Expedition Report

Late Glacial and Holocene glaciation in Tierra del Fuego

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18th November – 8th December 2023

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1 ACKNOWLEDGEMENTS

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2 Contents

3 EXPEDITION SUMMARY

In November and December 2023, a team of four researchers from the University of Edinburgh and Universidad Católica de Chile undertook fieldwork on two islands in Tierra del Fuego, southernmost Patagonia, to study the glacial history of the region. Despite the challenging terrain and weather conditions, the team successfully sampled 34 quartz-rich rocks deposited by past glacier re-advances on Isla Santa Inés, north of the Santa Inés Icefield, and Isla Grande, east of the Cordillera Darwin Icefield. These samples will be dated using cosmogenic nuclide exposure dating in order to reconstruct the Late Glacial and Holocene glacial history of the region. We then plan to use numerical glacier modelling to better understand the climate required to drive these glacier re-advances.

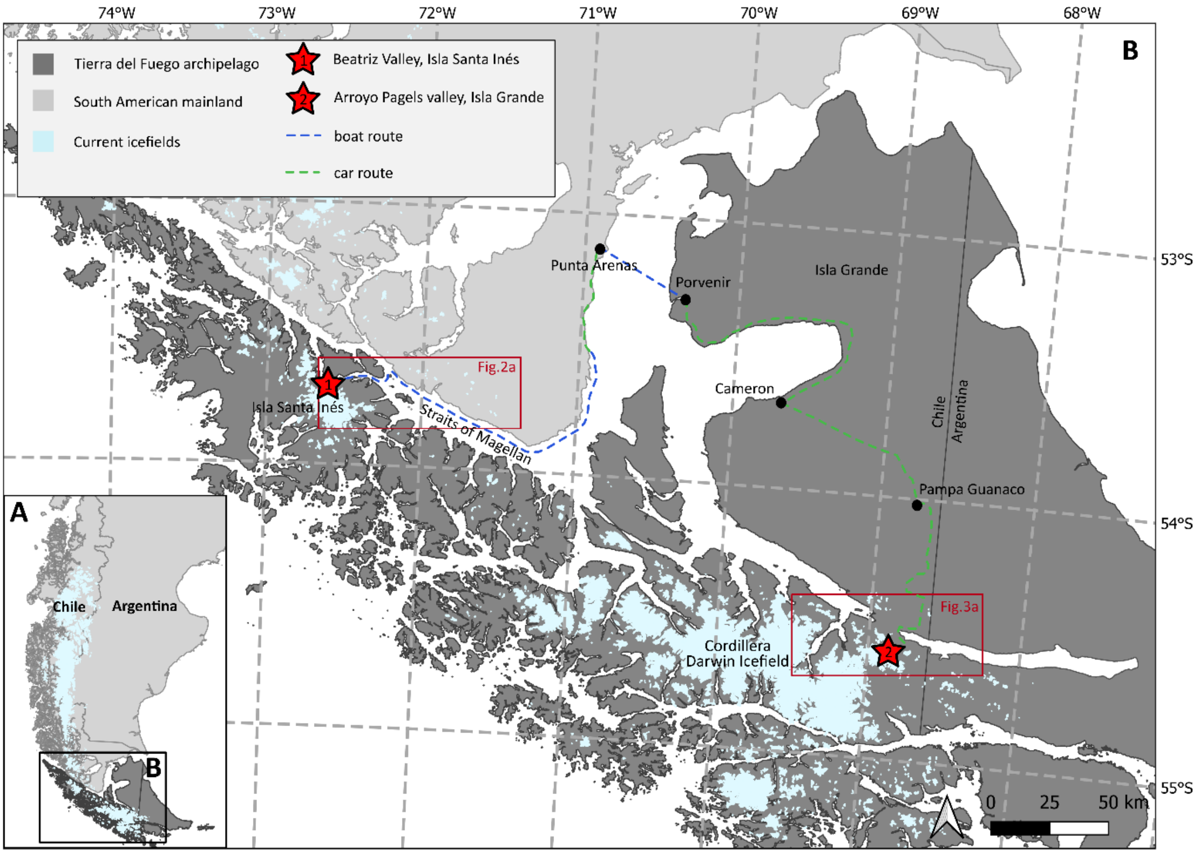

Figure 1. (A) Location of Tierra del Fuego, an archipelago of islands in southernmost Patagonia. (B) Our two study regions in the Tierra del Fuego archipelago and the route travelled.

4 INTRODUCTION

4.1 STUDY SITES

Figure 1 shows the location of the two regions in the Tierra del Fuego archipelago that were studied during this expedition: north of the Santa Inés Icefield on Isla Santa Inés and east of the Cordillera Darwin Icefield on Isla Grande. The aim of the expedition was to retrieve rock samples from boulders on moraines a few kilometres outside the current ice extent. Figures 2 and 3 show the Beatriz valley on Isla Santa Inés and the Arroyo Pagels valley on Isla Grande in more detail.

