The Pleistocene Glaciations of Chile

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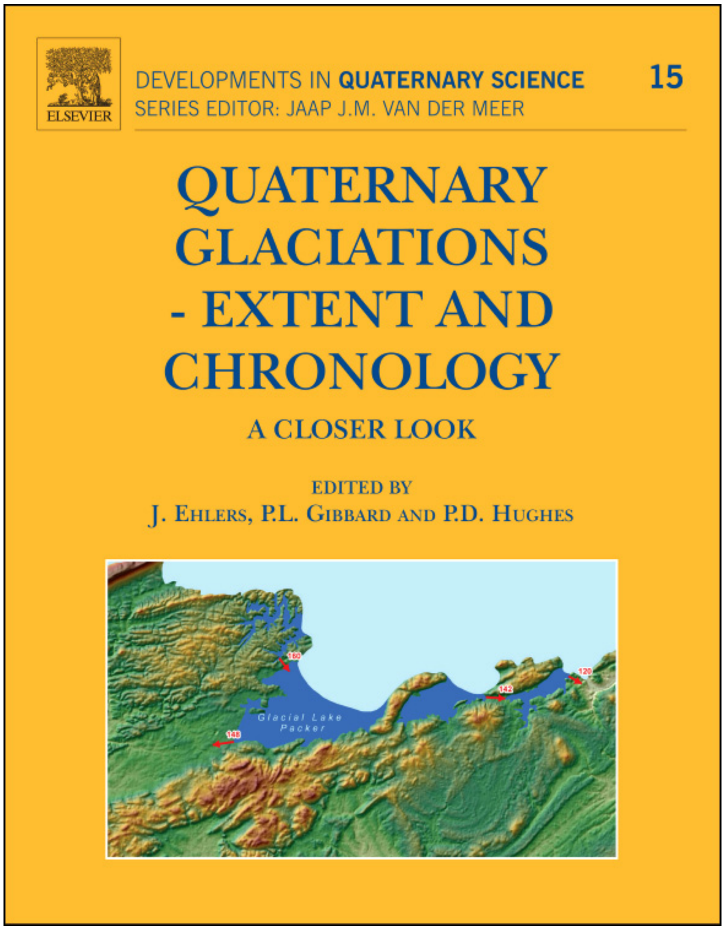

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Chapter 54

The Pleistocene Glaciations of Chile

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54.1. INTRODUCTION

Reconstructing the timing and extent of Quaternary glaciations in Chile (and South America more generally) has the potential to shed light on the nature of inter-hemispheric climate changes during this period and the forcing factors which may have been in operation. Of special interest to palaeoclimatologists is assessments of the timing of local glacial maxima (local LGMs) and the status, extent and timing of rapid climate change events in the Late-Glacial such as the Younger Dryas Chronozone (YDC) and Antarctic Cold Reversal (ACR).

This chapter provides an overview of the Quaternary glaciations of Chile. An earlier review (Harrison, 2004) discussed the scientific research on Chilean glaciations up to that point; the present review will not revisit much of this earlier work but concentrate on the large amount of recent research that has been published, especially in the arid Andes of northern and central Chile and in southern Chile. The chapter builds on a number of important recent reviews of the Late Pleistocene and Holocene glacial history of South America, especially those provided by Rodbell et al. (2009) and Zech et al. (2009).

Over the past few decades, there has been an enormous expansion in the amount of research on the Quaternary history of Chile. Covering 38° of latitude and interacting with important climatic systems such as the southern westerlies and South American Summer Monsoon, Chile has assumed considerable importance as a location where the patterns and timing of Southern Hemisphere climatic events can be reconstructed and where models of global climate change can be tested.

The Andes form one of the world's great mountain ranges and the extreme altitudinal, latitudinal and climatic variability of the Chilean Andes provides the setting for a remarkable range of glacial environments. These include glaciers with low accumulation and discharge rates in high arid mountains glaciers to lacustrine and tidewater calving glaciers which are among the most dynamic on earth.

54.2. THE ANDES

In northern Chile (between 18°S and 30°S), precipitation is low (commonly, 200–300 mm a^{-1}), the contemporary equilibrium line altitude (ELA) is at high altitudes and glaciers and small ice caps exist only on volcanic summits lying above 6000 m a.s.l. (Ammann et al., 2001). In central Chile (defined as lying between 30°S and 40°S), the ELA falls below 4000 m associated with increased precipitation and higher seasonality, and glaciers are common on the higher peaks. South of 37°S, the average altitude of the Andes decreases sharply to ca. 2000 m a.s.l. and glaciers are only found on peaks rising above 4000 m. In southern Chile (between 40°S and 55°S), the average altitude of the Andes lies between 1500 and 3000 m. South to 46°S, the ELA falls to 1800 m a.s.l., reflecting still higher precipitation. Records of atmospheric circulation across southern South America show strong inter-annual, inter-decadal and inter-centennial variability (Glasser et al., 2004). Climatic changes in South America are associated directly or indirectly through long-term (Ma) mountain-range uplift (Hartley, 2003); atmospheric teleconnections, with large-scale atmospheric/oceanic forcing such as the El Niño-Southern Oscillation (ENSO) (Aceituno, 1988; Allan et al., 1995; Diaz and Markgraf, 2000); the temperature gradient between tropical and extra-tropical region; the sea surface temperatures of the South Atlantic and South Pacific Oceans, and the circum-Antarctic ocean circulation (Villalba et al., 1997; Lamy et al., 2004).

Below 46°S, the climate changes to cool maritime and here are located the two last major stores of temperate ice on earth. The North Patagonian Ice cap (NPI) lies between 46°30′S and 47°30′S and covers an area of 3900 km^2. Its outlet glaciers are among the most active in the world and include the lowest latitude tidewater calving glacier, Glaciar San Rafael. The larger South Patagonian Ice cap covers an area of some 14,000 km^2 between 48°30′S and 50°30′S. Both ice masses owe their form and extent to

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the operation of the southern westerlies, interacting with the Humboldt Current, whose vigorous circulation and high precipitation accounts for the high ablation and accumulation rates of the glaciers, their mass balance gradients and outlet velocities. Precipitation ranges from ca. 3000 mm per year on the western seaboard to 10,000 mm per year at 700 m a.s.l. on the ice caps (Aniya and Enomoto, 1986). A marked climatic gradient exists over the icefields, with precipitation totals decreasing markedly to the east of the topographic divide (Harrison, 2010). The location and dynamics of the southern westerlies are important components of the Southern Hemisphere climate, and changes in this system may provide information on the nature and timing of inter-hemispheric climate variations and linkages. The southern westerlies vary in response to changes in the pressure gradients between the subtropical high and subpolar systems. During Late Pleistocene glaciations, it is hypothesised that the position of the westerlies moved north to between 45°S and 50°S, creating the wet/cool conditions that allow glaciation of the Chilean Lake District at 41°S (Hubbard, 1997; Denton et al., 1999a,b; McCulloch et al., 2000). This movement of the pressure systems northwards reduced precipitation between 50°S and 55°S thus inhibiting glacier expansion during glaciations in those latitudes (Hulton et al., 1994). It is assumed that the westerlies returned to their present position during the Late-Glacial, and the reconstruction of their variations is possible through reconstructions of glacier fluctuations and palaeoecological records. However, Zech et al. (2008) follow (Markgraf et al., 1992) by suggesting that this view has been disputed, and these issues are discussed later.

54.3. METHODS

Geomorphological mapping has been widely used to establish former ice limits (e.g. Caldenius, 1932, recently updated and augmented by Glasser et al., 2008). A number of dating techniques have previously been applied to moraine systems in Chile and their associated glacigenic deposits to help reconstruct the Quaternary history of the country. These techniques include radiocarbon (^{14}C) dating of moraines, peat bogs and lacustrine deposits in Patagonia (e.g. Mercer, 1965, 1968, 1976; Aniya, 1995; Denton et al., 1999b; Hajdas et al., 2003; McCulloch et al., 2005a,b). However, in the dry Andes with few opportunities for radiocarbon dating of organic material, accurate dating of glacial deposits has only recently been achieved with the introduction of Cosmogenic Radionuclide Dating (CRN) to these regions (e.g. Zech et al., 2006, 2007, 2009). CRN dating has been used in Patagonia (e.g. Kaplan et al., 2004, 2005, 2007; Fogwill and Kubik, 2005; McCulloch et al., 2005a,b; Douglass et al., 2006). Recently, and for the first time in South America, OSL dating has been used to date glacier fluctuations and in combination with CRN to support glacier chronologies (Winchester et al., 2005; Glasser et al., 2006; Harrison et al., 2008). $^{40}Ar/^{39}Ar$ and K–Ar dating of lava flows interbedded with glacigenic and glaciofluvial deposits has been employed by several workers (Wenzens, 2000, 2006b; Singer et al., 2004). Numerical ice-sheet modelling experiments have also significantly increased our understanding of the extent and dimensions of the former ice sheets and their interaction with former climates (e.g. Hulton et al., 1994, 2002; Sugden et al., 2002; Hubbard et al., 2005).

