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ROCKFALLS AND GLACIER CONTRACTION: CIRQUE DE TROUMOUSE, FRENCH PYRENEES

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ABSTRACT.- The incidence of rockfalls within the Cirque de Troumouse appears to have been triggered by ice wastage and the resultant geomorphological pattern of rockfall deposits affords an insight into the migration of headwall weathering zones. Observations of the rockfall deposits indicate clear geological controls which may be directly related to the exposure of the headwall zone during phases of glacier wastage.

RESUMEN.- Las caídas de piedras en el Circo de Troumouse parecen haber sido desencadenadas por la acción del hielo, y el modelo geomorfológico de depósitos de bloques resultante proporciona una idea sobre la migración de las zonas de meteorización en las paredes. Las observaciones de tales depósitos indican la existencia de claros controles geológicos que pueden relacionarse directamente con la exposición de la pared durante las fases de fusión glaciar.

RÉSUMÉ.- Les chutes des pierres dans le cirque de Troumouse paraissent avoir été déclenchées par l'action de la glace, et le modèle géomorphologique des dépôts de blocs résultant donne une idée de la migration des zones de météorisation dans les parois. Les observations de ces dépôts indiquent l'existence de contrôles géologiques très clairs qui peuvent être directement liés à l'exposition de la paroi durant les phases de fusion glaciaire.

Key Words: *Rockfall, Glacier, Holocene, Troumouse.*

1. Introduction

A number of recent studies have highlighted the dynamic nature of long-term environmental change within the Pyrenees (Jalut *et al.*, 1992; Gellatly *et al.*, 1992; Reille & Lowe 1993). Palaeo-environmental reconstructions recognise valuable signals of the unstable and occasionally sensitive nature

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of landscape evolution during the Postglacial period. During episodes of glacier contraction in the middle Holocene, rockfall incidence increased.

Within the Pyrenées, detailed field observations have been made in the Cirque de Troumouse where a series of rockfall deposits have been recorded. The relationship between rockfalls and reconstructed ice margins is examined, and the incidence of rockfall activity is considered within the the context of the Holocene deglaciation of the cirque (Gellatly *et al.,* 1992) and recent geomorphological change (Parkinson & Gellatly, 1991). Tlle sequence of glacier fluctuations is related to the sediment budget, slope instability and rockfall incidence and a model of late Holocene geomorphological evolution of the Cirque de Troumouse is proposed.

2. Cirque de Troumouse

The Cirque de Troumouse (alt. 2100 m) lies in the headwaters of the Gave de Pau. The cirque is one of the most extensive upland basins in the Pyrenées. During the Late Holocene, ice persisted in the Troumouse basin where a complex geomorphological history of glacial and periglacial landforms is recorded (Fig.1). Today 2 small glaciers remain in the cirque. The principal glacier, la Munia 2850-2700m, occupies a shallow basin less than 260 m long and 220 m wide beneath Pic la Munia (3133 m). A prominent late-19th/early 20th century moraine encircles the leading ice edge. The second, innominate glacier (2400 m) lies sheltered beneath the headwall of Péne Blanque. Former expansion of both glaciers to produce a coalescent ice lobe extending over the cirque floor is clearly indicated from the record moraine deposition (Fig.2).

The principal drainage of the cirque is from la Munia and associated, semi-permanent snowfields. Small streams feed Lac des Aires (2089 m) and these lakes in turn drain into the lower Heas valley. A subsidiary drainage pattern is associated with Lac d'Esbarris (2139 m) and Lac de Serre longue (2190 m). An ephemeral stream network drains NNW into the adjacent Cirque d'Estaube.

3. Glacial History

The present day snowline in the central high Pyrenées is estimated to lie about 2900-2950 m. The regional snowline rises above 3100 m further east, being generally lower on the northern slopes. Locally, topographic control exerts a strong influence on glacier survival. Clear comparative advantage is shown by glaciers below the north-facing headwalls, sheltered from insolation but receptive to the redistribution of snow cover. Within the Cirque de Troumouse the two surviving glaciers exhibit contrasting characteristics. La Munia, the more prominent of the two glaciers, is oriented NNW. It lies within 200 m elevation of the regional snowline in an exposed, shallow basin below

