Bulletin of Glaciological Research 21 (2004) 37–43

Morphostratigraphy of moraines in the Lago Tranquilo area, Chilean Patagonia

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(Received September 14, 2003; Revised manuscript received November 13, 2003)

Abstract

The valleys draining the Hielo Patagónico Norte in southern Chile contain a number of moraine belts, which record the past expansion of the icefield and its outlet glaciers. This paper describes the nature of the moraines in the Exploradores valley which drains the northern flanks of the icefield. Four moraine sequences are described and differentiated on the basis of their morphostratigraphic relationships. The moraines reflect stages of restricted glaciation confined to high valleys and more extensive valley-based glaciation. The work provides a scheme for a subsequent dating programme.

1. Introduction

The Hielo Patagónico Norte lies astride the southern Andes between 46°30′S and 47°30′S with an area of *c.* 4200 km² (Fig. 1). The outlet glaciers draining the icefield extend to lower latitudes than those of any other substantial ice mass in the world. The icefield is nourished by the mid-latitude weather systems and is characterised by abundant precipitation, high ablation rates, steep mass-balance gradients and high ice velocities. Together with sharp local topographic and climatological contrasts, these circumstances create a dynamic and temperate glacier system.

Although there are few detailed mass-balance studies, the available evidence suggests that these glaciers are extremely sensitive to climatic change. Well-developed moraines occur throughout the valleys draining the Hielo Patagónico Norte and reflect fluctuations of the outlet glaciers (Harrison, 2003). While there has been considerable work dating the most recent (Little Ice Age) glacial moraines in the area (eg Aniya, 1995; 1996; Aniya and Naruse, 1999; Aniya and Shibata, 2001; Glasser *et al.*, 2002; Winchester and Harrison, 1996; Winchester *et al.*, 2001; Harrison and Winchester, 1998; 2000) there has been little analysis of the nature or age of the earlier moraines. Although these moraines clearly relate to an earlier expansion in the volume of the icefield, which resulted in the extension of its outlet glaciers, there has been no previous attempt at mapping these nor in assessing their morphostratigraphic characteristics.

This paper reports on a research project that aims to analyse the morphostratigraphy of moraines in the Lago Tranquilo area of the Exploradores valley which formerly drained the northern flanks of the Hielo Patagónico Norte. The paper aims to place these in a chronological scheme based on their morphostratigraphy and provides a classification for a subsequent dating programme.

2. Study area

The Lago Tranquilo area lies at the eastern end of the Rio Norte and Rio Exploradores river systems, which together drain the northern flanks of the Hielo Patagónico Norte. The present watershed lies 1km to the west of Lago Tranquilo. Mountains to the north, south and west nurtured valley and cirque glaciers during the Quaternary and these, at various times, coalesced to produce large valley glaciers in the Rio Norte and the Rio Tranquilo valleys (Fig. 2).

3. Methods

The geomorphic and morphostratigraphic relationships of the Lago Tranquilo area were established through detailed geomorphological mapping of an area of approximately 35 km². This region extends from Los Cipreses in the west to Puerto Rio Tranquilo in the east and Los Tres Arroyos in the north to the valleys draining into Rio Norte in the south (Fig. 2). Field mapping was carried out using base maps reproduced from the 1: 50000 Chilean Instituto Geografico Militar map 4630-7240.

The geomorphology of the Lago Tranquilo area is complex. Therefore, it is critically important that the geomorphological maps not only accurately

