ka, probably in response to declining water depth from infilling by organic material, or a reduction in effective precipitation, or a combination of both (Cadd *et al.*, 2018). Their decline coincides with the appearance of epipelic (substrate-occupying) algae *Zygnema spp.*, which becomes abundant at 16 ka, indicating water depth had lowered to the point of an ephemeral waterbody or a permanently moist surface (van Geel, pers. comm., Skinner, pers. com., van Geel (1979)). The successional changes in abundance of *Myriophyllum spp.*, *Zygnema spp.* and *Botryococcus spp.* indicates water levels were slowly declining between 16.2 and 15 ka,
Figure 5-5 | Summary plot of aquatic environmental change at Hazards Lagoon. Aquatic plants are presented as percentages of the total terrestrial pollen sum. Algal spores are presented as accumulation rates in cysts cm\(^3\) year\(^{-1}\). µXRF Ti and Br are normalised as counts/thousand counts per spectrum with Ti on a broken axis. Strontium and calcium have been normalised as a ratio to Ti. All geochemical data has a 5-point weighted average.
but the moderate values of *Myriophyllum* spp and *Botryococcus* spp. and high values of *Zygnuma* spp. at 15 ka indicate the site did remain permanently wet throughout this phase.

The interpretation of a gradual decline in water depth over the early wetland phase (ca. 16.5 – 15 ka) is also supported by the gradual increase of μXRF Ca/Ti and Sr/Ti (Figure 5-5), which are indicative of evaporative carbonate minerals calcium carbonate (CaCO₃) and strontium carbonate (SrCO₃) in the sediment (Davies et al., 2015; Croudace & Rothwell, 2015; Kylander et al., 2011). The gradual increases in the precipitation of these minerals in the water column between ca. 16.5 – 15 ka indicates evaporative conditions were increasing and water depth declining through this period (Cohen, 2003; Kylander et al., 2011; Haberzettl et al., 2005). The sequence of changes to the aquatic environment indicate a transition from a deeper open water body to a shallower organic wetland over the early deglacial. Separating the drivers of this change is difficult as lake in-filling can be driven by increased organic inputs and/climate (Cadd et al., 2018). Considering the aquatic and terrestrial evidence collectively, it is likely that it was wetter during the lagoon phase, highlighted by the minimum carbonate minerals, but any gradual reduction in precipitation following the wetland transition at ca. 16.5 ka that could be inferred from the aquatic evidence must not have been significant enough to restrict the dominance of *Eucalyptus* spp. over the dry-tolerant taxa *Allocasua* spp and *Amperea* xiphoclada (D’Costa & Kershaw, 1997; Kershaw et al., 1994).

5.3.2 ANTIMATIC COLD REVERSAL- CA. 15 – 13 kyr

5.3.2.1 Terrestrial record

The Antarctic Cold Reversal (ACR; ca. 15 – 13 ka; Pedro et al. (2016)) was marked by a further expansion of dry-tolerant taxa at the expense of *Eucalyptus* spp. (Figure 5-4). *Allocasuarina* spp. reach peak proportions relative to *Eucalyptus* spp. and maintain their dominance in the landscape until a decline at ca. 13 ka. Additionally, the ACR period is also marked by a rapid expansion of
dryland heath shrub *Amperea xiphoclada* (from <1 to 7 %) and a resurgence in the presence of grasses and herbs, driven largely by Poaceae and Asteraceae (Figure 5-4). These taxa have also been shown to prefer dry conditions (D'Costa & Kershaw, 1997; Kershaw *et al.*, 1994), with *Amperea xiphoclada* additionally having a preference for sandy soils that would have become exposed at the edges of the wetland through this period under a declining water level (Kitchener & Harris, 2013). Together, the trends in the terrestrial vegetation record indicate that a considerable reduction in effective precipitation drove a contraction of *Eucalyptus spp.* woodland at the expense of *Allocasuarina spp.* and *Amperea xiphoclada* heath.