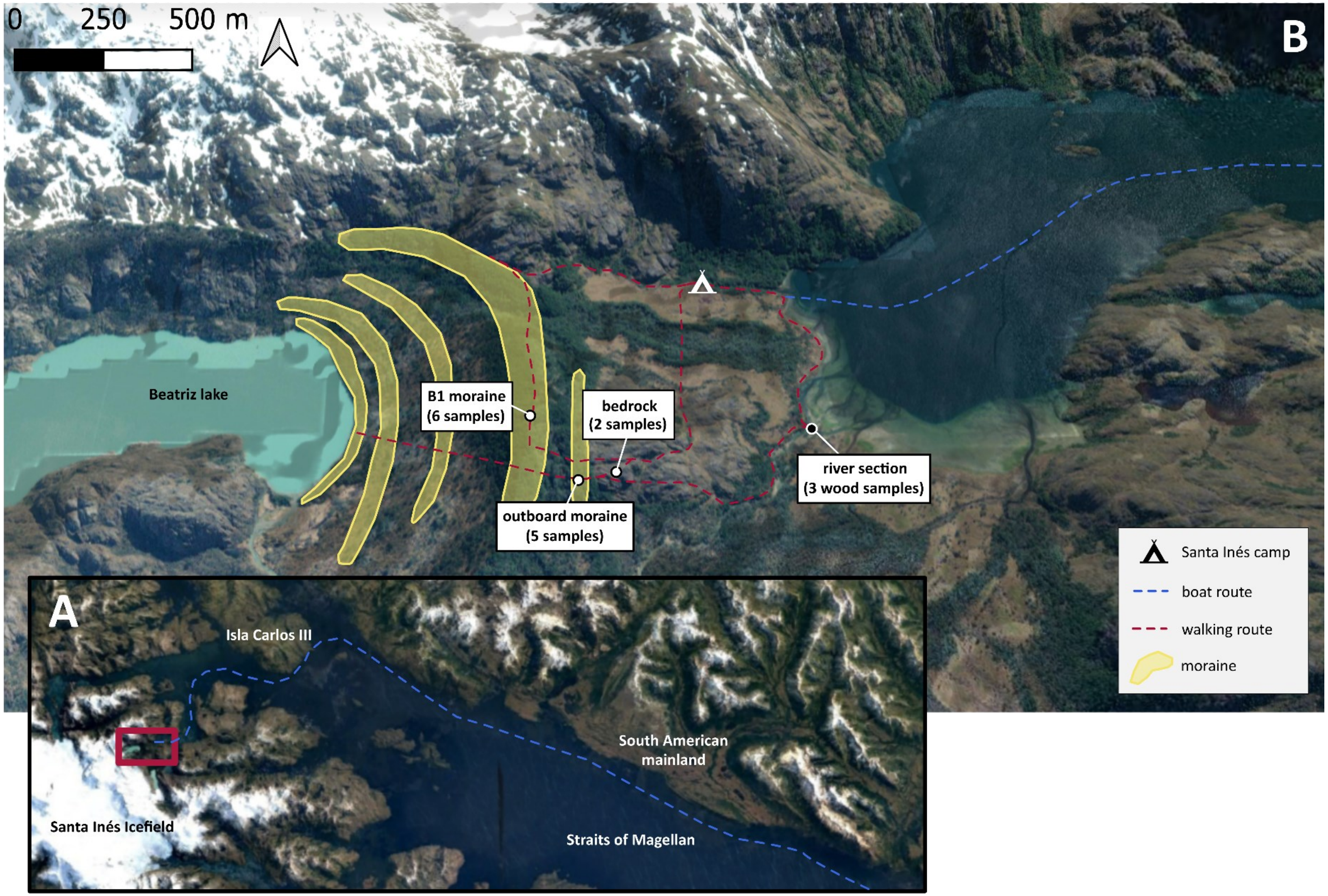

Figure 2. (A) Location of the Beatriz valley on Isla Santa Inés (Google Earth) (B) 3D map of our camp, route and sample sites in the Beatriz Glacier forefield on Isla Santa Inés (FatMaps).