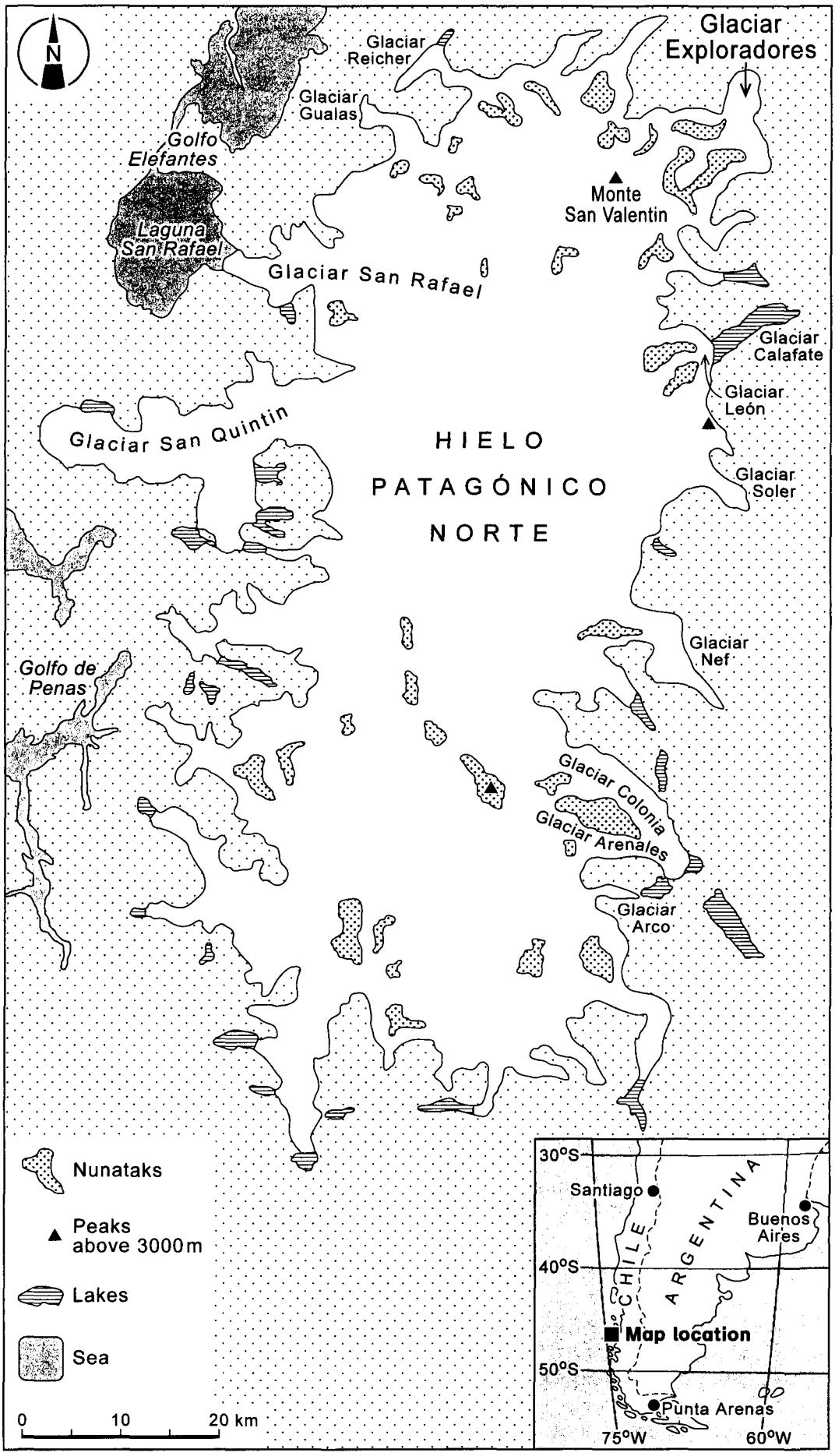

Fig. 1. The Hielo Patagónico Norte showing the main outlet glaciers.