54.4. THE MAXIMUM GLACIATIONS

While there has been much new research on the glacial history of Chile since 2004, most of it has concentrated (as before) on the Southern Andes, south of 35°. The sensitivity of the southern Andes to climate changes has meant that the most complete evidence for the Pleistocene maximum glaciation (occurring in the middle Pleistocene) has been found here. Much of this evidence comes from glacial sediments deposited to the east of the Andes. In southern Chile, the terminal positions of piedmont lobes from glaciers flowing to the west from the Andes at this time are located, in the main, below sea level.

The conditions suitable for the development of ice caps in southern Chile have probably existed for at least 14 Ma. Mercer (1983; cited in Clapperton, 1993) believed that ice sheets had existed in west Antarctica since the Late Miocene. These ice masses and their ice shelves produce cold, saline bottom water which surfaces as the cold Humboldt Current. This runs northwards up the Pacific coast of South America and cools the moisture-laden westerlies, creating the snow accumulations that nourish the Patagonian ice caps (Clapperton, 1993).

54.4.1. The Chilean Lake District

Early research in the Chilean Lake District between the Andes and the Pacific Ocean at 41–43°S identified four drift sheets on the basis of weathering characteristics of tills, clasts and moraine morphology (Porter, 1981). These drift sheets were taken to represent four glaciations and were assigned local names; the oldest to youngest being the Caracol, Rio Llico, Santa Maria and Llanquihue drifts (see Fig. 54.1). The oldest drift (Caracol) records a less extensive glaciation than does the Rio Llico and demonstrates that Andean glaciers in this sector flowed westwards as a continuous ice front. All the drifts pre-date the Last Glacial Maximum (LGM), although age data from them is patchy. Wood from the Santa Maria Till has given an age of $57.8 \pm 2.3/3.2$ ^{14}C ka BP, but Clapperton (1993) suggests that, in view of the possibility of contamination, it may be much older.

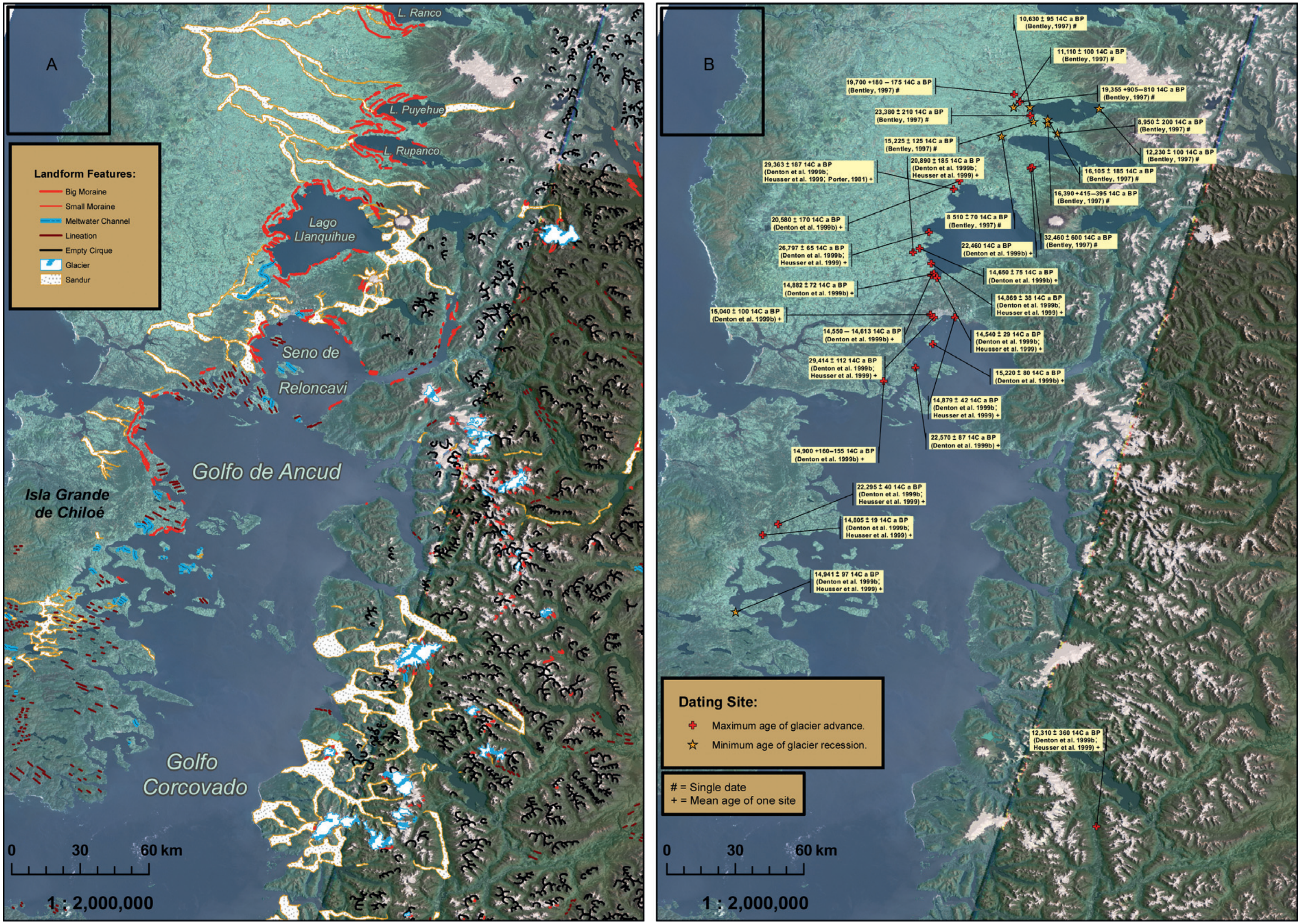


FIGURE 54.1 Data on Quaternary glacial extent in the western Chilean Lake District. The background is a pan-sharpened Landsat-7 image draped over a hillshade of the SRTM 90 m DEM. (A) Glacial geomorphology adapted from the mapping of Glasser et al. (2008). (B) Information on glacial extent from published dates, divided into those that provide maximum ages for glacier advance (crosses) and those that provide minimum ages for glacier recession (stars). The ages and sources of information are provided on the labels, which also indicate whether these represent a single date or the mean age of more than one date. This figure was prepared by Ingo Wolff.

54.4.2. The Patagonian Icefields

Current understanding of the terrestrial extent of the former Patagonian Ice Sheets owes much to the pioneering study of Caldenius (1932) who first mapped moraine systems to the east of the contemporary icefields. Caldenius (1932) distinguished four separate moraine belts, and he concluded from their state of preservation that the three inner moraine systems were relatively young. In accordance with the stages of the last Weichselian Glaciation in northern Europe, Caldenius named the three moraine limits (from inner to outer) the 'Finiglacial', the 'Gotiglacial' and the 'Daniglacial'.

The Finiglacial moraines were correlated to the LGM and the Daniglacial and the Gotiglacial moraine systems to the middle Pleistocene (Mörner and Sylwan, 1989). The fourth (outermost) moraine system, termed the 'Initioglacial' by Caldenius (1932), is still poorly constrained in age, but is thought to be between 1.1 and 2.3 Ma in age (Mörner and Sylwan, 1989; Singer et al., 2004). Rabassa et al. (2005) have argued from a synthesis of records that the oldest known Patagonian glaciations took place between approximately 7 and 5 Ma but moraine systems from these glaciations are not preserved and their occurrence is inferred mainly on stratigraphic and sedimentological grounds. Rabassa et al. (2005) suggest that a minimum of eight glaciations occurred in the Middle–Late Pliocene (Marine Isotopic Stages 54–82). The 'Great Patagonian Glaciations' developed between 1.168 and 1.016 Ma (MIS 30–34; Early Pleistocene).

Outside the LGM Fenix moraines at Lago Buenos Aires (Fig. 54.2), the Moreno moraines have been dated to 140–150 ka (Kaplan et al., 2004). To the east and outside these are another set of moraines dated to <1016 ka but >760 ka (Singer et al., 2004). The maximum extent of glaciation is dated to ca. 1100 ka (Singer et al., 2004). These ages are contested, however; Wenzens (2006a) has argued on geomorphological grounds (mainly the relationship between the moraines and dated outwash terraces) that both the Fenix and Moreno moraines are in fact LGM in age.