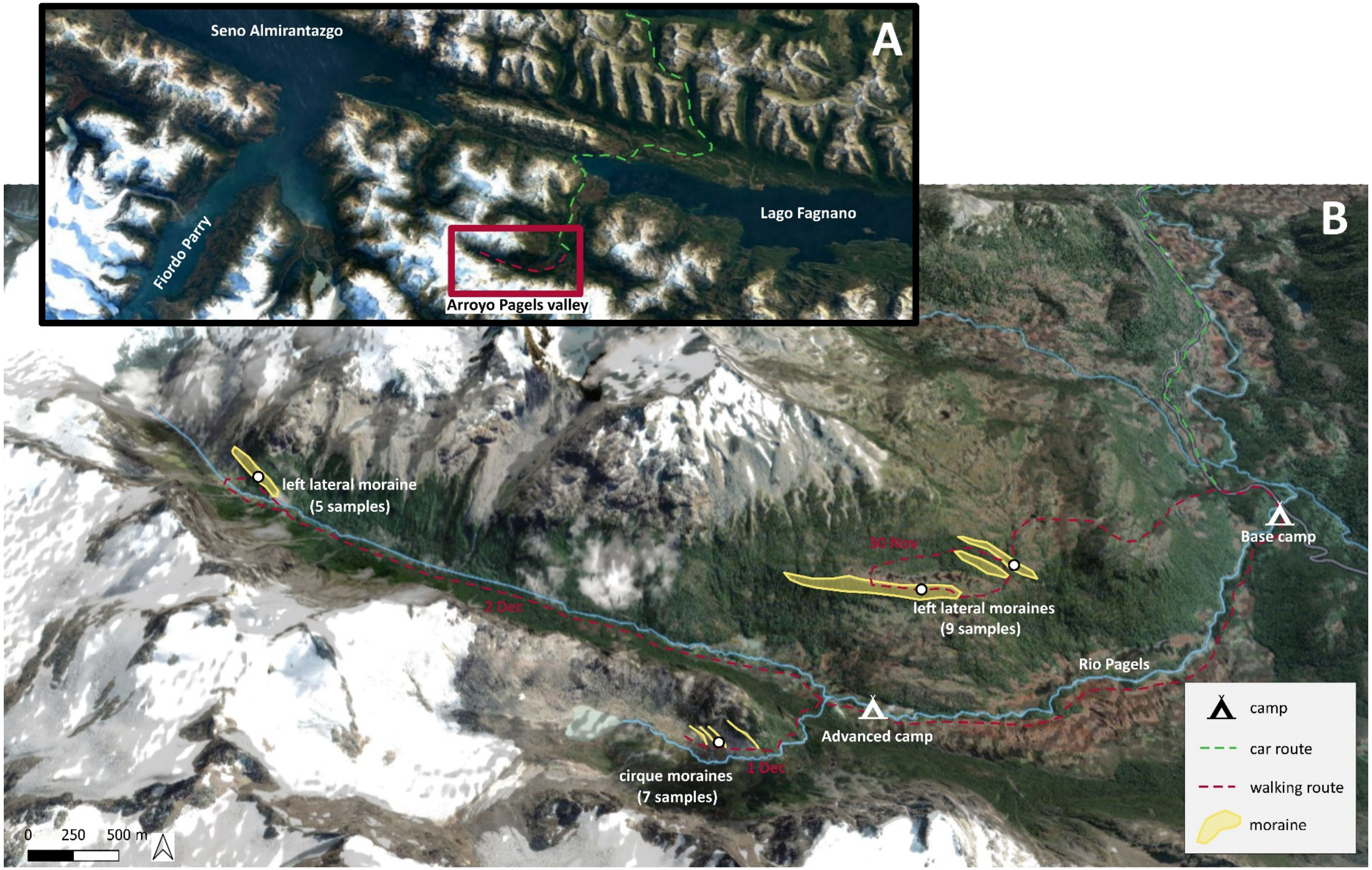

Figure 3. (A) Location of the Arroyo Pagels valley on Isla Grande (Google Earth). (B) 3D map of our camps, route and sample sites in the Arroyo Pagels Valley (FatMaps).

4.2 Scientific background

As the most southerly continental landmass outside Antarctica, southernmost Patagonia is an important region for studying past climate changes. Tierra del Fuego intersects the core of the Southern Westerly Winds (SWWs), which play an important role in global climate. Past glacier extent can be used as a proxy for past climate changes, since glacier extent is strongly controlled by fluctuations in temperature and precipitation. We can infer past glacier configurations from the landforms they leave behind and cosmogenic nuclide exposure dating is a technique that can be used to determine when the glacier was actively creating these landforms. This fieldwork on the Tierra del Fuego archipelago, involves using cosmogenic nuclide exposure dating of moraine boulders to reconstruct past glacier fluctuations in this region.

Although the last glacial maximum in Tierra del Fuego has been the subject of significant previous research (e.g. Clapperton et al., 1995; Coronato and Rabassa, 2011; Darvill et al., 2015a; 2015b; Kaplan et al., 2007; 2008; McCulloch et al., 2005; Peltier et al., 2021; Rabassa et al., 2000), the rate and timing of deglaciation, and subsequent small-scale re-advances, are less well understood because scientists seldom visit the islands surrounding the Santa Inés and Cordillera Darwin Icefields. This region is remote and experiences challenging weather conditions, making the islands logistically difficult to access.