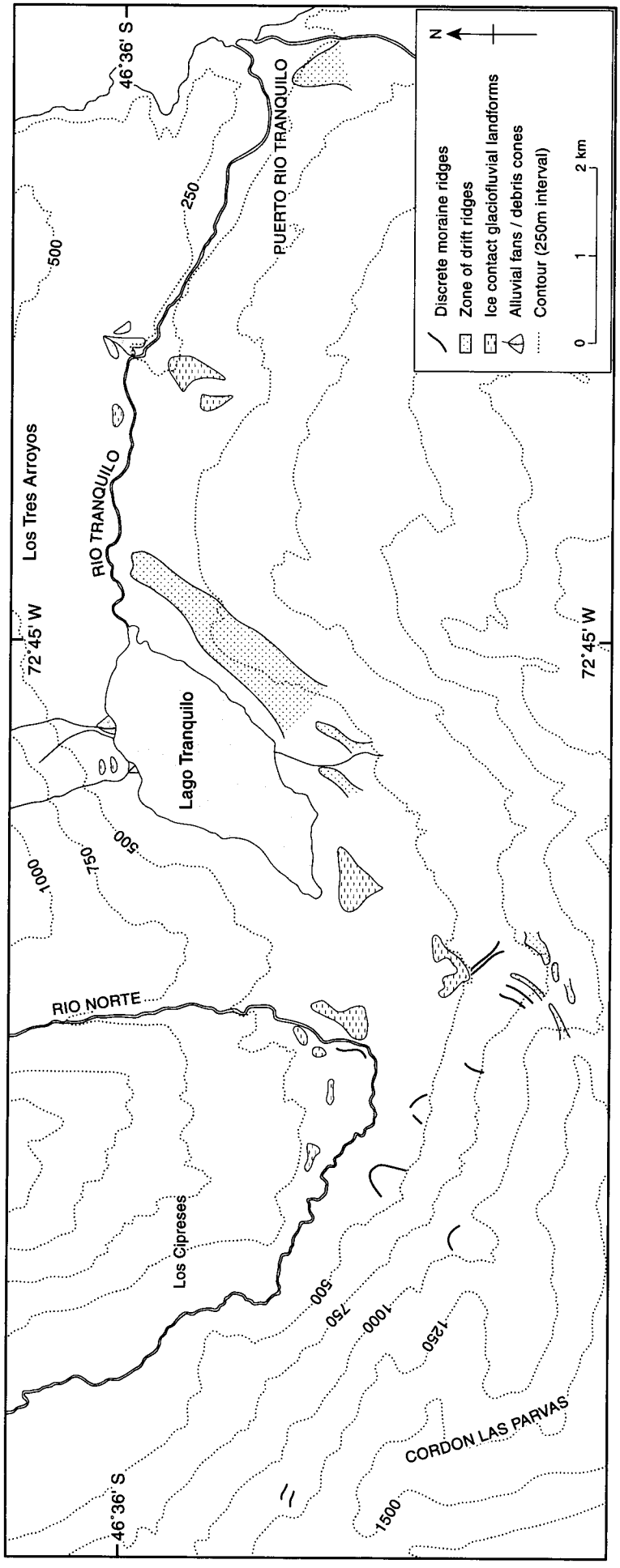

Fig. 2. Lago Tranquilo area of the Exploradores valley.

reflect the spatial and genetic complexity of landforms, but also summarise the geomorphology in a sufficiently simplified form to enable the viewer to readily comprehend them (Anderson *et al.*, 1998). Consequently, genetically similar landforms were mapped collectively as landform assemblages, though some individual landforms were represented as distinct entities to avoid oversimplification and to fulfil the research aims.

4. Glacigenic landforms and sediments

Glacial landforms in the Lago Tranquilo area can be grouped into four distinct landform assemblages on the basis of their morphological and topographic characteristics (Table 1). These are referred to as the Stage One, Two, Three and Four landform assemblages.

4.1. Stage One glacial landform/sediment assemblage

Landforms

Stage One moraines are associated with recent glacier recession and are found at the snouts of contemporary valley and cirque glaciers (Fig. 3). The largest of these moraines occurs as a terminal ridge in front of Glaciar Exploradores.

Sediments

In April 2003, a large low-lying waterlogged area existed between Lago Bayo and the snout of Glaciar Exploradores, preventing access to the glacier snout. Therefore no sedimentary descriptions were possible at the moraine.