54.4.3. The Magellan Straits

There is evidence for pre-LGM glacial advances in the Magellan Straits area and Bahía Inútil at Punta Dungeness, Punta Angostura and Segunda Angostura (see Fig. 54.3). The moraine belts are some 50 km apart and 10 km wide. Recent work has suggested that the Segunda Angostura moraine is a composite feature, possibly formed by three different glacier advances. Using relative age determinations based upon weathering of moraines and surface clasts, Porter (1989) correlated three sets of moraines on both sides of the Magellan Strait. Shells incorporated into the Primera Angostura moraine yielded infinite radiocarbon ages of greater than 47.0 ^{14}C ka BP (Clapperton, 1993). The advanced weathering of these moraines compared to the younger (probably Last Glaciation age) Segunda Angostura moraines suggests that they may be of pre-Last Glaciation age and perhaps are as old as 140 ka. On the basis of this estimate, Porter (1989) argued for an age of between 0.74 and 1.2 Ma for the moraines at Punta Dungeness. Since there is evidence of more than one glaciation at Segunda Angostura, Clapperton (1993, p. 357) believes 'that the drifts of possibly all major Quaternary glaciations are present along Magellan Strait'. Later work (Clapperton et al., 1995) argues that the maximum extent of glacial ice occurred during the early part of the last glacial cycle, possibly before 30,000 years ago.

54.5. THE EARLY/MIDDLE WEICHSELIAN/ WISCONSINAN GLACIATION

54.5.1. Dry Andes

In the dry Andes of northern and central Chile (30°S), Zech et al. (2006, 2007) have used CRN to date extensive glacial advances in the Cordon de Dona Rosa to 42/39 ka BP. The central Andes are an important region for Quaternary research, as they are situated in the transition zone between the tropical and mid-latitude atmospheric systems (Zech et al., 2006). However, until recently, the absence of organic material for dating has restricted the opportunities for glacier reconstruction (Ammann et al., 2001). Zech et al. (2006) used CRN on moraines dated to around 32 ka and speculate that these pre-LGM glacier advances were driven by increased precipitation in association with a northward movement of the southern westerlies in response to increased Antarctic sea ice extent (Mosola and Anderson, 2006).

54.5.2. The Chilean Lake District

In this region, large moraine complexes are common on the western sides of the major lakes (Fig. 54.1). Commonly three ridges and associated outwash deposits are found and have been regarded as Last Glaciation in age (Porter, 1981; Mercer, 1983); the largest and most extensive of these moraines are the outermost in the sequence. Glacial deposits and landforms assigned to Marine Isotope Stage (MIS) 4 and 3 have been assigned the chronostratigraphical term 'Llanquihue' by Clapperton (1993) since the moraine sequence in the vicinity of Lago Llanquihue in the Chilean Lakes District of southern Chile is the most closely dated sequence from the country. The stage Llanquihue I records glacier advances from 70 to 65 ka; Llanquihue II covers the period from 28 to 18 ka and Llanquihue III from 15 to 14 ka. The latter two advances are described in the next section. Radiocarbon dating of a log from peat deposits overlain by tills in the outermost moraine complex of

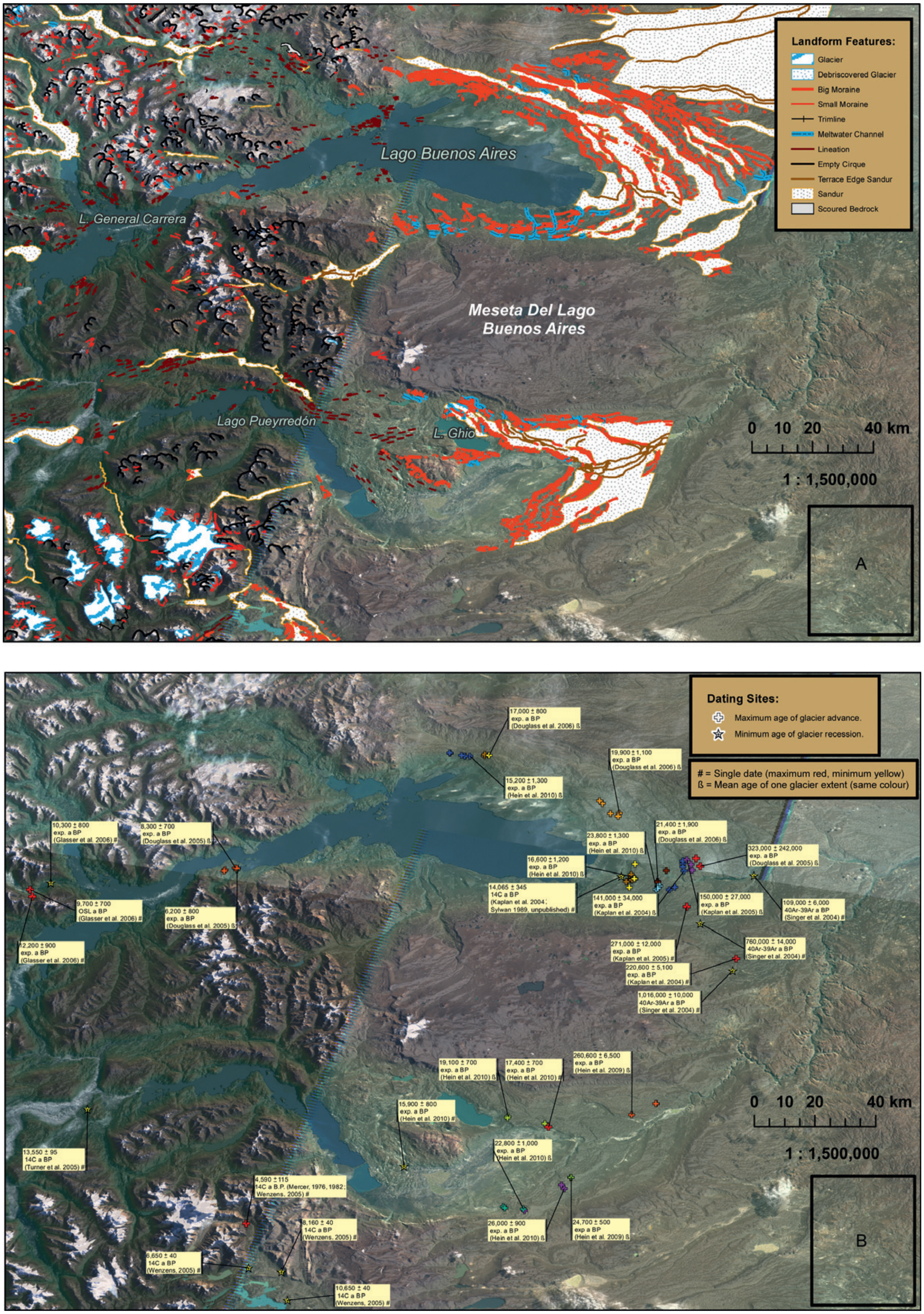
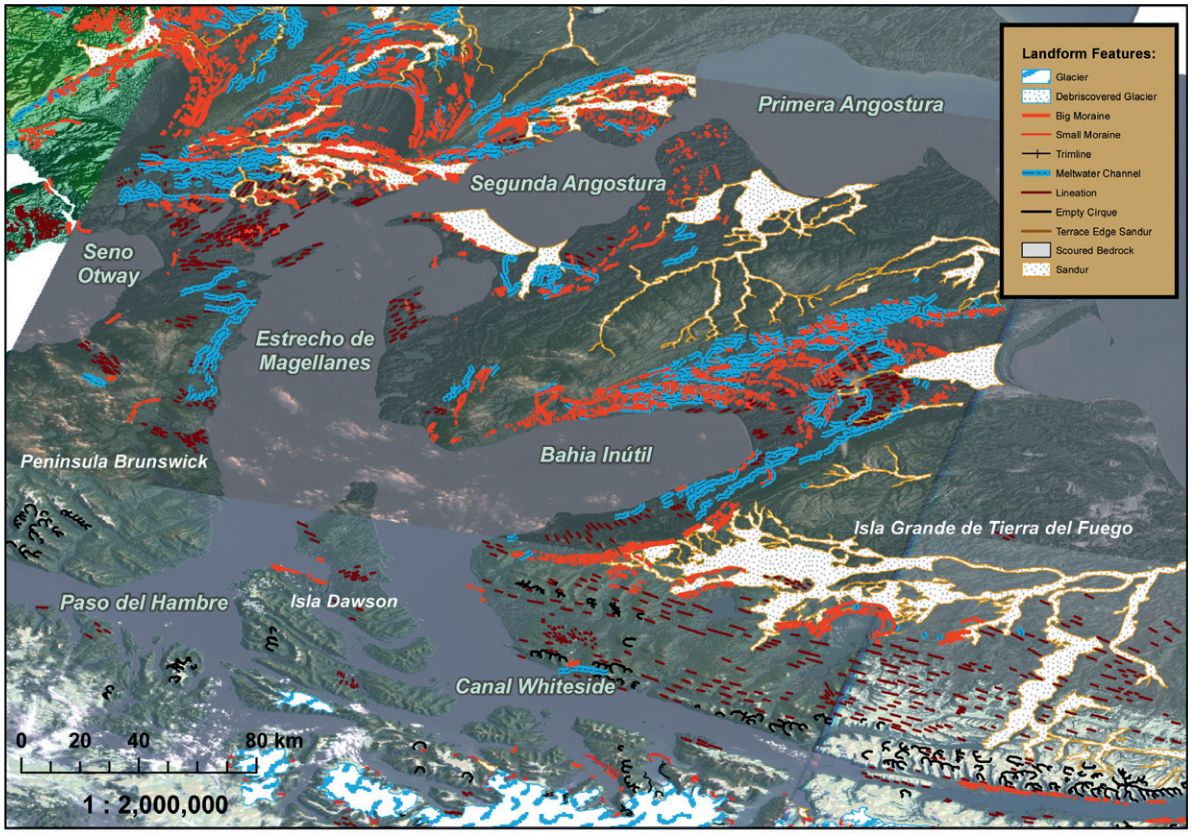