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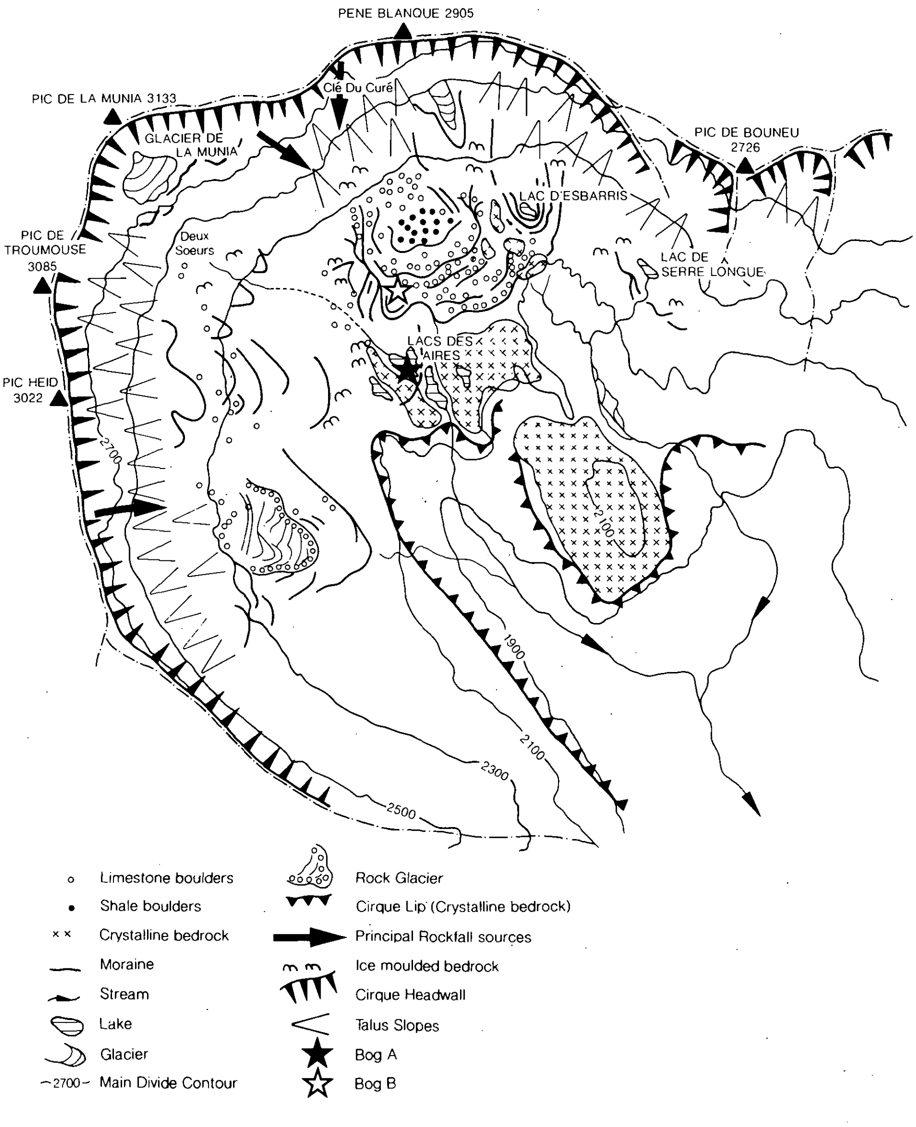

Figure 1. Geomorphological Map, Cirque de Troumouse.