The shift in vegetation and climate is also reflected in changes in fire activity through the ACR. Low charcoal from ca.14.7 to ca. 13.4 ka is coincident with the contraction of *Eucalyptus spp.* in the landscape, and a shift to a period of high fire activity between ca. 13.4 and 13 ka reflects a reassumed dominance of the fire-promoting *Eucalyptus spp.* over fire-sensitive *Allocasuarina spp.* (Figure 5-4). Two sustained peaks (occurring over more than one sample) in fire activity occur around the onset (ca. 14.9) and conclusion (ca. 13.3) of the ACR. These peaks are not a reflection of an increase in overall fuel (i.e. total *Eucalyptus spp.* present), but rather are reflections of the climate-driven transition between *Eucalyptus spp.* dominance and *Allocasuarina spp.*. These periods mark phases of increasing fuel availability and a sufficiently dry climate to allow burning (i.e. increased available fuel; Pausas and Paula (2012)). It is noted that a single charcoal sample was arbitrarily excluded from the interpretations as it was determined to be unrepresentative of the fire activity trend and rather was a result of a stochastic taphonomic event, based on the following rational: (1) it was a single peak occurring in a period of low values, (2) it was an unrealistically high value, 430% larger than the next highest peak and (3) it occurred when the wetland was dry and woody vegetation could have occupied areas close to the core site, increasing the likelihood of an unrepresentative depositional event.
Mackenzie and Moss (2014) concluded that fire activity at Hazards Lagoon is climate limited, based on what they describe as ca. 4000-year lag between *Eucalyptus spp.* expansion and increased microscopic charcoal at ca. 14 ka. From this, they assert that fire activity was high during the ACR and invoke a decline in moisture balance as the driver. This assertion is supported by Jones *et al.* (2017), who also concluded that fire was climate limited at nearby Stoney Lagoon and that fire activity was high during the ACR. Both records are hampered by poor chronologies and critically, low sample resolutions that bias their data toward long-term (multi-millennial scale) trends, thus, making them insensitive to the short-term fluctuations, such as is recorded during the ACR in this record. Further, neither records analysed macroscopic particles, which are far more effective for local fire history reconstructions (Whitlock & Larsen, 2002; Larsen & MacDonald, 1998; Higuera *et al.*, 2007). This record therefore presents a much more detailed reconstruction of fire activity through the ACR and provides a more thorough interpretation of the drivers of fire activity at Hazards Lagoon.

5.3.2.2 Aquatic environment

The aquatic pollen and spore record indicates a sudden change in wetland conditions concurrent with the onset of the ACR at ca. 15 ka (Figure 5-5): *Myriophyllum spp.* and *Zygnema spp.* vanish, *Botryococcus spp.* fall to minimum levels and Restionaceae expands into the wetland. The disappearance of *Myriophyllum spp.* and *Zygnema spp.* from the record, together with the expansion of Restionaceae, indicates that the littoral zone was mostly dry, and sedges and rushes occupied the substrate of the wetland, preventing the growth of epipelagic algae where standing water did occur. Shallow, perhaps seasonal pools are likely to have supported *Botryococcus spp.*, while the very high levels of authigenic carbonate in the sediments support the inference that the onset of dry conditions drove water levels down.
5.3.3 LATE DEGLACIAL CA. 13 – 10.5 kyr

5.3.3.1 Terrestrial environment

The late deglacial period (ca. 13 – 12 kyr) sees a resurgence in *Eucalyptus* spp. forest and contraction of *Allocasuarina* spp. woodland, together with a major decline in the presence of grasses and herbs (Figure 5-4). This suggests an increase in effective precipitation at Hazards Lagoon, following the preceding dry ACR period. Fire activity falls, likely reflecting a reduction in fuel availability due to the continued increase in moisture and the likely expansion of the wetland forcing the fringing forests further from the core site.