FIGURE 54.2 Data on Quaternary glacial extent in the Lago Buenos Aires–Lago Pueyrredon area. The background is a pan-sharpened Landsat-7 image draped over a hillshade of the SRTM 90 m DEM. (A) Glacial geomorphology adapted from the mapping of Glasser et al. (2008). (B) Information on glacial extent from published dates, divided into those that provide maximum ages for glacier advance (crosses) and those that provide minimum ages for glacier recession (stars). The ages and sources of information are provided on the labels, which also indicate whether these represent a single date or the mean age of more than one date. This figure was prepared by Ingo Wolff.



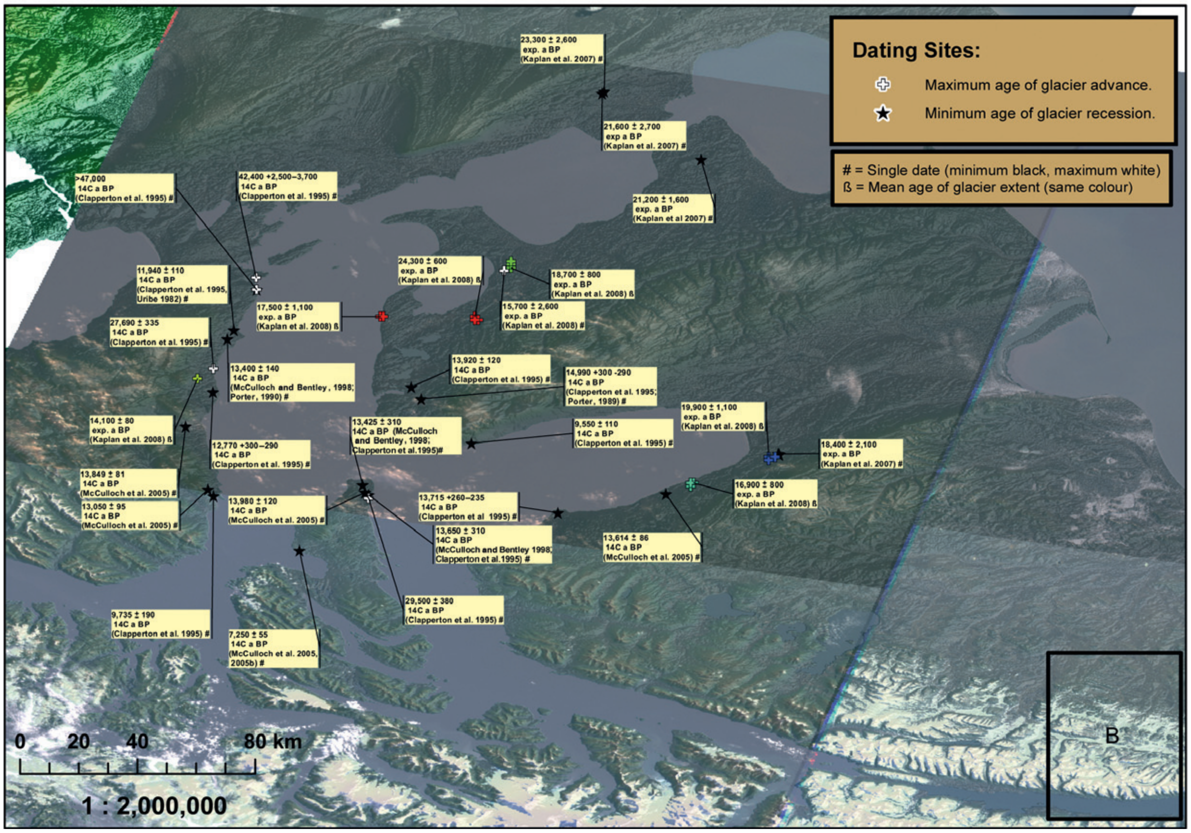


FIGURE 54.3 Data on Quaternary glacial extent in the Magellan Strait region. The background is a pan-sharpened Landsat-7 image draped over a hill-shade of the SRTM 90 m DEM. (A) Glacial geomorphology adapted from the mapping of Glasser et al. (2008). (B) Information on glacial extent from published dates, divided into those that provide maximum ages for glacier advance (crosses) and those that provide minimum ages for glacier recession (stars). The ages and sources of information are provided on the labels, which also indicate whether these represent a single date or the mean age of more than one date. This figure was prepared by Ingo Wolff.

Llanquihue I near Puerto Varas has shown them to be older than 39 ^{14}C ka BP. Other evidence from the northern part of the region suggests that the glaciers during the Last Glaciation reached their maximum positions before about 40 ka BP. Zech et al. (2008) argue that this indicates drier conditions during the course of the last glaciation from 40 to 18 ka and a southwards movement of the westerlies over this time period.

On the basis of the oxygen isotope record from deep sea cores, Mercer (1983) concluded that Llanquihue I moraines probably represented a glacier advance at about 73 ka and were therefore of MIS 4 age. Further evidence that the Llanquihue I moraines pre-date the LGM was presented by Heusser (1981) from radiocarbon dating of peat from kettle holes inside the outermost Llanquihue I moraine on Isla Chiloé. The peat deposits (at Taiquemo, 8 km west of Quemchi) were dated to 42.7 ± 1.2 ka, and this date supports the pattern of glaciation and moraine development suggested by Mercer (1983) and Laugenie (1984) from the Lago Llanquihue area, although this date is probably a minimum age. Evidence for interstadial conditions occurring between cold phases of the Last Glaciation is also available from the Chilean Lake District. Pollen analysis of cores from peat basins to the west of the glaciation limit shows that climatic conditions varied considerably from >43 to 28 ka Heusser (1981, 1983). Between 45 or so and 28 ka, conditions in the region were warm and dry. Following 28 ka, pollen taxa show the onset of very cold conditions reflecting the climatic deterioration of the LGM.

54.5.3. The Patagonian Icefields

Marking the eastern end of Lago Buenos Aires, moraines stratigraphically within the limits of the 'Greatest Patagonian Glaciation' of 1.1 Ma are a series of pre-LGM moraines. These represent glacial advances dated to 140–150 ka (MIS 6) (Kaplan et al., 2005). Further south in the Lago Pueyrredón valley, Hein et al. (2009) dated moraines from the 'Hatcher Glaciation' to 260 ka (MIS 8).

54.6. THE LAST GLACIAL MAXIMUM AND LATE-GLACIAL

With the introduction of radiometric dating techniques, many of the moraines of Chile which were assumed to have been constructed during the LGM (MIS 2) have been shown to span a much longer period of the Pleistocene (Clapperton, 1993). However, many moraine complexes (especially those from drier northern Chile) are undated. Nonetheless, moraines of probable LGM age are found throughout the country and, especially in the Chilean Lake District and in Patagonia, are chronologically reasonably well constrained.

54.6.1. Northern and Central Chile

High snowlines (above 5000 m a.s.l.) and aridity throughout much of the Pleistocene have meant that the high mountains and volcanoes of the northern Andes display relatively little evidence for glacier advance during the LGM. Earlier work (e.g. Clapperton, 1993) reported that some summits above 5000 m a.s.l. in northern Chile were probably unglaciated throughout the Pleistocene and only the highest summits (above 6000 m) may have LGM-age moraines. More recent studies have demonstrated considerable climatic shifts in northern Chile at this time.

In the Cordon de Dona Rosa, glacier advances are dated to the Late-Glacial (ranging from 19 to 15 ka BP) and to 18–13 ka BP in the Encierro valley (Zech et al., 2006; Fig. 54.4). Climate reconstructions from northern Chile suggest that increased winter precipitation may have triggered the early LGM glacial advances; with increasing aridity following the LGM glaciers became more restricted (Stuut and Lamy, 2004; Maldonado et al., 2005).