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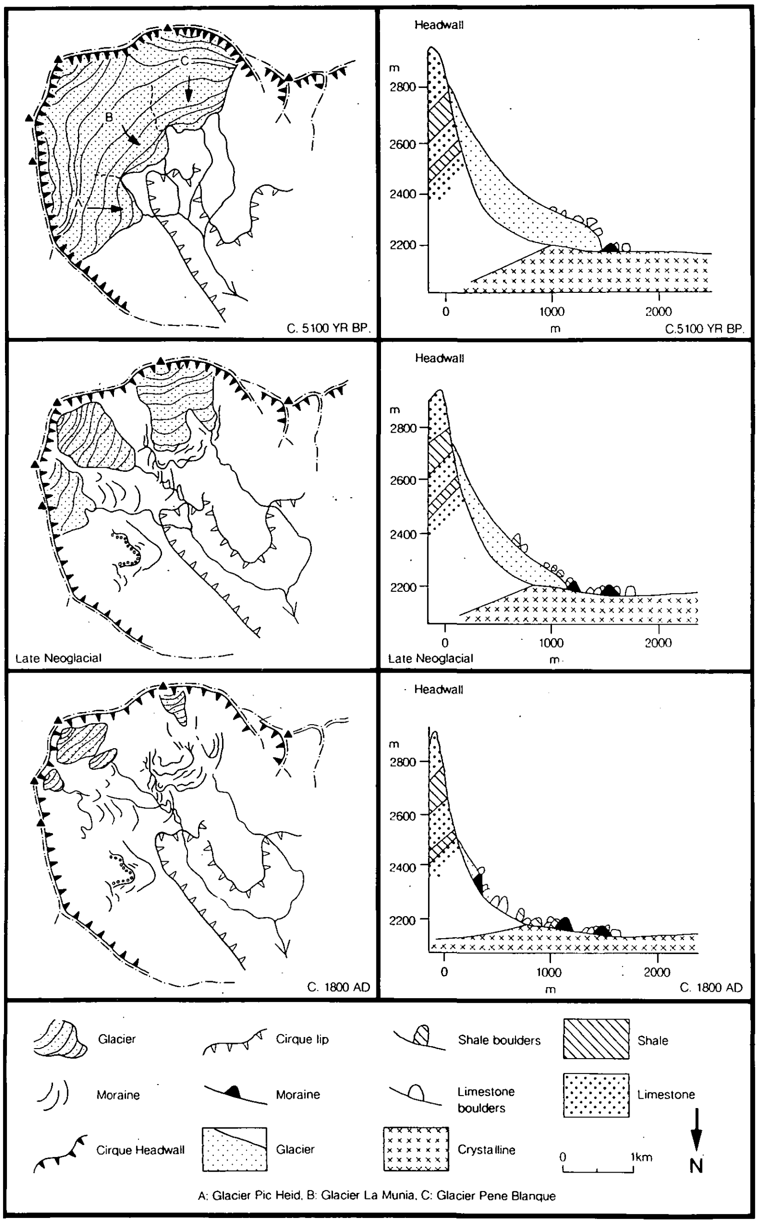

Figure 2. Schematic diagrams of glacial history in Cirque de Troumouse; a) Maximum Neoglacial ice expansion, pre- 5100 YR BP b) Late Neoglacial and onset of deglaciation c) Little Ice Age, c 1800 AD

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Pic de la Munia. In contrast, the glacier beneath Péne Blanque is orientated due North, and terminates around 2450 m, that is, c. 450 m below the estimated regional snowline. The more complete moraine sequence is associated with this latter glacier. During the Little Ice Age both glaciers enlarged. Glacier Péne Blanque did not expand beyond the existing moraine limits at 2352 m and twentieth century recession has been characterised by ice thinning and downwasting. La Munia expanded at least as far as 'les Deux Soeurs' 2359 m on the talus slopes below the headwall during the early 18th century. Its full Little Ice Age limits are not known. Clearly both glaciers responded to a considerable lowering in the regional snowline during the Little Ice Age period (c.2500 m, see Table 1.).

The glaciers in the cirque expanded and coalesced during the late-Holocene as is demonstrated by the deposition of moraines on the cirque floor. The palaeosnowlines and ELA's were estimated from accumulation-area ratios of the former glacier extent. Surfaces of each of the glacial extents were approximated from topographic maps and aerial photograplls using moraine limits. The glacier surfaces were contoured at 50m intervals and a graph of cumulative percentage at each altitude derived for each phase of cirque glaciation. Accumulation-area ratios (AAR) of 0.65 and 0.6 are presented for comparison (Table 1.).

Alternative methods for the calculation of the ELA's were found to be unreliable. Meierding (1982) suggests the use of the maximum altitude of lateral moraines for determining former ELA's. However, strong topographic control of the headwall imposes height restrictions on the extent of lateral moraines. Similarly the use of the 'glaciation threshold' and 'cirque floor altitude' are both inappropriate measures of ELA as the Cirque de Troumouse is at the head of a glaciated valley. None of these methods can account for

TABLE 1.

Reconstructed equilibrium -line altitudes for the glaciers in the Cirque de Troumouse, using the height of lateral moraines and accumulation/area ratios of 0.65 and 0.6.

Glacier	Max. Alt. Lateral Moraine	Age yr	ELA (0.65)	ELA (0.6)
Péne Blanque	2140 m	>4815 BP	2220	2250m
La Munia	2090 m	>5190 BP	2230	2245
Péne Blanque	2155 m	Neoglacial	2270m	2295
La Munia	2150 m	Neoglacial	2265m	2280
Péne Blanque	2350 m	1850 AD	2490m	2510
La Munia	2350 m	1850 AD	2500	2505
Péne Blanque	2375 m	1910 AD	2515	2510
La Munia	2165 m	1910 AD	2520	2510

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the additional influence of snow-blowing and snow nourishment within the cirque, a factor which clearly contributes to the enhanced lowering of the regional snowline and glacial expansion (Gellatly *et al.*, 1992).