The onset of the Holocene (ca. 12 ka in this record), appears to have brought drier and possibly warmer conditions, as highlighted by the expansion of dry-tolerant and warm tolerant *Allocasuarina* spp. to peak values at this time (Figure 5-4) (D'Costa & Kershaw, 1997; Kershaw et al., 1994; Kitchener & Harris, 2013). No increase in fire activity is recorded following the transition to the drier Holocene conditions at Hazards Lagoon, which would have been due to the marked decrease in *Eucalyptus* spp. abundance.

5.3.3.2 Aquatic environment

The return to wetter conditions in the late deglacial only had a marginal effect on the aquatic biota within the wetland, with a slight reduction in the presence of Cyperaceae and Restionaceae and minor increase in *Botryococcus* spp. observed (Figure 5-5). Wetland carbonate precipitation responds more readily to the change in conditions, with values of both calcium- and strontium carbonate falling markedly following the conclusion of the ACR, indicating a reduction in wetland evaporative conditions and an increase in water levels. Following the onset of the Holocene, emergent sedges and rushes increase their dominance, highlighted by peak values of Restionaceae, possibly indicating a further drying out of the wetland.
5.4 Climatic Interpretations at Hazards Lagoon

Overall, the proxy-data at Hazards Lagoon through Termination I indicates that changes to the hydroclimate elicited strong responses from the terrestrial and aquatic environments. Terrestrial fossil pollen and charcoal reveal an expansion of dry-tolerant taxa through the ACR, aquatic fossil pollen and spores indicate a drying out of the wetland during the ACR and sediment geochemistry suggests the precipitation of evaporative carbonate minerals in the wetland was exceptionally high. Together, these lines of proxy evidence provide explicit support for the hypothesis that Hazards Lagoon became drier during the ACR.

5.5 Tasmanian Climate during the Antarctic Cold Reversal

The multi-site, multi-proxy analysis conducted for this thesis reveals anti-phased east-west changes in the Tasmanian hydroclimate through the ACR (Figure 5-7). The Lake Rolleston record indicates that the climate in western Tasmania became cooler and wetter during the ACR, whereas the Hazards Lagoon record indicates the climate in eastern Tasmania became drier. These results provide the first robust, high-resolution records of climatic change through the ACR in Tasmania. The cooling observed in western Tasmania during the ACR (Figure 5-1) is in agreement with (1) modelling interpretations of a temperature depression at this time (Pedro et al., 2016), (2) low resolution western Tasmanian pollen data (Fletcher & Thomas, 2010a), (3) proxy-data from other southern landmasses (Calvo et al., 2007; Newnham et al., 2007; Vandergoes et al., 2008; Putnam et al., 2010) and (4) Antarctic ice core records (WAIS Divide Project Members, 2015). The interpretation that western Tasmania became wetter and eastern Tasmania drier is also further supported by unpublished Tasmanian proxy-data from Lake Selina in the west, 4 km north of Lake Rolleston (Figure 5-6b), where a decline in evaporative conditions is observed (Figure 5-7d), and from Lake Tiberias in the east, 80 km southwest of
Hazards Lagoon (Figure 5-6b), where an increase in evaporative conditions is observed (Figure 5-7c; Fletcher, unpublished).

Figure 5-6 | Map showing (a) modern zonal Southern Westerly wind speed with locations of proxy-data sites mentioned in the discussion, as well as the path of the Leeuwin Current and the location of Cape Leeuwin, and (b) the correlation between Southern Westerly wind speed and annual rainfall in Tasmania with the location of study sites from this thesis in yellow and other proxy-data sites mentioned in the discussion in green. Created by Michela Mariani.