54.6.2. Southern Chile

After the Great Patagonian Glaciations, 14–16 cold (glacial/stadial) events alternated with corresponding warm (interglacial/interstadial) equivalents (Rabassa et al., 2005). They argue that the LGM occurred between 25 and 16 ka (MIS 2; Late Pleistocene) and that two readvances (or still stands) took place during the Late-Glacial (15–10 ^{14}C ka BP). During the Quaternary, the Patagonian icefields expanded and contracted in response to this climatic forcing a number of times (Heusser, 2003; Harrison, 2004; Sugden et al., 2005). At times they coalesced to form the much larger Patagonian Ice Sheet. Modelling studies (Hulton et al., 1994, 2002) and evidence from marine sediment cores (Lamy et al., 2004; Kaiser et al., 2007) are in close agreement that the regional ice maximum coincided with an ~6 °C sea surface temperature lowering in the southeast Pacific off southern Chile.

54.6.3. The Chilean Lake District

Mercer (1976) provided the first radiocarbon dates for the terminal moraines around the largest lake basin, at Lago Llanquihue, demonstrating that the innermost moraines belonged to the last glaciation and that there had been at least three, and probably four, prior advances. The glacial maximum occurred at ca. 19.45 ka, and a final advance reached the western shore of Lago Llanquihue at 13 ka. Porter (1981) confirmed and refined the chronology with many more radiocarbon dates and demonstrated that the advances occurred before 30 ka, between 20 and 19 ka, and shortly after 13 ka. More recent work on the timing of Llanquihue glacial advances has yielded a more comprehensive picture of Lake District glaciation (Bentley, 1997; Denton et al.,

FIGURE 54.4 Early LGM lateral moraines from the Encierro valley in the arid Andes of Chile. Picture by Zech.

1999b; Anderson et al., 1999). Denton et al. (1999b) dated LGM positions to the interval 29.4 to 14.55 ^{14}C ka BP with a maximum extent at ca. 21 ^{14}C ka BP. The high-resolution radiocarbon chronology of Lowell et al. (1995) identified at least six glacier advances during the later part of the last glaciation. Radiocarbon dates on three glacier lobes (Llanquihue, Seno Reloncavi, Castro) have established that advances occurred at least once before 35, at 29.2, 26.9, 23.1 and 21 ka, and between 14.5 and 14.7 ka (Fig. 54.1). Unfortunately, no data exist for the ages of the glacier advances east of the Andes in this sector.

Work in the region by Lowell et al. (1995) and Denton et al. (1999b) supported by 450 radiocarbon dates has refined the chronostratigraphy of MIS 2 in this region (see Fig. 54.1). The moraine chronology shows that full glacial conditions existed almost without interruption throughout the period from 29.4 to 14.5 ^{14}C ka BP, although pollen evidence from Isla Grande de Chiloe suggests that full glaciation did not commence there before about 26 ^{14}C ka BP. During the advances of the LGM, this work suggests that the snowline was depressed by about 1000 m compared to today.

The ^{14}C dates in the northern Chilean Lake District indicate that the piedmont lobes reached their maximum extent during the LGM sometime between 29.4 and 14.5 ^{14}C ka BP (Bentley, 1997; Denton et al., 1999b). The southern lobes also advanced to maximum positions some time before 49.9 ^{14}C ka BP (Denton et al., 1999b). There is therefore reasonable certainty that the large arcuate moraines formed in front of glaciers 1–13 represent a number of separate advances, most recently during the LGM. The expansion of glaciers into the Chilean lake basins occurred during an interval of known global cooling, but it has also been suggested that the advance was driven largely by a northwards migration of the polar front, which resulted in a substantial increase in precipitation in the Lake District (Heusser, 1989, 1990; Hulton et al., 1994; Lamy et al., 2004).

From a synthesis of key proxy records, McCulloch et al. (2000) concluded that there was a sudden rise in temperature that initiated deglaciation of the Patagonian Ice Sheet synchronously over 16° of latitude at 14.6–14.3 ^{14}C ka BP (17.5–17.15 ka). There was a second step of warming in the Chilean Lake District at 13–12.7 ^{14}C ka BP (15.65–15.35 ka), which saw temperatures rise to close to modern values. A third warming step, particularly clear in southern Chile, occurred ca. 10 ^{14}C ka BP (11.4 ka). Following the initial warming, there was a lagged response in precipitation as the westerlies, after a delay of ca. 1.6 ka, migrated from their northern glacial location to their present latitude, which was attained by 12.3 ^{14}C ka BP (14.3 ka) (McCulloch et al., 2000). Recent work in the Chilean Lake District (Massaferro et al., 2010) used pollen and chironomid records to argue that the latter part of the LGM (at 20–17.6 ka) was characterised by extreme cold and wet conditions, followed by gradual warming until

16.8 ka. Noticeable cooling started after 14 ka, correlating with the ACR and this intensified from 13.5 to 11.5 ka, coincident with the end of the ACR and YDC.

54.6.3.1. North Patagonian Icefield Region

East of the North Patagonian Icefield, glacial lineations indicate that ice discharge was concentrated into large, fast-flowing, topographically determined outlet glaciers (Glasser et al., 2005, 2008; Glasser and Jansson, 2005). Dates for advances of these eastern outlet glaciers have been obtained from CRN dating (Kaplan et al., 2004, 2005, 2006; Turner et al., 2005; Douglass et al., 2006), using ^{40}Ar/^{39}Ar and K–Ar dating (Singer et al., 2004), ^{14}C dating (Wenzens, 2006b) and using a combination of CRN and OSL dating (Glasser et al., 2006). The area at the eastern end of Lago General Carrera/Lago Buenos Aires in Argentina is one of the most comprehensively dated in this area of South America. Working eastward from the lake shore, the youngest moraines here (the Menucos moraines) have been dated to 14.4 ka (Douglass et al., 2006). The next moraine system to the east, the Fenix moraines, has been dated to the LGM at between 15 and 23 ka (Kaplan et al., 2004). To the south of here recent work by Hein et al. (2010) in the Lago Pueyredòn Valley used CRN to date boulders on Rio Blanco moraines to 27–25 ka.

54.6.3.2. South Patagonian Icefield Region

The terminal moraines at the heads of Lago Viedma and Lago Argentino have been dated to the LGM by Wenzens (1999, 2005). Further west, at Puerto Bandera, the prominent moraines that protrude into Lago Argentino have been dated to between 10.39 and 13.0 ^{14}C ka BP (Strelin and Malagnino, 2000). Recession from the Puerto Bandera moraines is indicated by dates of 6.74±0.13 and 10.0±0.14 ^{14}C ka BP from within this limit (Mercer, 1968). To the south, around the margins of the contemporary South Patagonian Icefield (SPI) in the Torres del Paine area, Marden and Clapperton (1995) defined the LGM extent at a point only ca. 70 km from the contemporary icefield. Younger moraines, located closer to the contemporary SPI, are dated to 13.2±0.8 ka (Fogwill and Kubik, 2005) and between 9.1 and 12.7 ^{14}C ka BP (Marden and Clapperton, 1995). Other moraines in the region, although stratigraphically similar to LGM moraines, remain undated (Fig. 54.5).

54.6.3.3. The Magellan Straits and Bahía Inútil (53–55° S)

Much of the research in this region by researchers such as Coronato et al. (1989), Coronato (1995), Clapperton (1993), Clapperton et al. (1995), Benn and Clapperton (2000) and

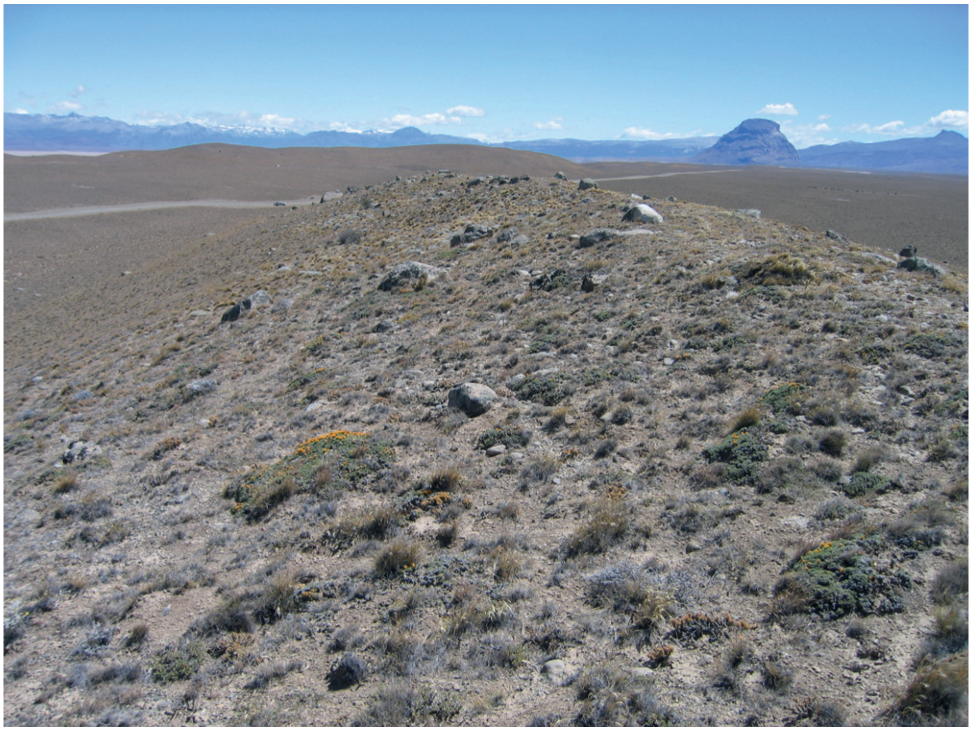


FIGURE 54.5 Undated moraines to the east of the SPI. Photograph by Glasser.