The glacial and periglacial landforms in the eastern section of the cirque remain undated. The rock glacier deposit is problematic. Rock glaciers from elsewhere in the Pyrenees have been dated to the Late-Glacial ('Tardiglaciare'), 'Younger Dryas' and Neoglacial events (Taillefer 1983, Hazera, 1983). The time-transgressive nature of rock glacier surfaces, and the possibility of reactivation during periods of climatic deterioration preclude accurate age interpretation of these features within the high Pyrenean cirques at the present time.

4. Geological evolution of the cirque

The Cirque de Troumouse lies within the axial zone of the Pyrenees, a belt of intensely folded and faulted Palaeozoic rocks (Parish, 1984). Pre-Mesozoic basement rocks outcrop near the lip of the cirque at 2100 m. These are comprised of granitic gneisses, marbles and schists. The basement rocks are overlain by Upper Cretaceous white limestones. A series of springs demarcate the extent of the limestone across the floor of the cirque near the

Figure 3. Rockfall deposits and glacial deposits below the headwall, Cirque de Troumouse. The extension fault is picked out by the major gully system of the Cle de Cure.

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Lacs des Aires. The headwall is comprised of tectonised sediments of the Lower Gavarnie Nappe with outcrops of Silurian shales overlain by Lower Devonian, interbedded limestone and shale. The uppermost rocks of the headwall are massive outcrops of grey or white limestone forming the Sugar Marble Formation. Within the Cirque de Troumouse a series of lithological units are exposed in a sequence of thrust slices forming a piggy-back series. An extension fault cuts across the headwall and may be traced over the lower basin. Its line is clearly depicted by the Clé de Curé to the east of Péne Blanque. This prominent gully is the source of debris for a series of major rockfall events (Fig. 3).

The cirque floor is extensively covered with glacial and periglacially-derived deposits, derived from the headwall. Moraines comprised of limestone and shale debris from off the headwall rest directly upon the crystalline bedrock. Isolated outcrops of granitic gneisses have been mapped on the cirque floor suggesting that the drift cover is between 3-5 m in thickness. Superimposed upon the glacial drift are extensive rockfall deposits, which can be traced to probable source areas along the headwall. Lac des Aires rests entirely within the crystalline bedrock region. The other two prominent lakes are formed within the drift cover.

5. Geomorphological mapping

Landforms within the cirque are predominantly glacial or nivational in origin. Seasonal snow and ice melt influences both talus slopes on the headwall and the pattern of ephemeral drainage within the cirque. Figure 1 shows the principal geomorphic features in the cirque. The western and central cirque basin is dominated by well-defined terminal moraines. Outwash below La Munia has probably detroyed further deposits relating to former ice advances. The eastern cirque basin is characterised by a relict rock glacier, moraine and nivational ridges.

Located within the moraine complexes are a series of shallow bogs. Material sampled from these bogs have yielded details of the sedimentary records of late-Holocene environments within the cirque. The basal and near-basal sediments from two bogs have been radiocarbon dated (Gellatly *et al.*, 1992) and indicate a period of ice withdrawal shortly after 5190 $\pm$ 90 BP which was interrupted by a short readvance between 4955 $\pm$ 90 BP and 4654 $\pm$ 60 BP. Subsequently ice contracted within the Cirque and two further periods of moraine deposition occurred although these remain undated. 'Little Ice Age' expansion of the glaciers led to the deposition of moraines below the cirque headwall at 2350 m.

Extensive rockfalls have fallen onto the glaciers throughout the Holocene and rockfall-derived material has been incorporated into the moraines. Certain of the former ice front positions are occasionally delimited by discrete boulder-lines. Rockfalls continued to occur during deglaciation of the cirque, partially burying older moraines. The rockfalls can be traced to the

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different lithological units of the headwall, suggesting a relationship between deglaciation, headwall exposure and slope failure (Fig. 2). During periods of more extensive ice cover, glaciers expanded and obscured much of the headwall slope area. Debris detached from the headwall accumulated at the foot of the glacier lobes adjacent to, or resting on the outermost, Holocene moraines. Subsequent downwasting and ice marginal retreat resulted in debris from lower down the headwall being released, and different lithologies contributed to the pattern of rockfalls. As the glacier snouts receded, rockfall debris accumulated closer to the base of the headwall. A time-transgressive pattern of rockfalls of specific provenance is recorded on the cirque floor, marking the progressive thinning and retreat of the glaciers. Bands of limestone and shaley deposits mirror the progressive exposure of geological outcrops on the headwall. Such a relationship is particularly well developed for the central and western section of the cirque in association with the extension fault of the Clé du Curé, below Péne Blanque (Fig.3).