5.6 THE SOUTHERN WESTERLIES DURING THE ANTARCTIC COLD REVERSAL

5.6.1 TASMANIA

The synchronous changes in Tasmanian hydroclimate both east and west of the central ranges during the ACR indicate that the island experienced enhanced Southern Westerly flow during this interval. An increase in westerly flow during the ACR explains (1) the inferred increase in effective precipitation in western Tasmania, as rainfall in the west this is positively correlated with westerly wind flow (Figure 5-6b) (Hill et al., 2009; Garreaud, 2007) and (2) the inferred
decrease in effective precipitation in eastern Tasmania, as rainfall in the east is negatively correlated with westerly wind flow (Figure 5-6b) (Hill et al., 2009; Garreaud, 2007). The validation of anti-phased west-east moisture signals during the ACR eliminates any ambiguity in attributing the changes in Tasmanian hydroclimate to changes in the strength of Southern Westerly flow. From these results, this thesis is able to provide robust support for either an expansion of the northern edge of the Southern Westerly wind belt in the Australian sector during the ACR, or an equatorward latitudinal shift.
Figure 5-7 | Summary plot of Tasmanian hydroclimate change through the Antarctic Cold reversal. (a) Ratio of *Allocasuarina* spp./*Eucalyptus* spp. from Hazards Lagoon reflecting relative dominance of dry-tolerant *Allocasuarina* spp., (b) Hazards Lagoon Ca/Ti reflecting changes in evaporative conditions (higher= more evaporative, lower= less evaporative), (c) Lake Tiberias Ca/Ti (Fletcher, unpublished), (d) Lake Selina Ca/Ti (Fletcher, unpublished), (e) Lake Rolleston Ca/Ti and (f) Lake Rolleston µXRF Pb profile (counts/thousand counts per spectrum) reflecting the rate of bedrock weathering in the catchment. ACR= Antarctic Cold Reversal.
5.6.2 THE AUSTRALIAN REGION

The interpretation of an equatorward expansion or shift of the Southern Westerlies over Tasmania during the ACR is in direct contrast with the findings of De Deckker et al. (2012). Based on interpretations of proxy-data from southern Australian marine core MD03-2611 (Figure 5-6a), these authors argue for a poleward position of the Southern Westerlies during this period. Their interpretation relies on the premise that an equatorward position of the Southern Westerlies restricts the penetration of the Leeuwin Current around Cape Leeuwin in western Australia (Figure 5-6a), while a poleward position allows the Leeuwin Current to penetrate around the Cape and along the southern Australian coast to their core site (36°43.8'S, 136°32.9'E) (De Deckker et al., 2012). Based on this interpretation, they contend that the presence of Leeuwin Current-indicating foraminifera Globigerinoides ruber at their site during the ACR is facilitated by a poleward displacement of the Southern Westerlies. This assertion directly disagrees with the findings of this thesis. To reconcile these two proxy records, an alternative interpretation of the MD03-2611 data is provided.

Although De Deckker et al. (2012) contend that an equatorward position of the Southern Westerlies restricts the penetration of the Leeuwin Current around Cape Leeuwin, this may only be true under periods of extreme equatorward displacement, such as during the Last Glacial Maximum (Stolfi, 2018; Wells & Wells, 1994; De Vleeschouwer et al., 2016). Under a more moderate equatorward displacement, when the interhemispheric thermal gradient is less extreme (Shulmeister et al., 2004), such as during the ACR (Pedro et al., 2016), it is possible that the penetration of the current is actually enhanced by increased Southern Westerly influence, as greater surface wind stress drives the current further east along the southern Australian coast (Cirano & Middleton, 2004), but does not divert it at Cape Leeuwin (Figure 5-6a). Indeed, this process is what drives modern seasonal variations in Leeuwin Current penetration, where it is
strongest during the Austral winter when the Southern Westerlies are expanded equatorward (Pearce & Pattiaratchi, 1999; Cirano & Middleton, 2004; Feng et al., 2009).