Glacier recession from this moraine has been dated by dendrochronology to the end of the nineteenth century (Lara pers. comm.). Moraines of similar morphology and relationship to contemporary glaciers are widely reported from other glaciers of the Hielo Patagónico Norte and dated by lichenometry and dendrochronology to the "Little Ice Age" (*e.g.* Winchester and Harrison, 1996; Winchester *et al.*, 2001). However, Aniya and Naruse (1999) dated similar moraine formation to 1300 BP in the Soler valley and it is clear that such moraines may have been

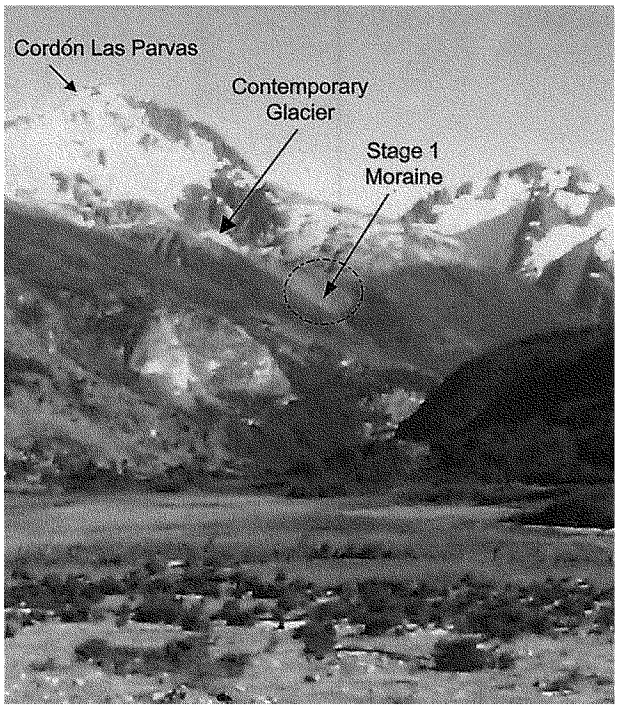

Fig. 3. Stage 1 moraine in the vicinity of a small valley glacier, west of Lago Tranquillo.

formed during several episodes of glacier expansion and retreat. As a result, there is some ambiguity as to the age of the Exploradores moraine, which will be resolved by a planned dating programme. However, in this paper we tentatively suggest that this moraine was last in contact with the glacier during the Little Ice Age.

4.2. Stage Two glacial landform/sediment assemblage

Landforms

Stage Two moraines are restricted to <20m high sharp-crested terminal moraines deposited at the mouths of tributary valleys at altitudes above *c.* 850 metres above sea level.

Sediments

Natural exposures in the Stage Two moraines show that they are composed entirely of sandy boulder gravel. Although texturally variable, the sandy boulder gravel is typically a massive boulder gravel in

Table 1. Morphological and topographic characteristics of glacial landform assemblages associated with glacial Stages One to Four in the Exploradores valley.

	Stage One	Stage Two	Stage Three	Stage Four
Altitude range of drift	470-700m	180-700m	400-900m	<200-700m
Maximum moraine ridge thickness	15m	40m	25m	15m
Moraine ridge slope gradients	10-25°	10-30°	10-40°	10-25°
Maximum drift sheet thickness	20m	14m	2-3m	20m
Bedrock striations	Frequent	Frequent	Not observed	Rare/degraded

a sand matrix. The following proportions are typical: gravel 60%, sand 30% and mud <10%. Clast distribution within this facies is variable, with gravel-sized clasts occurring either in clusters or in contact with one another. Lithological counts (n=100) show that the gravel-sized clasts comprise granite (72%) and schist (28%). The gravel-sized clasts are predominantly subrounded (60%) and subangular (36%), with lower percentages of rounded (2%) and well rounded (2%) clasts. The largest boulders have b-axes of up to 1.5 m.

Interpretation

Texturally, the sandy boulder gravel is very similar to the sandy boulder gravel described by Glasser and Hambrey (2002) at the contemporary margins of Glaciar Soler on the eastern side of the Hielo Patagónico Norte. Here they were interpreted as an ice-marginal deposit formed from the mixing by glaciotectonic processes, slumping and stream sorting of different parent populations (basal glacial, supraglacial and glaciofluvial sediments) at the glacier margin. Evidence for this interpretation comes from the heterogeneous sediment texture, clast roundness and low proportions/absence of striated and faceted clasts.