This proposed sequence of glacier contraction, wastage and slope instability is supported with sedimentary evidence from the two bogs located within the moraine limits (Fig.1). The low amount of organic matter in the bog sediments points to reduced biological activity in lakes which were probably fed by glacial melt waters. The sudden increase in organic matter reflects both a warming in climate but also the reduction in glacier melt waters. The sedimentary sequence from the two bogs demonstrate the greater disturbance within Bog B where spikes of coarse sand and slope wash material interrupt the progressive accumulation of organic material. No such interruptions are shown in the sequence from Bog A, which is positioned further away from the headwall and appears to be less disturbed by the rockwall weathering.

6. Discussion

Rockfalls occurring in a glacial environment are usually modified resulting in redeposition and sorting. The glacier system frequently provides an effective removal mechanism for slope debris. According to Whalley (1984) the overall efficiency depends on the removal rates and on local factors. Within the Cirque de Troumouse, topographic factors, that is the expanse of headwall and the enlarged cirque basin-floor are relevant when examining the association between debris input and glacier dynamics.

The spatial-temporal pattern of rockfall activity in mountainous regions has been related to climate change, geological controls and geotechnical properties (Whalley *et al.*, 1983). Studies in Iceland, suggested that mechanical triggers may help to better explain the incidence of rockfall activity whilst climate controls may not be of particular importance (Whalley *et al.*, 1983). However, Gardner (1987) examines the association between rockfalls and long-term glacier fluctuations and notes that progressive thickening and

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thinning of glaciers can result in 'large areas of marginal and headwall rock surfaces being exposed to the *ranzdkluft* weathering environment over long periods of time', (Gardner, 1987, p.60).

Weathering of debris on the headwall is integral to the explanations regarding debris supply and the timing of debris inputs into the glacial system. The unusually high headwalls in certain Pyrenean cirques may be explained by the migration of the headwall weathering zone in response to glacier fluctuations (Fisher, 1955; Gardner, 1987). During periods of glacier expansion a subsidiary ice body developed at the base of the headwall, and a contiguous ice body with La Munia would have developed. However, during periods of glacier contraction the two ice bodies would have been topographically severed and the model of glacier behaviour presented here invokes an opportunity for a vertical lowering of the headwall weathering zones.

The rockwall geology is important since the differentiation of lithological units permits the demarcation of unique source areas for debris and points of slope failure. The extension fault of the Clé de Curé is a clear source of large debris failures, whilst the junction between the crystalline basement rocks and the early slip horizon of the Silurian shales represent another possible zone of differential weathering.

These rock types and their stratigraphic arrangement appears to be favourable to weathering and failure. Further work is required to determine the different levels of susceptibility of the individual units of the Lower Gavarnie nappe present on the headwall. Examination of the postdepositional (both primary and secondary deposition from the ice) rockfall erratics suggests that the Silurian shales, from near the lower headwall slopes weather at a faster rate than the clasts and boulders of sugar marble and bedded limestones despite these latter two units having been both exposed for a longer period of time. In some instances individual boulders of Silurian shale (>2ton) are almost buried under a carapace of weathered debris.

Progressive vertical migration of the headwall weathering zone may, through time have helped to accentuate the anomalously steep rockwall in the Cirque de Troumouse. This is the largest, most extensive cirque basin in the Pyrenees, and it is unusual in that the cirque floor at 1700-1850 m was occupied by glaciers throughout the Holocene. The series of discrete, rockfall events took place during the phase of late-Holocene ice wastage. The rockfall deposits appear to have been partially redeposited by ice into well defined ridges which lie sub-parallel to the former ice margin, and are to a certain extent incorporated into moraine deposits. By implication the rockfalls must have occurred prior to or in association with phases of ice marginal deposition. The rockwall erratics are virtually absent beyond the limit of the outermost moraine in the cirque. There is limited stratigraphical evidence of catastrophic slope failure off the headwall which would have buried all previous glacigenic records. Rather, a model for progressive slope failure and debris release are inferred, and a model for glacier transport and redistribution is proposed.

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7. Conclusion

Records of Holocene ice retreat indicate that the glacial history may be associated with the sequence of rockfalls and slope instability. Patterns of Holocene ice withdrawal and geomorphological instability can be reconstructed using the distinctive rockfall units. Although the spatial distributions remain undated, the relative stratigraphic sequence can be determined with reference to the diagnostic geological control of the headwall, and its exposure with ice withdrawal.

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