Following this alternative interpretation, the proxy-data from core MD03-2611 support the inference of this thesis that the Southern Westerlies were shifted equatorward during the ACR. At ca. 18 ka, there is minimal presence of *G. ruber* (Figure 5-8c), which is consistent with the Leeuwin Current being diverted at Cape Leeuwin under glacial conditions (Stolfi, 2018; Wells & Wells, 1994; De Vleeschouwer et al., 2016). The current then recommences penetration along the southern coast as the Southern Westerlies shift poleward in response to a warming Southern Hemisphere from ca. 18 ka and *G. ruber* presence increases (Figure 5-8c). Its presence then declines from ca. 16.2 – 14.5 ka (Figure 5-8c), synchronous with declining westerly flow over Tasmania (Figure 5-8a,b), indicating the wind belt has contracted further poleward and surface wind stress over the current has reduced. Between ca. 14.5 – 13 ka, during the ACR, there is a resurgence in the presence of *G.ruber* in MD03-2611, concomitant with strengthened westerly flow over Tasmania (Figure 5-8a-c). This indicates that the Southern Westerlies have again shifted equatorward and accelerated the Leeuwin Current along the southern Australian coast but have not moved far enough north to divert the current at Cape Leeuwin. This alternative interpretation supports the contention that the winds were positioned equatorward during the ACR and thus reconciles the proxy-data from core MD03-2611 with (1) the robust terrestrial proxy-data from Tasmania provided in this thesis, (2) the leading understanding of ocean-atmosphere interhemispheric climate dynamics (Markle et al., 2017; Pedro et al., 2018) and (3) the conceptual understanding of Southern Westerly dynamics during Termination I (Denton et al., 2010; Toggweiler et al., 2006).
Figure 5-8 | Summary plot of hemisphere-wide Southern Westerly proxy-data from 18 – 11 ka showing (a) Lake Rolleston (western Tasmania) µXRF Pb profile reflecting the rate of bedrock weathering in the catchment (greater weathering= more precipitation), (b) Hazards Lagoon (eastern Tasmania) Ca/Ti reflecting changes in evaporative conditions (greater evaporative conditions= less precipitation), (c) core MD03-2611 (southern Australian coast) G.ruber % (higher presence= greater penetration of the Leeuwin Current; De Deckker et al. (2012)), (d) Hollywood Cave (New Zealand Southern Alps) speleothem δ¹⁸O (more depleted values= more precipitation; Whittaker et al. (2011)), (e) core MD07-3088 (Chilean coastal margin, southern South America) ¹⁴C surface reservoir age (younger ages= enhanced upwelling; Siani et al. (2013)), and (f) cores TN057-14, TN057-13 and E27-23 (Southern Ocean) biogenic opal flux (greater opal= enhanced upwelling; Anderson et al. (2009)). ACR= Antarctic Cold Reversal.
Prior to the data presented here, the lack of a robust proxy-dataset from the Australian sector precluded an interpretation of a zonally symmetric (hemisphere-wide) shift in the Southern Westerlies during the ACR, as predicted by Denton (2010) and Toggweiler et al (2006). The results of this thesis reveal zonally symmetric and synchronous changes to terrestrial hydroclimates in Tasmania (Figure 5-7; this study; Fletcher, unpublished), New Zealand (Figure 5-6a, Figure 5-8d; Whittaker et al. (2011)) and Patagonia (Figure 5-6a; Moreno et al. (2015); Moreno et al. (2012); Moreno et al. (2018b)) through the ACR. With further support from Southern Ocean upwelling proxy-data (Figure 5-6a, Figure 5-8e,f; Anderson et al. (2009); Skinner et al. (2010); Siani et al. (2013)) and Leeuwin current dynamics (Figure 5-6a, Figure 5-8c; De Deckker et al. (2012)), these changes can be attributed to an equatorward shift in the Southern Westerlies during the ACR. These findings (1) provide support for the proposed response of the Southern Westerly wind belt to the rapid climatic changes that characterised Termination I in the Southern Hemisphere (Denton et al., 2010; Toggweiler et al., 2006), and (2) reveal that the Southern Westerlies varied in a zonal symmetric manner beyond that previously established last over the last 14 kyr (Fletcher & Moreno, 2011), to at least 16 ka.