It is clear that these moraines and sediments are older than the 'Little Ice Age' moraines developed in the region. However, their small size and position suggest that they reflect a short-lived climate deterioration, probably during the latter part of the Holocene.

4.3. Stage Three glacial landform/sediment assemblage

Landforms

Stage Three glacial deposits and landforms form large (*c.* 100 m high) sharp-crested terminal and lateral moraines and are mainly found to the west and south of Lago Tranquillo (Figs. 4 and 5). Several of the lateral moraines form multiple features. Boulders are common on their surfaces and up to 8m or so in height; many are weathered with considerable spalling of surface layers. The altitude of these landforms falls from 600–900 metres above sea level in the east of the area to 400 metres above sea level further west.

Sediments

A *c.* 15 m high natural exposure in the inner flank of one of the Stage Three moraines in the tributary valleys shows that these moraines are composed of two distinct sedimentary facies, with *c.* 5 m of sandy boulder gravel overlying *c.* 10 m of sandy gravel.

The sandy boulder gravel, although again texturally variable, is typically a massive boulder gravel in a sand matrix. The following proportions are typical: gravel 60%, sand 30% and mud <10%. Clast distribution within this facies is variable, with clasts occurring either in clusters or in contact with one another. Lithological counts (n=100) show that the gravel-sized clasts comprise granite (60%) and schist (40%). The gravel-sized clasts are subrounded (52%) and subangular (48%). The largest boulders have b-axes of up to 2 m.

The sandy gravel facies is a moderately well sorted unit, consisting of gravel (70%) and sand (30%). Lithological counts (n=100) show that the gravel-

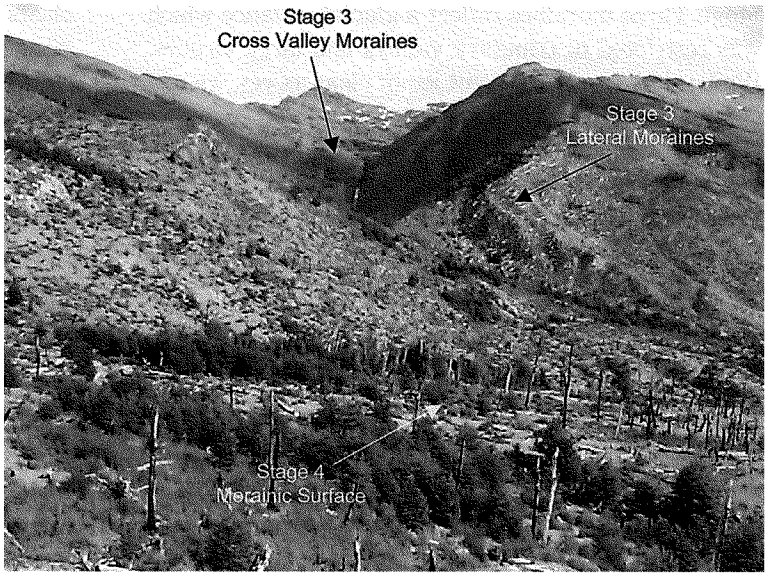

Fig. 4. Stage 3 moraines to the west of Lago Tranquillo. Stage 4 surface in the foreground.