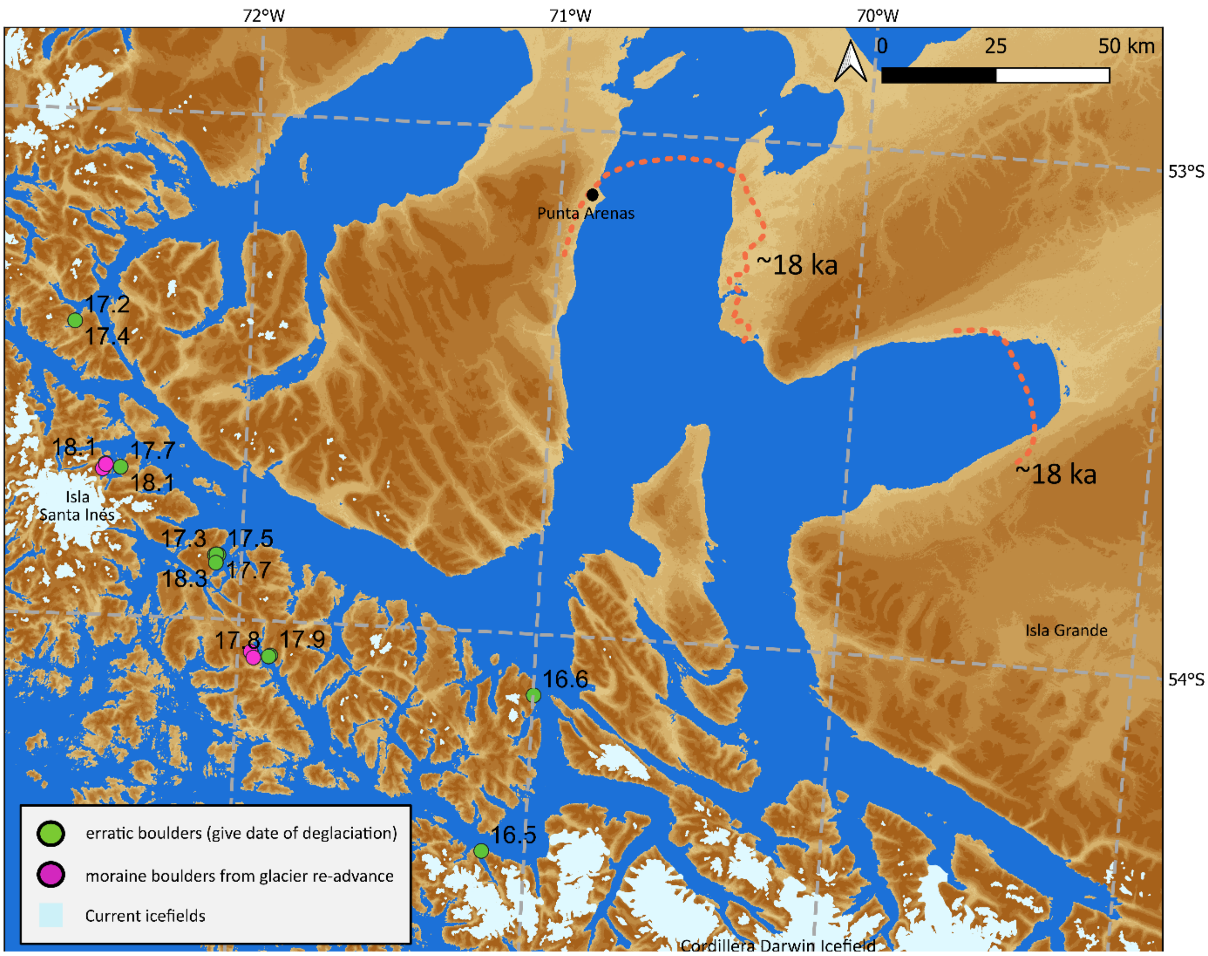

Figure 4. Deglaciation from the last glacial maximum occurred rapidly at around 17 ka. The orange dashed line shows the innermost moraine from the last glacial, deposited around 18 ka. The green circles and associated ages are erratic boulders we sampled during fieldwork in 2022 and dated using cosmogenic nuclide exposure dating. Their ages represent the time when ice retreated from that region, demonstrating that deglaciation occurred very rapidly.

In order to investigate deglaciation and the separation of the Cordillera Darwin and Santa Inés icefields, we conducted fieldwork in the region last year, funded by Bob McCulloch's Fondecyt research grant[3]. We chartered a sailing boat to access these remote islands and sample erratic boulders for surface exposure dating and we were able to infer that deglaciation was earlier and more rapid than initially thought (Figure 4). During the field season, we also identified a series of small moraines only a few kilometres outside the present-day icefields, but due to challenging weather imposing time constraints on our sailing time, we were only able to sample a select few of these moraines. Due to their proximity to the current glacier margins, initial findings from the 2022 fieldwork and previous radiocarbon dating (Hall et al., 2014; 2019), we believe these moraines were deposited during the Late Glacial to early Holocene. Glacier fluctuations during this time are not well-constrained and further investigation would greatly improve our wider understanding of past glacier and climate changes in the region.

Therefore, this 2023 expedition, revisited these islands to sample boulders from these moraines close to the Santa Inés and Cordillera Darwin Icefields. The samples will be dated using cosmogenic nuclide exposure dating to reconstruct the Late Glacial and Holocene glacial history on these remote islands. This glacial reconstruction will then be used alongside numerical glacier modelling to better understand the climate required to drive these glacial re-advances.

4.3 Research aims and objectives

Scientific aims: The expedition aimed to answer the following research questions:

1) How did the glaciers behave on the remote islands of Tierra del Fuego during the Late Glacial and Holocene?
2) What are the drivers of this glacier behaviour?

Scientific objectives: These aims were achieved with the following research objectives:

1) Geomorphological mapping of glacial landforms surrounding the Santa Inés and Cordillera Darwin Icefields using aerial photography, satellite imagery and fieldwork
2) Sampling of 4-6 boulders on each terminal moraine limit for cosmogenic ^{10}Be exposure dating to determine their age
3) Numerical glacier modelling to investigate the sensitivity of these glaciers to past changes in temperature and precipitation

[3] 1200727 - 'Solving the Paradox of conflicting glacial chronologies: reconstructing the Cordillera Darwin Ice Sheet (53-55°S) during the last glacial/interglacial transition (LGIT)'

4.4 Meet the team

Figure 5. Photo of the team about to board the boat to Isla Santa Inés. From left to right: Andy Hein, Rob Bingham, Carla Huynh and Juan-Luis Garcia.

Carla Huynh

Carla is a PhD student at the University of Edinburgh and the expedition leader. This expedition formed the second field season of Carla's PhD research studying the last glacial cycle in southernmost Patagonia. Carla has a BSc in Geology and MRes in Polar and Alpine change, and has fieldwork experience in Greenland, Scotland, Greece, Spain and Italy. The focus of Carla's PhD is to use cosmogenic nuclide exposure dating to reconstruct the glacial history in southernmost Patagonia and use this alongside numerical glacier modelling to better understand the climate required to drive these glacier changes. A previous field season focussed on the onset of deglaciation in Tierra del Fuego and this expedition aims to focus on a series of moraine just a few kilometres outside the current ice extent, that were likely formed by glacier re-advances during the Late Glacial or Holocene.

Andy Hein

Andy is a senior lecturer and manager of the Cosmogenic Nuclide laboratory at the University of Edinburgh and Carla's main PhD supervisor. He specialises in Quaternary palaeoclimate research, with a focus on geochronology and glacial geomorphology, particularly the application of cosmogenic isotope dating to glacial landforms. Andy has undertaken extensive fieldwork in southern South America, as well as Antarctica.