5.6.4 IMPLICATIONS FOR GLOBAL CLIMATE CHANGE DYNAMICS

These findings have implications for our understanding of (1) interhemispheric ocean-atmosphere climate dynamics, (2) the internal mechanisms that drive glacial terminations, and (3) the global carbon cycle. The findings provide the first empirical evidence of a hemisphere-wide shift of Southern Westerly circulation through a period of global millennial-scale climate change. The hemisphere-wide data presented here (Figure 5-8) reveals that the Southern Westerly wind belt was displaced southward following the collapse of the Atlantic Meridional Overturing Circulation (AMOC) during Heinrich stadial 1 (HS 1) in the Northern Hemisphere.
(Figure 5-9b; McManus et al. (2004)). It then migrated north (Figure 5-9e-g; Anderson et al. (2009)), coupled with the Intertropical Convergence Zone (ITCZ) (Figure 5-9c,d; Montade et al. (2015), Denniston et al. (2013)), once the AMOC again strengthened and northward ocean-atmosphere heat transport increased during the Southern Hemisphere ACR and Northern Hemisphere Bolling-Allerød (Figure 5-9a,b, i; McManus et al. (2004); WAIS Divide Project Members (2015); Buizert et al. (2014)). The reconstruction of Southern Westerly dynamics in this thesis have provided support for the hypothesis that the relationship between shifts in major atmospheric circulation belts and concomitant changes in ocean circulation can explain synchronous interhemispheric heat transport during periods of rapid climate change (Markle et al., 2017; Pedro et al., 2018), such as Termination I (Denton et al., 2010).

By confirming that the Southern Westerlies shifted equatorward during the ACR coupled with the ITCZ in the Australian sector (Figure 5-9c-g), this thesis also provides support for the leading conceptual understanding of the internal climate mechanisms that drive glacial terminations (Denton et al., 2010; Toggweiler et al., 2006). Denton (2010) and Toggweiler et al (2006) propose the poleward displacement of the Southern Westerlies during Northern Hemisphere stadials (i.e. HS1 and the Younger Dryas) and concomitant Southern Hemisphere warm periods is the critical process that drives atmospheric CO$_2$ concentrations to the levels required to sustain interglacial conditions. This thesis has observed an equatorward shift in the Southern Westerlies (Figure 5-9e-g) coeval with reduced Southern Ocean upwelling (Figure 5-9g) and a plateau in Antarctic ice core CO$_2$ (Figure 5-9h; (WAIS Divide Project Members, 2015)). These results support the proposed relationship between Southern Westerly variation and CO$_2$ during Termination I, adding weight to the contention that the wind belt’s position relative to the Southern Ocean’s critical latitudes is a key regulator of long-term variations in global atmospheric CO$_2$ (Toggweiler et al., 2006; Anderson et al., 2009; Fletcher & Moreno, 2011; Moreno et al., 2010; Saunders et al., 2018; Lovenduski et al., 2008; Le Quéré et al., 2009).
Figure 5-9 | Summary plot showing empirical evidence supporting the role of the Southern Westerlies in atmospheric CO₂ variation and interhemispheric climate dynamics through Termination 1. (a) NGRIP Greenland temperature (Buizert et al., 2014), (b) $^{231}$Pa/$^{230}$Th from core GGC5 off the Bermuda Rise reflecting AMOC strength (McManus et al., 2004), (c) index of coupled ITCZ-Southern Westerly position over South America (Montade et al., 2015), (d) Ball Gown Cave speleothem $\delta^{18}$O reflecting changes in the Indo-Australian summer Monsoon (ITCZ) (Denniston et al., 2013), (e) Lake Rolleston Pb profile reflecting Southern Westerly strength over western Tasmania, (f) Hazards Lagoon Ca/Ti reflecting Southern Westerly strength over eastern Tasmania, (g) Southern Ocean Opal flux reflecting wind-driven upwelling (Anderson et al., 2009), (h) WAIS Divide CO₂ reflecting atmospheric CO₂ concentration (WAIS Divide Project Members, 2015) and (i) WAIS Divide $\delta^{18}$O reflecting Antarctic temperature (WAIS Divide Project Members, 2015). ACR= Antarctic Cold Reversal; HS 1= Heinrich Stadial 1; B-A= Bølling-Allerød; YD= Younger Dryas.
CHAPTER 6: CONCLUSION