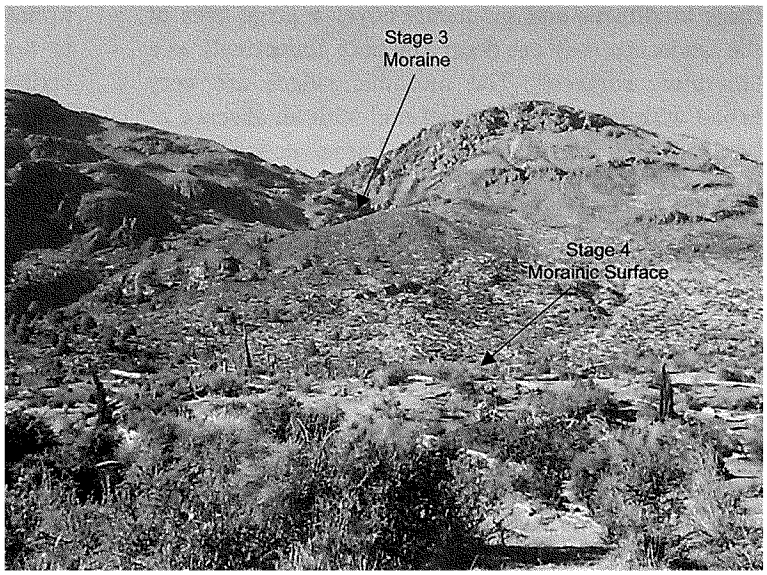

Fig. 5. Stage 3 moraine and Stage 4 drift-covered surface to the south of Lago Tranquillo.

sized clasts comprise granite (70%) and schist (30%). The gravel-sized clasts are subrounded (58%), subangular (40%) and angular (2%). The largest gravel-sized clasts have b-axes of up to 0.1 m.

Interpretation

The sandy boulder gravel in the Stage Three moraines is interpreted as an ice-marginal deposit formed from the mixing by glaciotectonic processes, slumping and stream sorting of different parent populations (basal glacial, supraglacial and glaciofluvial sediments) at the glacier margin (see interpretation of Stage Two sandy boulder gravel, above). The sandy gravel facies is interpreted as a reworked glaciofluvial deposit on the basis of its sorting, clast roundness and absence of striated and faceted clasts (Glasser and Hambrey, 2002).

The landforms and sediments associated with Stage Three moraines reflect a glacial advance which was restricted to tributary valleys and large cirques. Whilst the age of this event is not clear as yet, we can speculate that it represents a significant climatic deterioration during the Holocene or the Late-Glacial. In the Leones valley to the south, the large glacial moraine damming the eastern side of the Lago Leones has been dated to *c.* 3000 years BP using OSL dating of lacustrine sediments 5 m below the crest of the moraine (Haresign *et al.*, unpublished data) and it would be surprising if such a climatic event was not represented in other valleys draining the icefield.

4.4. Stage Four glacial landform/sediment assemblage

Landforms

Stage Four depositional landforms include moraines; drift hummocks; bedrock-cored ridges; large fans and kames, and their associated sediments (Fig. 5). These are concentrated in an area 1-2 km to the west, south and east of Lago Tranquillo. Since these landforms and sediments cover a large area of the landscape they are described here collectively as a "morainic surface". The morainic ridges are very broad with low relative relief and with an absence of boulders on their surfaces. These deposits are restricted to below 500 metres above sea level.

Sediments

Natural exposures in the moraines, drift hummocks and bedrock-cored ridges of the Stage Four morainic surface are rare and observations are confined to hand-excavated sections. These show that the morainic surface generally forms a thin (*c.* 0.5 - 2 m thick, but locally thicker in places) layer of sandy gravel, sandy boulder gravel or diamicton draped on a gently undulating bedrock surface. The sandy gravel and sandy boulder gravel are texturally similar to those described above as part of the Stage Three glacial landform/sediment assemblage. The diamicton is a massive, clast-rich silty diamicton, comprising gravel (50%), sand (40%) and mud (10%). The gravel-sized clasts are typically subrounded (66%) and subangular (32%), with minor angular (2%). Lithological counts (n=200) show that the gravel-sized clasts are typically dominated by schist (88%) with lower proportions of granite and other undifferentiated rocks (12% combined). Striated and faceted clasts are common, with up to 26% striated clasts and 32% faceted clasts in samples of 50.