Rob Bingham
Rob is a Chair of Glaciology and Geophysics at the University of Edinburgh and one of Carla's PhD co-supervisors. His research addresses the cause and pace of polar ice sheet change and the contributions of polar ice sheets to global sea levels. Rob has previously conducted extensive cryospheric, geophysical and geomorphological fieldwork across the Arctic, Antarctic and Patagonia.

Juan-Luis Garcia
Juan-Luis is an associate professor and director of the Cosmogenic Isotopes and Paleoclimate Laboratory at Universidad Católica de Chile. He is a glacial geomorphologist, specialising in the drivers of past glaciations in the southern hemisphere. Juan's research primarily focuses on reconstructing past glacial and climate histories as well as historic to present-day glacier dynamics in the Central and Southern Andes and has undertaken extensive fieldwork throughout Patagonia.

5 Logistics

5.1 Route, maps and terrain

Google Earth and FatMaps imagery were used to identify potential camps, sample sites and routes of approach prior to the expedition. Dense vegetation, peat bogs and river crossings were identified as the biggest obstacles and made walking across the terrain challenging and slow. In addition to this, we discovered that a large population of non-native beavers have dramatically changed the landscape on Isla Grande, creating extensive beaver dam networks and felling large areas of native trees, providing a further obstacle on our routes to sample sites.

5.2 Permits

A permit was obtained from CONAF (494/2023) with the help of Bob McCulloch, who has previously conducted fieldwork on the islands of Tierra del Fuego. The process of obtaining a CONAF permit to conduct science and remove samples was not straightforward and we would recommend applying at least 6 months prior to fieldwork.

5.3 Communication

We used an iridium satellite phone and a Garmin inReach for communication between the boat and the field camp and we pre-arranged to call at 8pm every evening to save on satellite phone battery and credit. We also brought handheld radios for communication between team members in the field, but were carried and not used.

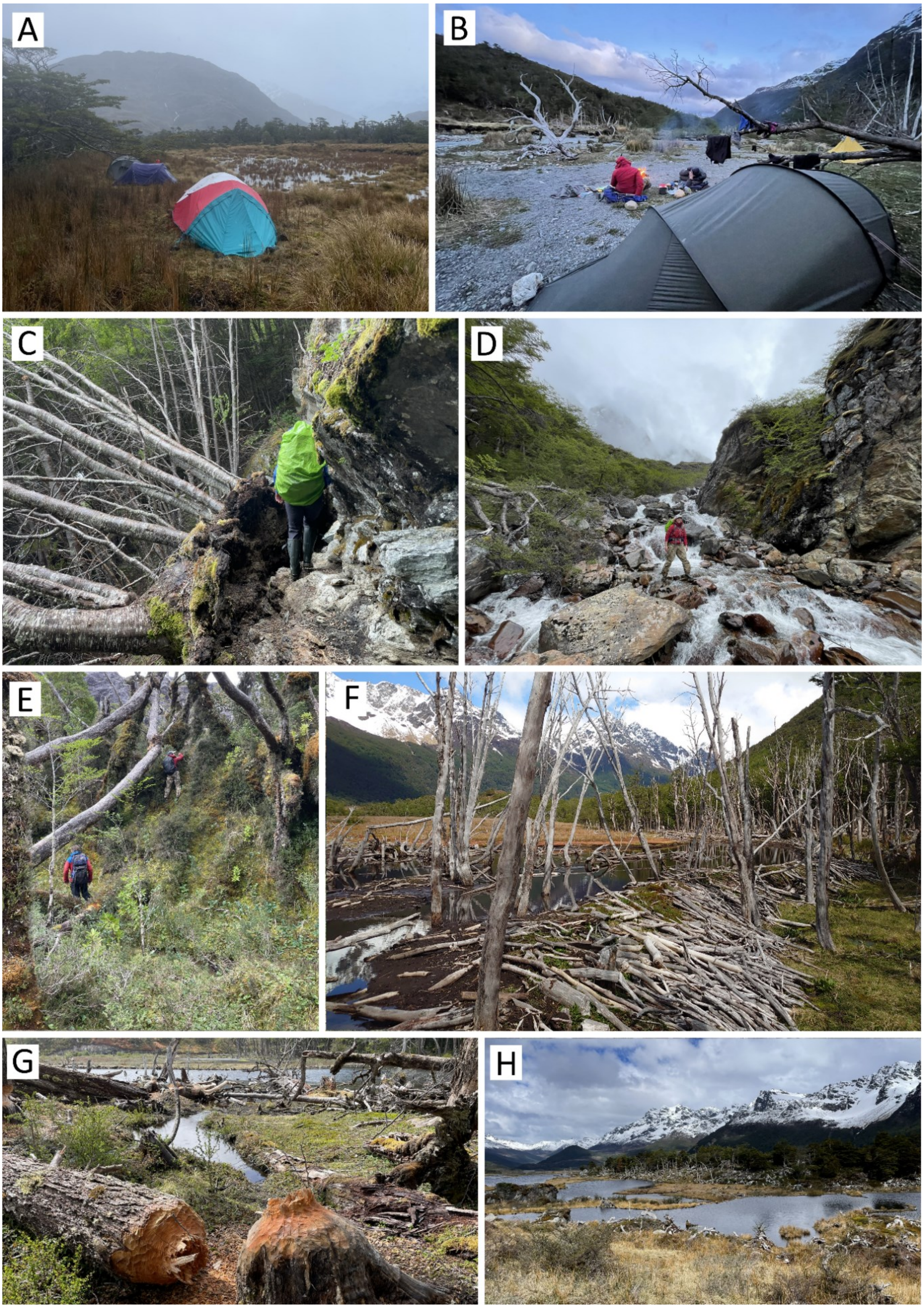

Figure 6. Terrain and landscapes of Tierra del Fuego. (A) Camp on Isla Santa Inés (in a peat bog!) (B) Advanced camp in the Arroyo Pagels valley on Isla Grande. (C) Hiking up the steep valley side to the cirque moraines through dense vegetation and felled trees. (D) River crossing in the Arroyo Pagels valley. (E) Negotiating the steep vegetated banks enroute back to camp on Isla Santa Inés. (F) A beaver dam on Isla Grande. (G) An example of the damage beavers are having on the landscapes of Tierra del Fuego. (H) Extensive beaver dams near the left lateral moraines on the upper slopes of the Arroyo Pagels valley.