This thesis has used proxy information entrained in lake sediments to reconstruct environmental change at two Tasmanian sites through millennial-scale climate event, the Antarctic Cold Reversal (ca. 14.7 – 13 ka; Pedro et al. (2016)). This was undertaken in an effort to deduce changes in the dynamics of the Southern Hemisphere Westerly wind belt through Termination I so that we may improve our understanding of (1) how the Southern Westerlies respond to rapid climate change, (2) their role in coupled ocean-atmosphere interhemispheric climate dynamics, (3) their role in glacial terminations and (4) their influence over the global carbon cycle. This thesis aimed to achieve these objectives by addressing the following research questions:

**RQ 1: How did the hydroclimate of western Tasmania change through the Antarctic Cold Reversal?**

The environmental reconstruction at Lake Rolleston revealed that western Tasmania experienced increased precipitation during the Antarctic Cold Reversal.

**RQ 2: How did the hydroclimate of eastern Tasmania change through the Antarctic Cold Reversal?**

The environmental reconstruction at Hazards Lagoon revealed that eastern Tasmania experienced reduced precipitation during the Antarctic Cold Reversal.

**RQ 3: Did the influence of the Southern Westerlies change over Tasmania through the Antarctic Cold Reversal?**
Yes- a wetter west and drier east indicates that Southern Westerly flow was enhanced over Tasmania through the Antarctic Cold Reversal.

**RQ 4: How did the Southern Westerlies respond to the rapid climate change of the Antarctic Cold Reversal?**

The Southern Westerlies were *displaced equatorward* during the Antarctic Cold Reversal in response to changes in the interhemispheric thermal gradient following the strengthening of the Atlantic Meridional Overturning Circulation.

**Impact of findings**

The proxy-based reconstruction of environmental conditions in western and eastern Tasmanian during the Antarctic Cold Reversal has filled a data-gap that has (1) reconciled proxy-data from the Australian sector with the leading conceptual understandings of ocean-atmosphere interhemispheric climate dynamics (Markle et al., 2017; Pedro et al., 2018) and glacial terminations (Denton et al., 2010; Toggweiler et al., 2006), and (2) revealed hemisphere-wide shifts in the latitudinal position of the Southern Westerlies synchronous with changes in atmospheric CO₂ concentration.

These findings provide an insight into how the highly-influential Southern Westerlies may respond to future human-induced climate change and, somewhat ominously, how they might influence the future rate of CO₂ release from one of the largest carbon sinks on the planet (Frölicher et al., 2015), the Southern Ocean.


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Fletcher, M.-S. (2009). *The Late Quaternary Palaeoecology of Western Tasmania*. (PhD), The Univeristy of Melbourne, Parkville.


Lamy, F., Hebbeln, D., & Wefer, G. (1999). High-resolution marine record of climatic change in mid-latitude Chile during the last 28,000 years based on terrigenous sediment parameters. *Quaternary Research, 51*(1), 83-93.


Mariani, M., & Fletcher, M. S. (2016). The Southern Annular Mode determines inter-annual and centennial-scale fire activity in temperate southwest Tasmania, Australia. *Geophysical research letters.*


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