The fans are large (*c.* 80 m high and 250 m wide) accumulations of sand and gravel located at the mouths of tributary valleys. The largest of the fans, at the mouth of the Rio Norte Valley, is primarily composed of a locally crudely-bedded to well-sorted sandy cobble gravel. It is texturally variable but typical proportions are gravel (80%) and sand (20%). Lithological counts (n=200) show that the gravel-sized clasts comprise schist (86%) and granite (14%). The gravel-sized clasts are subrounded (78%), rounded (16%), subangular (4%) and well rounded (2%). The largest gravel-sized clasts have b-axes of up to 0.5 m.

The kame features, located on the valley floor, are low (*c.* 7m high), elongated (*c.* 15 m diameter) mounds of sand and gravel. Sections through the kames show well-stratified units composed of variable amounts of sands and gravels. In many cases the units show evidence of post-depositional faulting.

Interpretation

The sandy boulder gravel and sandy gravel are texturally similar to those described above as part of the Stage Three glacial landform/sediment assemblage and are therefore similarly interpreted as ice-marginal deposits and reworked glaciofluvial sediments respectively. The diamicton is interpreted as a basal glacial deposit on the basis of clast roundness (subrounded and subangular clasts), and the presence of numerous striated and faceted clasts. In addition, it is texturally similar to basal glacial deposits described from contemporary temperate glaciers of the Hielo Patagônico Norte (Glasser and Hambrey, 2002).

The large fans composed of sand and gravel at the mouths of tributary valleys are interpreted as alluvial fans deposited adjacent to, or onto, glacier ice in the main valley. Evidence for this is their position relative to the main valley, their sedimentary composition (locally crudely-bedded to well-sorted sandy cobble gravel with subrounded and rounded clasts and no striated clasts). Sedimentologically, these deposits are very similar to those described from contemporary glaciofluvial environments at temperate Patagonian glaciers (Glasser and Hambrey, 2002).

The faulted and bedded sand and gravels exposed in the kames demonstrate that they were deposited in an ice-contact environment in association with buried masses of ice. The activity of glaciofluvial meltwater

streams is suggested by the well-bedded nature of the sand and gravel units. Such sediment associations are typical of those found in proglacial locations in other Patagonian valleys (*e.g.* Aniya, 1987; Harrison and Winchester, 1998).

Collectively, these landforms and sediments comprise a main valley glaciation event. To the west and north of Lago Tranquillo, the valley glaciers have produced a landscape dominated by glacial erosion of bedrock. The few drift landforms developed in this eastern sector of the valley comprise Holocene alluvial and debris cones at the mouths of tributary valleys. The only well-developed moraine here occurs near the present snout of Glaciar Exploradores and this is interpreted here as being younger than Stage Four.

5. Discussion

No dates are yet available in which to place these glacial stages into chronological context and we are therefore unable to place them into either a Mercer-type or Aniya-Type moraine date scheme. We can, however, compare their morphological and spatial characteristics to those of moraines developed in other valleys in the region. In many of the valleys draining the eastern side of the icefield, three or four distinct glacial stages can be recognized. For instance, in the Leones valley 20 km to the south of the study area, three major moraine systems are recognized (Harrison and Glasser, unpublished data). On morphostratigraphic grounds, and based upon their size and position with regard to the present-day ice front, these correlate with Stages One, Three and Four described in this study and display similar landform/sediment associations. Further correlations between the moraine sequences observed in the Exploradores valley and those from other valleys draining the icefield will require large-scale mapping of the glacial geomorphology of the icefield.

Acknowledgments

This work was funded by grants from the Royal Geographical Society (grant RGS 03/02) the QRA and the UK Natural Environment Research Council (grant NER/B/S/2002/00282). We thank Raleigh International for field logistical support in Chile. We extend our thanks to the following people at Raleigh International who provided field assistance in March/April 2003: Esther Baker, Ruth Creamer, Lucy Dickinson, Ali Gentleman, Richard Halliday, Mike Lee, Steve Mahoney, Wang Pui Ming, Dan Morrice, Bram Nawijn, Andy Nelson, Angelo Nunes-Gomez, Karen Straw and Catherine Sweeney. The figures were drawn by Antony Smith and Ian Gulley of the Institute of Geography and Earth Sciences, University of Wales, Aberystwyth.

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