5.4 Budget

5.4.1 Grant income

Grant	Income
MEF	£5,000.00
JWCT	£500.00
Geological Society of London	£1,500.00
QRA	£1,500.00
John Muir Trust	£1,500.00
SAGES	£750.00
NERC RTSG	£2,500.00
Total income	**£13,250.00**

5.4.2 Outgoing costs

Expense	Cost
3 x international flights	£6,337.15
car hire and fuel	£1,354.38
accommodation	£440.08
boat to/from Isla Santa Inés	£3,888.53
equipment	£157.00
food	£504.07
other transport (ferry, taxis, train to airport)	£108.45
shipping samples to Edinburgh	£742.39
Iridium SIM card	£209.39
luggage storage	£28.57
Total	**£13,770.01**

5.5 Environmental impact

The most significant negative environmental impact of this expedition was the unavoidable carbon cost of flights to the study region (~13.07 CO_2e tonnes). However, under the new carbon sequestration scheme launched in 2023 by the University of Edinburgh, all unavoidable emissions will be directly sequestered by restoring forests and peatlands. Where possible, we ensured that most samples were removed discretely using a hammer and chisel, which produces 'natural-looking' surfaces and only used an angle grinder where there were no natural fractures to exploit. All waste was carried with us and disposed of appropriately in Punta Arenas.

6 Expedition diary

6.1 Preparation in Punta Arenas

Andy, Carla and Rob flew from the UK on 18th November, arriving in Punta Arenas on the 19th and meeting Juan-Luis on the 21st. We spent the first few days planning and preparing for fieldwork: saving potential places of interest as waypoints on the GPS, buying food supplies and gas, collecting the generator that Juan-Luis had sent from Santiago and testing out the satellite phone. We also spent a day, a few kilometres north of Punta Arenas, sampling loess deposits for OSL dating. There is controversy as to whether the underlying glacial till was deposited during or prior to the last glacial cycle. The samples will be sent to the OSL laboratory at the University of Liverpool and will hopefully provide a minimum age constraint on this glacial till.

6.2 Part 1: Isla Santa Inés (22-27th Nov)

The initial plan was to leave early on the morning of 23rd November to sail to Isla Carlos III and then onwards to Isla Santa Inés. However, the wind was forecast to be lower on 22nd and the western Straits of Magellan is notoriously rough and challenging in adverse conditions. Whalesound, the bird and whale-watching company that were facilitating our transfer to the island, contacted us a few hours before to notify us of our early departure, and we set sail from Punta Carrera that evening.

Figure 7. (A) Being dropped off by zodiac to Isla Santa Inés. (B) Alone on the island, we prepare to carry our kit up to establish camp. (C) We became very accustomed to the mess tent during the wet mornings and evenings at camp. (D) A brief and welcomed break in the rain gave us an opportunity to dry out some of our kit.

The seas were rough overnight despite the earlier departure and Carla was sea sick. Meanwhile Rob was completely oblivious to the boat lurching all over the place and slept soundly in the forepeak all night! We arrived on Isla Carlos III on the morning of the 23rd and were dropped off on Isla Santa Inés in the early afternoon. It hadn't stopped raining since we left Punta Arenas and as we set up our field camp in the peat bog, we wondered if it would rain persistently until we were picked up in 4 (or 5?) days. Andy, Carla and Juan-Luis, who had visited Isla Santa Inés on fieldwork last year, recalled that they were the wettest days of the field season and according to the closest active meteorological station, averages 322 days a year with precipitation. The odds were not in our favour…

Since our pick up from the island was heavily dependent on the weather, we had prearranged to call on the satellite phone at 8pm each evening and we thought we had at least 3 full days in the field to achieve our aims. So that evening we set up camp and huddled around our food box in the mess tent as it continued to rain and we came up with a plan for the next few days.

Figure 8. (A) and (B) Sampling from boulders on the prominent B1 moraine crest. (C) the boulders on the outboard moraine had thicker (~20 cm) moss cover and were likely deposited by an earlier glacial advance. (D) the river section where ~2 metres of peat overlie glacial outwash. We sampled wood incorporated in the glacial outwash for radiocarbon dating.

Much to our surprise it wasn't raining when we woke up on the 24th November and life in the bog suddenly seemed a lot easier. We were able to dry out some of our kit and even got a glimpse of the Beatriz and Nati Glaciers. We hiked up the vegetated 'B1' moraine ridge behind camp in search of quartz-rich boulders on the moraine crest. The dense forest growing on the ridge made for interesting bushwhacking and progress was slow. To begin with it was hard to spot any boulders at all, as they were covered in moss up to 10 cm deep, but as we got used to our surroundings, we started seeing them everywhere. We spent the day uncovering thick layers of moss in search of quartz-bearing rocks and as we made our way south along the B1 moraine, the crest became more prominent and we started to find some boulders worth sampling. We sampled 6 boulders from the crest of the B1 moraine that day and also observed a concentration of boulders deposited outboard of this moraine crest. We revisited this older glacial till on 25th November and collected five further samples from this older moraine and two bedrock samples outboard of these to give us minimum ages for deglaciation.