McCulloch and Davies (2001) in southernmost Patagonia was reviewed by Harrison (2004). Large moraine complexes, consisting of multiple moraine sets and associated glacial lineations, are developed in the areas occupied by former outlet glacier in Seno Skyring, Seno Otway, Estrecho Magallenes and Bahía Inútil. The LGM in this area is reasonably well established at 23–25 ka for a terminal moraine in the Magellan Strait (McCulloch et al., 2005a, b) and 18–20 ka in Bahía Inútil (McCulloch et al., 2005a, b; Kaplan et al., 2007). A deglacial recessional stage of the LGM (between 10.315 and 12.7 ^{14}C ka BP) on Isla Dawson has also been reported by Rabassa et al. (1986) (Fig. 54.3).

Recently, Kaplan et al. (2008) used CRN, amino acid dating and reviewed earlier ^{14}C dating from this region of southernmost Patagonia. CRN dates on moraines mapped by Bentley et al. (2005) show glacial advances at 24.6±0.9 ka, 18.5±1.8, and 17.6±0.2 in the Magellan Straits and 20.4±1.2 and 17.3±0.8 ka in Bahía Inútil (Kaplan et al., 2008). Late-Glacial moraines dated to 15.5 and 11.7 ka by radiocarbon dating are located at the head of the Straits of Magellan and Bahía Inútil (McCulloch et al., 2005a,b). Kaplan et al. (2008) argue that the last glaciation in southernmost Patagonia began around 31 ka, with the maximum ice extent at 25 ka and with major ice recession occurring after 19 ka. Following the LGM, ice recession was very rapid in response to warming. They compare LGM and Late-Glacial events from the Magellan Straits area with reconstructed glaciations from Lago Buenos Aires and show that in both regions 4–5 moraine belts were constructed between 25 and 16 ka. The timing of deglaciation differs, however; the Magellan Straits were largely ice-free by 17 ka, while to the north at Lago Buenos Aires, ice was still extensive at 15–14 ka (Fig. 54.3).

54.7. GLACIATION DURING THE YOUNGER DRYAS CHRONOZONE AND ANTARCTIC COLD REVERSAL

Assessing the global significance of the Younger Dryas cold event is of considerable interest to palaeoclimatologists wishing to test hypotheses on the timings and forcings of global climate change. There are several views on the nature of climate change in southern South America during the last Glacial–Interglacial transition, although the final pattern is likely to be more complex than any of them. The first recognises the dominance of Antarctic climate signals in the palaeoclimate record and thus the existence of an antiphase relationship between Northern and Southern Hemisphere climates at this time (Blunier et al., 1998). Similar views support this bipolar see-saw relationship driven by changes in deep-water formation at high latitudes (Broecker, 1998). The second main view argues that there is an in-phase synchronous relationship between the hemispheres (e.g. Denton et al., 1999a,b) suggesting that the trigger for climate change at this time was atmospheric rather than oceanic in origin.

It is clear that resolution of these issues is crucial to our understanding of inter-hemispheric climatic teleconnections during the Pleistocene. The Younger Dryas in the Northern Hemisphere was associated with a strong April–July insolation maximum, a period of Milankovitch cyclicity unfavourable for ice-sheet growth (e.g. Berger, 1990). In the Southern Hemisphere, the winters at this time would have been relatively shorter than now, and therefore, the accumulation phases of glacier mass balance might well have been less effective. This could have tended to reduce the impact of Younger Dryas forcing on ice cap and glacier growth. The role of Milankovitch cyclicity should therefore be borne in mind when discussing the likelihood of Younger Dryas glacier expansion in Chile.

In southern South America, however, identifying climate changes during the YDC is hampered by the presence of other cooling events at around this time, notably the ACR, a period of lower temperatures recorded in Antarctic ice cores, at 14.8–12.7 ka BP (Blunier et al., 1997, 1998; Raynaud et al., 2000; Blunier and Brook, 2001; Ahn and Brook, 2008).

Recent studies in the Torres del Paine region of Patagonia (Moreno et al., 2009) have clarified the relationship between Late-Glacial cold events in this region. Using CRN and ^{14}C dating, they show that the Late-Glacial maximum readvance in southwest Patagonia occurred at 14.8–12.6 ka at the time of the ACR EPICA Dome C record (Stenni et al., 2003). Like other researchers in the region, they found no evidence for an YDC glacial event and suggest that the pattern and timing of Late-Glacial climate change in southern South America is latitudinally dependent (cf. Sugden et al., 2005) and argue that the position of the Antarctic Polar Front determines the strength of Late-Glacial cooling signals.

The geomorphological and palaeoecological evidence for a general Younger Dryas glacier advance in Chile is therefore equivocal (Markgraf, 1993). Numerous, undated moraines exist within the LGM limit and outside Neoglacial limits, and this has tempted some workers to suggest that they represent glacial advances coeval with the Younger Dryas (e.g. Marden and Clapperton, 1995). Similarly, there is some pollen core evidence of climate changes at this time, although other studies find no evidence for these changes. The evidence discussed here comes from the Chilean Lake District, various locations around the North and SPIs and from Tierra del Fuego.

The evidence to show cooling from palaeoecological studies in the vicinity of the Chilean Lake District and the North Patagonian Icefield is certainly ambiguous. Some workers show a climate shift during the Pleistocene–

Holocene transition (e.g. Heusser, 1993), although other workers do not (Ashworth et al., 1991; Markgraf, 1991, 1993; Lumley and Switsur, 1993; Bennett et al., 2000).

54.7.1. The Chilean Lake District

Little geomorphological evidence has yet been reported from the Chilean Lake District which can be attributed to Younger Dryas glacier advances. However, at around 41°S, a glacial advance at Lago Mascadi has been dated using radiocarbon dating to between 11.4 and 10.15±0.09 ^{14}C ka BP (Hajdas et al., 2003), preceding the Younger Dryas by around 550 years. Generally, though, the glacier/climate record in this region is (as elsewhere) partly obscured by the presence of deep lakes into which the glaciers must have advanced. These created the conditions for glacier calving and this partly decoupled the glacier fluctuations from climate change. As a result, glacier expansion during short-lived episodes of climate deterioration may have been attenuated by an increase in calving fluxes.

The main evidence for a Younger Dryas climatic reversal in this region comes from palaeoecological reconstructions by Heusser and Streeter (1980), Heusser (1984) and Heusser et al. (1999). The latter work demonstrates that from 12.2 to 10.0 ^{14}C ka BP, there was an expansion of cold-tolerant species and an opening of the forest canopy and suggests that this reflected a temperature decrease in the order of 2–3 °C. This argument is countered by work which suggests that changes in some of the indicator species used by Heusser et al. (1999) may be related more to changes in soil and groundwater levels than to changes in climate (Markgraf, 1989). In addition, the fossil beetle records do not support the evidence for a cooling in this period (Hoganson and Ashworth, 1992; Ashworth and Hoganson, 1993). Near Alerce in the Chilean Lake District at 41°S, Heusser and Streeter (1980) employed palynology to show reduced temperature and increased precipitation at around 10.4 ^{14}C ka BP.

54.7.2. The Patagonian Icefields

Although large moraine systems lying outside the Holocene glacier limits exist around the margins of the NPI and SPI, very few of these have been dated. The only information about the likely climatic conditions that prevailed during the Younger Dryas period around the NPI comes from pollen analysis and radiocarbon-dated organic sequences in small lakes on the Taitao Peninsula, to the west of the icefield. These results (Lumley and Switsur, 1993; Bennett et al., 2000) show that there is no evidence for a climatic deterioration in the region during the YDC. Indeed, Bennett et al. (2000, p. 326) argue that 'the YDC was in fact a period of stable, or possibly slightly increasing, temperatures'. This supports earlier results by Hoganson and Ashworth (1992) who used beetle remains to suggest that no cooling occurred during this time in the region. In addition, in southern Patagonia, White et al. (1994) presented evidence for considerable warming at 10.0 and 12.8 ^{14}C ka BP. Further south in the Chilean Channels, Ashworth et al. (1991) report similar findings. However, Massaferro and Brooks (2002) used chironomid data from the Taitao Peninsula to show cooling during the YDC.

The geomorphological evidence for glacier expansion during the YDC is similarly equivocal and hampered by the absence of well-dated moraine sequences in the outlet valleys. The only moraines dated from this time are from the Exploradores valley of the NPI where Glasser et al. (2005) used CRN dating and OSL methods to date a significant glacial advance between 12.5 and 9.6 ka.

South of the NPI, there is conflicting evidence for the nature of climate change during Younger Dryas times. Recent retreat of Glaciar Tempano (48°45′S) exposed organic deposits dated to 11.07±0.16 and 11.1±0.17 ^{14}C ka BP (Mercer, 1976). This suggests that there was no Younger Dryas advance of the glacier beyond its twentieth century limit. However, a number of workers have identified large moraines lying within the limits of the LGM and around the margins of the SPI (e.g. Caldenius, 1932; Mercer, 1976; Clapperton, 1983), and it may be that these represent a glacier advance during the Younger Dryas. At the present, few of these moraines have been closely dated. Clapperton (2000) hypothesises that they may correlate with moraine stages in the Chilean Lakes region (although no Younger Dryas moraines have been found here) and the Magellan Straits. Marden (1997) dates end moraines in the region to between 11.88 and 9.18 ^{14}C ka BP. At Glaciar Grey on the southern side of the SPI, a glacial advance dated by tephrochronology occurred between 12.01 and 9.18±0.12 ^{14}C years BP (McCulloch et al., 2000). Ackert et al. (2008) use CRN to date the Puerto Bandero moraine on the eastern flank of the SPI to 10.8±0.5 ka, near the end of the YDC, contemporaneous with the highest shoreline of Lago Cardiel. They suggest that these events show that increased precipitation during YDC times rather than cooling drove glacier behaviour.

54.7.3. The Magellan Straits

Ice had retreated into several of the upland valleys of the Cordillera Darwin by 13.3 ^{14}C ka BP (Clapperton et al., 1995; McCulloch and Bentley, 1998). Between 12,700 and 10.3 ^{14}C ka BP, the ice readvanced to the north up the Straits of Magellan, and the culmination of this is constrained by tephrachronology to 12.01 and 10.3 ^{14}C ka BP. This period spans the ACR (McCulloch et al., 2000). Palaeoenvironmental information covering this time period has been gathered by Accelerator Mass Spectrometry

(AMS) dated pollen and diatom cores from the Straits of Magellan. The evidence to show significant climate change at the time of the ACR or YDC is ambiguous; between 12.3 and 10.3 ^{14}C ka BP, there were numerous and short-lived changes between heathland and grassland but these variations in vegetation do not necessarily represent temperature changes. Slightly wetter conditions are indicated by the transitions to heathlands and these increases in precipitation might have been sufficient to trigger glacier advances. At 10.3 ^{14}C ka BP, the arrival of *Nothofagus* signals a rise in temperature; after this, a period of aridity occurred until ca. 8.5 ^{14}C ka BP.

54.8. DISCUSSION

While a number of patterns may be discerned in the timing and extent of glaciations in Chile. The most complete evidence of Pleistocene glacier fluctuations and associated palaeoenvironmental reconstructions comes from the well-dated moraine sequences and palaeoecological information covering the LGM.

In the arid mountains of northern and central Chile, the limited available evidence suggests an 'early' LGM at 42–39 ka (Zech et al., 2009; see Fig. 54.4). In southern Chile, there appears to be a regionally synchronous LGM at around 27–25 ka which is also generally in-phase with the global LGM (Schaefer et al., 2006), followed by a readvance in several locations which is probably related to the ACR at 14.8–12.7 ka.

After this, Chile warmed synchronously and deglaciation followed. This pattern is nearly global in extent and Denton (2000) argues that this may reflect changes in oceanic deep-water production. However, as McCulloch et al. (2000) note, the evidence shows that there was no time lag between deglaciation in the Northern Hemisphere and southern South America. Glaciation in the Chilean Lake District is probably associated with, and partly driven by, northward movement of the southern westerlies belt (e.g. Moreno, 1997; Denton et al., 1999b) concomitant with northward expansion of Antarctic sea ice (e.g. Heusser, 1989). In Magellan Straits area, Benn and Clapperton (2000) argue on the basis of geomorphological evidence that permafrost was present at sea level during the LGM. The capacity of such cold air masses to hold moisture would be relatively reduced, and as a result, glacier expansion may have been limited by accumulation. McCulloch et al. (2000) suggest that after deglaciation, it took some 2500 years for the southern westerlies to move south to their present position in the vicinity of 50°S. They further suggest that this southerly movement of the westerlies occurred following reorganisation of the oceans after the last termination. This took place after a delay of 1600 years, took about 2500 years to complete and the delay coincides with the Heinrich 1 iceberg discharge event in the North Atlantic (Denton, 2000). They hypothesise that this event suppressed thermohaline circulation and reorganisation of the oceans occurred only after this was restarted, allowing the southerly movement of the westerlies from the latitudes of the Chilean Lake District. McCulloch et al. (2000, p. 415) conclude that 'This scenario explains the ca. 1.6 ka wet transitional period following the initial warming in the Chilean Lake District and the precipitation peaks in the Taitao and Magellan areas some 2.5 ka after the initial warming'. However, it should be noted that there is debate over the position of the southern westerlies at this time. Markgraf (1989) and Markgraf et al. (1992) argue that the southern westerlies were positioned further south during the LGM. Markgraf and Kenny (1997) further suggest that the southern westerlies did not vary their latitudinal position seasonally as much as at present and were located around 43–45°S. In addition, glacier–climate modelling studies from northern Chile by Kull and Grosjean (2000) suggest that an equatorward displacement of the westerlies cannot account for the Late Pleistocene glaciation in the region.

54.8.1. Some Problems

Harrison (2004) identified a number of unresolved problems which had to be addressed before a more complete understanding of Pleistocene glaciations in Chile could be achieved. Six years later, at least five pressing issues can be identified; several of them (the status of Younger Dryas-age and Neoglacial glacier advances) have direct relevance to understanding the nature of climate linkages between the hemispheres during cold climate episodes.

54.8.1.1. Glaciation of Western Patagonia

With the exception of three mid-Holocene radiocarbon dates obtained from two western outlet glaciers of the SPI (Mercer, 1970) and research on the moraines of the San Rafael Glacier on the NPI, very few moraines older than late Holocene have been dated on the western flanks of the Patagonian icefields. In addition, and with few exceptions (Glasser et al., 2006; Harrison et al., 2008), the bulk of the research on moraines on the eastern side of the icefields has employed radiocarbon dating on organic material within moraine sequences or lake deposits (Wenzens, 1999), or CRN dating on boulders deposited on moraine surfaces (Ackert et al., 2008). It is known that both of these techniques have limitations in the Patagonian context; radiocarbon dating only usually produces minimum ages, while use of CRN is restricted to the drier eastern flanks of the icefields with limited vegetation cover and soil development to interfere with the isotopic signal. Hence, no CRN dates have been successfully obtained from the wetter and heavily vegetated western side of the Patagonian Icefields.

This, combined with the more restricted occurrence of moraines along the western margins of the icefields (most western outlet glaciers terminate as calving glaciers and evidence is therefore offshore in fjords), has meant that very few attempts have been made to date the Late Quaternary expansion of the icefields in the west, and this must be seen as a significant omission in our attempts to reconstruct their behaviour and the trends of climate change in southern South America.