That evening Carla went to recce the river south of camp to see if it was possible to cross towards the Alejandro Glacier the following day. She found a decent crossing point, but more interestingly also came across a river section of glacial sands, gravels and cobbles dipping towards the fjord, overlain by ~2 metres of peat. We headed back to this section on 26th November to record our observations in more detail and collect some samples for radiocarbon dating. Happy with our haul of samples, we then walked (bushwhacked) a transect perpendicular to the moraine crests down to Beatriz Lake, where we had an amazing view over the Beatriz and Nati Glaciers.

As we were cooking dinner at camp that evening, we were expecting news that we might be picked up the following day. Instead, we found out that the zodiac was on its way to pick us up in a few hours' time and we would sleep moored up on Isla Carlos III before sailing back to Punta Arenas on 27th November. We were treated to hot showers, red wine and King Crab with their whale watching clients and as we headed back to the mainland, we saw a pod of Sei whales.

Figure 9. (A) Bushwhacking down to Beatriz Lake. (B) Carla takes a dip. (C) Pick up by zodiac from Isla Santa Inés. (D) A pod of Sei whales spotted on the sail back to Punta Arenas.

6.3 Part 2: Eastern Cordillera Darwin (28th Nov – 4th Dec)

No rest for the wicked. Having returned to Punta Arenas at 10 pm on 27th, our hire car was delivered to us at 1 am and we were off again on the 28th. A quick restock of food and a spare jerry can of fuel for our long drive south and we were on the road. We caught the ferry across to Porvenir and spent the next day driving along the dirt tracks of the Y-85 road on Isla Grande, across the mountain ranges of Parque Karukinka, past Lago Fagnano, to the end of the road in the eastern Cordillera Darwin. Here, we made basecamp and prioritised our target sampling sites for the next few days.

On 30th November, we hiked up to the prominent left lateral moraines on the northern flank of the Arroyo Pagels valley and collected five samples from the innermost moraine and four samples from the outermost (Figure 10A). On 1st December, we established an advanced camp ~5 km up valley and hiked up to the cirque south of our camp, where we had identified a series of smaller moraine crests in satellite imagery. We discovered at least 7 distinct moraines, of which most were unvegetated bouldery moraines that were likely deposited relatively recently. However, the outermost moraines had considerable tree growth around and on top of the boulders and a thin layer of moss, suggesting an earlier period of glaciation in the cirque. We collected three samples from an inner unvegetated moraine and four from the outermost vegetated moraine, then headed back down to camp before we ran out of sunlight.

We saved the biggest sampling day until last, heading up valley to a left lateral moraine ~5 km from our advanced camp on 2nd December. Although not far in distance, the constant clambering over fallen trees, negotiating our way around beaver dams, gulley's, peat bogs and rivers made for a long day. A single 0.37-mile section of what we later termed the 'horror mile' took us 45 minutes and entire route ended up becoming an 11-hour day. We collected five samples from the moraine before heading back to the advanced camp, back through the 'horror mile' and coming face to face with a beaver along the River Pagels near our camp. With quartz-bearing samples successfully collected from all of our planned sites, we ambled back to basecamp on 3rd December and began the long drive back across Tierra del Fuego.

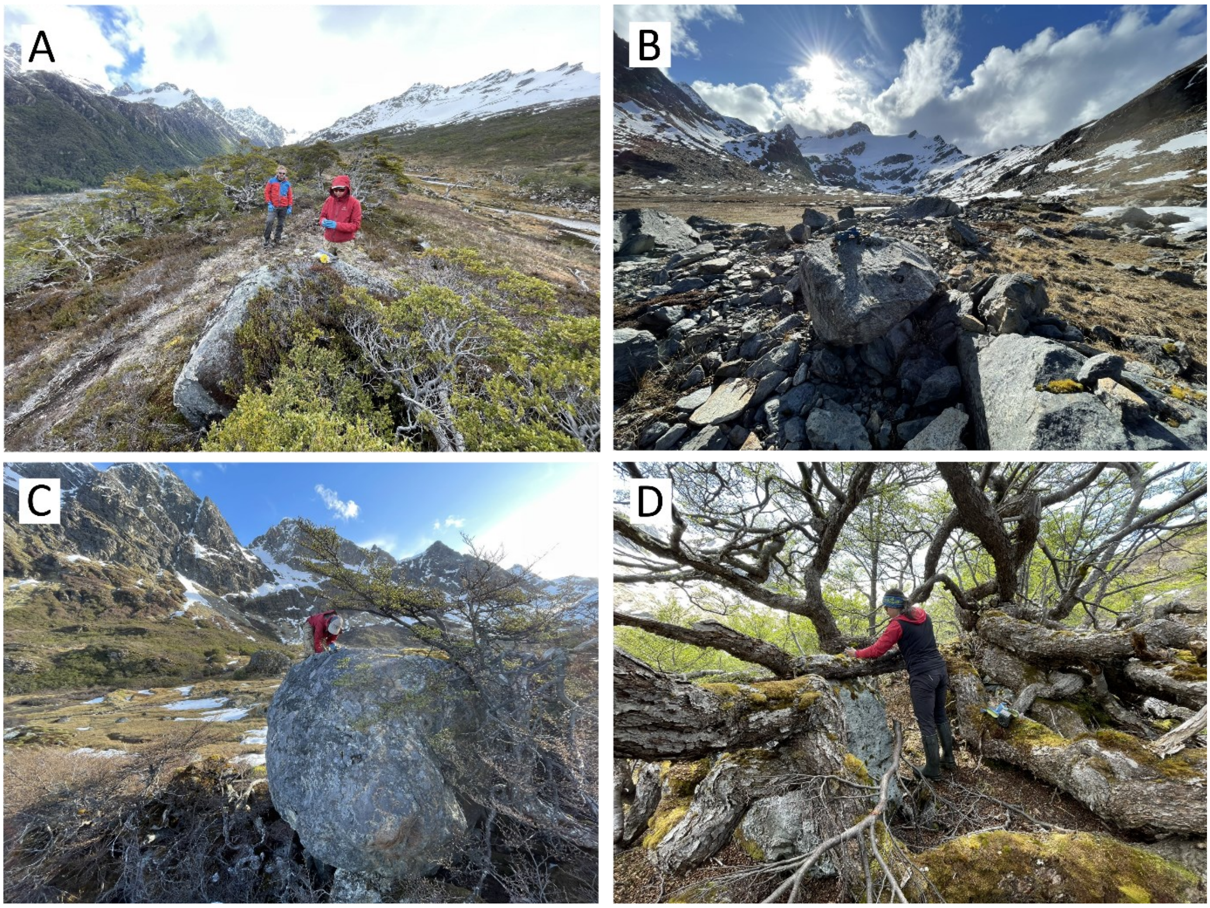

Figure 10. (A) The prominent left lateral moraines on the northern side of the Arroyo Pagels valley, where we collected 9 samples from two moraines on 30th November. (B) One of the inner non-vegetated bouldery moraines in the cirque above basecamp, sampled on 1st December. (C) A boulder on one of the outer moraines in the cirque, where considerable tree growth around the boulders and limited moss cover suggests two periods of glaciation of this cirque. (D) Sampling from the left lateral moraine further up valley on 2nd December, where trees have grown around and on top of most sample sites.

6.4 Post-fieldwork admin

We had a few days in Punta Arenas before our flights home to arrange the postage of our samples back to Edinburgh. This proved more challenging and expensive than we had envisaged. We had a few issues with the Chilean postal service on fieldwork last year and eventually received our samples in a very poor state. For that reason, we had intended to air freight this year's samples with an Antarctic logistics company, but with a quote of over £1000, we settled on the Chilean postal service again. We'd recommend having multiple printed copies of permits for anyone planning on shipping samples out of Chile.

7 Future Work

The samples collected during this expedition will now undergo cosmogenic chemistry to extract Beryllium-10, which will be measured at the AMS facility at SUERC. This will tell us how long our samples have been exposed to the atmosphere, and hence how long since they were deposited by the glacier. We will use this glacial history of the two sample sites to better understand the Late Glacial and Holocene climate in the region using numerical glacier modelling.

8 LIST OF SAMPLES COLLECTED

Latitude	Longitude	Elevation	sample_ID	dating_method
-53.15528	-70.98453	208	PA-SKI1	OSL
-53.15504	-70.98489	210	PA-SKI2	OSL
-53.73268	-72.48553	2	BG23-W1	radiocarbon
-53.73268	-72.48553	2	BG23-W2	radiocarbon
-53.73268	-72.48553	2	BG23-W3	radiocarbon
-53.73114	-72.49537	103	BG23-B01	TCN
-53.73106	-72.49553	98	BG23-B02	TCN
-53.73104	-72.49547	100	BG23-B03	TCN
-53.73107	-72.49548	99	BG23-B04	TCN
-53.73136	-72.49527	102	BG23-B05	TCN
-53.73184	-72.495	102	BG23-B06	TCN
-53.73188	-72.49451	105	BG23-B07	TCN
-53.73357	-72.49406	98	BG23-B08	TCN
-53.73334	-72.49406	86	BG23-B09	TCN
-53.73334	-72.49389	84	BG23-B10	TCN
-53.73319	-72.49404	98	BG23-B11	TCN
-53.73315	-72.49314	84	BG23-Br12	TCN
-53.73312	-72.49291	74	BG23-Br13	TCN
-54.59334	-68.87117	401	EC23-B01	TCN
-54.59336	-68.87151	404	EC23-B02	TCN
-54.59336	-68.87159	402	EC23-B03	TCN
-54.59346	-68.87253	403	EC23-B04	TCN
-54.59322	-68.87056	396	EC23-B05	TCN
-54.59099	-68.8629	410	EC23-B06	TCN
-54.59085	-68.86333	416	EC23-B07	TCN
-54.59083	-68.8633	413	EC23-B08	TCN
-54.59081	-68.86363	419	EC23-B09	TCN
-54.60672	-68.897	519	EC23-B10	TCN
-54.60648	-68.89741	520	EC23-B11	TCN
-54.6065	-68.89739	519	EC23-B12	TCN
-54.60629	-68.89401	524	EC23-B13	TCN
-54.60617	-68.89424	529	EC23-B14	TCN
-54.60601	-68.89462	534	EC23-B15	TCN
-54.60653	-68.89384	519	EC23-B16	TCN
-54.58305	-68.94732	507	EC23-B17	TCN
-54.58309	-68.94768	495	EC23-B18	TCN
-54.58322	-68.9475	494	EC23-B19	TCN
-54.58319	-68.94759	506	EC23-B20	TCN
-54.58377	-68.94704	481	EC23-B21	TCN

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