West of the Andes and in the vicinity of the NPI, there is geomorphological evidence in the form of terminal moraines along the eastern and southern arms of Lago Presidente Rios for an independent ice mass on the Taitao Peninsula. Heusser (2002, 2003) also mapped these moraines and suggested that they formed sometime after 14.355 ^{14}C ka BP (based on a minimum date from nearby Laguna Stibnite provided by Lumley and Switsur, 1993). The arrangement of the moraines indicates that a locally nourished ice cap developed on the peninsula, which was entirely independent of the nearby NPI. The existence and preservation of these moraines at this latitude and this close to sea level is difficult to explain for two reasons:

(a) If the Taitao ice cap is LGM or pre-LGM in age, then this implies severely restricted expansion of glaciers (< 10 km of expansion) from the NPI at the LGM. This is difficult to reconcile with dated geomorphological evidence elsewhere (e.g. the Chilean Lake District immediately to the north) where large west-flowing outlet glaciers developed at the LGM. It is also difficult to imagine a climatological setting where temperature and precipitation allowed the growth of a substantial ice cap on the low-lying Taitao Peninsula but little or no expansion of existing glaciers in the high-accumulation area of the Andes currently occupied by the NPI. If the Taitao ice cap is LGM in age, one possible explanation is that outlet glaciers from the LGM Patagonian Ice Sheet were prevented from over-running the Taitao Peninsula because of vigorous ice flow and associated iceberg calving in the deep NE–SW Elefantes Channel, which separates the peninsula from the mainland. This would allow a separate LGM ice mass to develop on the peninsula.

(b) If the Taitao ice cap is not LGM or pre-LGM in age, then it must have formed some time after the LGM. In this case, it most likely dates from the ACR or from glacier expansion during the YDC (13.3–12.0 cal ka BP; 11.4–10.2 ^{14}C ka BP; Hajdas et al., 2003). Glacier expansion in this area during the YDC is, however, incompatible with palaeoecological evidence derived from lake cores on the peninsula that suggests no significant cooling occurred in the YDC (Bennett et al., 2000), although YDC cooling has been reported from palaeoecological records further south on Tierra del Fuego (Heusser and Rabassa, 1987). Indeed, a radiocarbon-dated pollen sequence from nearby Laguna Stibnite on the Taitao Peninsula provides evidence for an early deglaciation (before 14.0 ka BP) and no evidence for a YDC climatic reversal in this region of Chile (Lumley and Switsur, 1993). Evidence from the chironomid (midge) assemblage record is equivocal, with changes in assemblages during the Late-Glacial and Holocene indicating that the climate may have become cooler and drier during the YDC at nearby Laguna Stibnite (Massaferro and Brooks, 2002), but not ~300 km to the north at Laguna Facil (Massaferro et al., 2005).

Further dates are clearly required from the Lago Presidente Rios moraines in order to determine their age and palaeoclimatological significance. Based on the geomorphological record, it seems most likely that the LGM Patagonian Ice Sheet was prevented from over-running the Taitao Peninsula because of the deep NE–SW Elefantes Channel. This would allow a separate LGM ice mass to develop on the peninsula at this time without the need to invoke glacier advances during the YDC.

54.8.1.2. Undated Moraine Systems

As has been seen, most of the available information on the glaciations of Chile comes from the Chilean Lake District, the Patagonian Icefields and the Magellan Straits region. Elsewhere, for instance, in the arid north of the country, very little is known of the glacial history despite the pioneering work of Zech and co-workers. Consequently, large gaps exist in the mapped extents of the ice limits. However, large moraine complexes exist in most of the mountainous regions of Chile and in many piedmont locations; most are undated.

54.8.1.3. Ice Sheet Trimlines

Glacial trimlines marking the upper limits of the PIS are evident in most mountain regions of Patagonia. Despite this, almost no information is available on their age and only in three cases have they been used to assess the thickness of former ice masses. Fieldwork by SH in the Nef valley in 1998 and in the Leones valley in 2000 identified lateral moraines some 700 m upslope of the late Holocene glacier limits and terminal moraines 10 km or so downvalley of these. The age and climatic significance of these glacial systems are not known at present, but it is clear that they reflect a considerable reduction in ELA below present values. Recent work in the Rio Chacabuco Valley has identified and mapped glacial trimlines marking the upper limits of the former PIS and used CRN to date these limits (Boex et al., 2010). When complete, this will be the first detailed assessment of the thickness of the PIS at times in the past and will add considerably to our understanding and modelling of the dynamics of this ice mass.

54.8.1.4. What Is the Record of Glacier Fluctuations During Neoglaciation?

Glasser et al. (2004) reviewed evidence for Holocene glacier advances in Patagonia. From this, they concluded that during the early Holocene (10.0–5.0 ^{14}C ka BP), atmospheric temperatures east of the Andes were about 2 °C above modern values in the period 8.5–6.5 ^{14}C ka BP. The period between 6.0 and 3.6 ^{14}C ka BP appears to have been colder and wetter than present, followed by an arid phase from 3.6 to 3.0 ^{14}C ka BP. From 3.0 ^{14}C ka BP to the present, there is evidence of a cold phase, with relatively high precipitation. West of the Andes, the available evidence points to periods of drier than present conditions between 9.4–6.3 ^{14}C ka BP and 2.4–1.6 ^{14}C ka BP. Holocene glacier advances in Patagonia began around 5.0 ^{14}C ka BP, coincident with a strong climatic cooling around this time (the Neoglacial interval). Glacier advances can be assigned to one of three time periods following a 'Mercer-type' chronology, or one of four time periods following an 'Aniya-type' chronology. The 'Mercer-type' chronology has glacier advances 4.7–4.2 ^{14}C ka BP; 2.7–2.0 ^{14}C ka BP and during the Little Ice Age (LIA). The 'Aniya-type' chronology has glacier advances at 3.6, 2.3, 1.6–1.4 ^{14}C ka BP and during the LIA (also see Porter, 2000; Harrison et al., 2007). They concluded that these chronologies should be regarded as broad regional trends, as there are also dated examples of glacier advances outside these time periods.

54.8.1.5. The Non-Linear Response of Glaciers to Climate Forcing

Hein et al. (2010) suggested that the small difference in timing of the LGM ice extent between the area to the east of the NPI and the Chilean Lake District may reflect the partial decoupling of fast-flowing outlet glaciers from the climate record. This non-linear response of Patagonian glaciers to climate forcing was identified by Harrison (2004) as a potentially important issue for climate reconstructions from glacial extents, especially in Chile with a wide range of glacial environments driven by a range of dynamic variables (e.g. arid high mountain glaciers with high sublimation rates and low precipitation; lacustrine and tidewater calving glaciers on icefields with high mass fluxes; high-velocity palaeoglaciers flowing into regions of high aridity during Pleistocene glaciations).

The assumption that glacier behaviour reflects a linear response of the glaciers to climate forcing is questioned by the behaviour of certain glaciers whose characteristics mean that their response to first-order climate forcing is partly obscured by second-order controls. An interesting example of this is the modelling study of Kaplan et al. (2009), who demonstrated that the drainage morphology of the southern Andes changed radically from a non-glaciated to a glaciated landscape through the Quaternary. Glacial modification of the mountains caused changes in topography that meant that successive glaciations decreased in extent through time. Thus, the extent of Quaternary glaciations is not necessarily purely climatically driven; landscape modification by glacial erosion also plays a role.

In addition, there are difficulties in identifying the glacier/climate signal from calving glaciers. The proximity of the Pacific Ocean to the Andes mountains in much of southern Chile means that during periods of glacier expansion, many of the glacier termini ended in the sea and therefore experienced tidewater calving. Freshwater calving also affected many of the Pleistocene glaciers in the Chilean Lake District and on the eastern side of the icefields which terminated in deep freshwater lakes (e.g. Warren and Aniya, 1999). It is well known that calving processes established second-order controls on glacier behaviour and therefore partly decouple and obscure the glacier/climate signal (e.g. Van der Veen, 2002). Since much of our geomorphological evidence for climate change in Chile is derived from the position and ages of moraines associated with glaciers which are calving or have calved in the past, the problem of assigning climatic inference to oscillations of calving fronts is a serious one. The picture is further complicated by the different calving responses in freshwater and tidewater. Further, many of the climatic reconstructions from the Chilean Lake District and the Magellan Straits area are partly based upon dates of the fluctuations of piedmont lobes with low ice gradients. It has been suggested that the termini of such ice masses may oscillate in response to variations in bed conditions rather than climatic inputs (Glasser and Jansson, 2005). These factors mean that considerable caution should therefore be exercised when reconstructing palaeoclimates from the positions of moraines.

54.9. CONCLUSIONS

Chile's position in the Southern Hemisphere straddling 38° of latitude and its possession of one of the longest and most complete terrestrial records of glaciation in the world means that the country has become a critical global location for testing models of climate change. While considerable gaps remain in our knowledge of the timing and extent of glaciation in Chile and of the drivers behind them, it is clear that the behaviour of the southern westerlies and the Humboldt current are crucial variables. There does not appear to be a Younger Dryas signal in the southern Chile palaeoecological record, yet there are glacier advances in this region which span both Younger Dryas and ACR times. This may represent a return to southerly latitudes of the southern westerlies. Finally, it is clear that there are a large number of problems in the Pleistocene glacial history of Chile and these will only be resolved by a combination of accurate dating and multi-proxy geomorphological, climate modelling and palaeoecological approaches.

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