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LATERAL MORAINES OF GLACIER DE TSIDJIORE NOUVE: FORM, DEVELOPMENT, AND IMPLICATIONS

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ABSTRACT. The relationship between supraglacial lateral moraines and lateral dump moraines at Arolla, Switzerland, is discussed. A detailed study of the lateral moraines of glacier de Tsidjiore Nouve reveals their complex form (as superimposed and nested ridges) and the current mode of development (possibly related to the passage of a kinematic wave). Sedimentological analysis indicates that much of the constituent debris is of supraglacial origin; it is transported either directly from the base of slopes flanking the Pigne d'Arolla ice-fall or via englacial septa comprising marginal sediment incorporated in the accumulation zone. A calculation of the volume of debris in the lateral moraines suggests that glacier de Tsidjiore Nouve has recently been more active in transporting and depositing supraglacial debris than in glacial erosion *sensu stricto*.

RÉSUMÉ. *Moraines latérales du glacier de Tsidjiore Nouve: forme, développement et conclusions.* On discute les rapports entre les moraines latérales de surface et les moraines latérales de dépôt à Arolla en Suisse. Une étude de détail des moraines latérales du glacier de Tsidjiore Nouve révèle leur forme complexe (avec des ondulations en séries surimposées) et leur mode normal de développement (peut-être lié au passage d'une onde cinématique). Une analyse indique que beaucoup des sédiments constitutifs sont d'origine supra-glaciaire; ils sont transportés soit directement depuis le pied des pentes bordant les chutes de sérac de Pigne d'Arolla ou par l'intermédiaire d'impuretés intraglaciaires comprenant des sédiments marginaux incorporés dans la zone d'accumulation. Un calcul du volume de sédiment dans les moraines latérales porte à conclure que le glacier de Tsidjiore Nouve a été récemment plus actif pour le transport et le dépôt de sédiments supraglaciaires que pour l'erosion glaciaire *sensu stricto*.

ZUSAMMENFASSUNG. *Seitenmoränen am Glacier de Tsidjiore Nouve: Form, Entwicklung und Folgerungen.* Die Beziehungen zwischen Seitenmoränen auf der Oberfläche und seitlich abgelagerten Moränen auf Arolla, Schweiz, werden diskutiert. Eine detailierte Untersuchung der Seitenmoränen des Glacier de Tsidjiore Nouve lässt deren komplexe Form (als überschobene und verzahnte Rücken) und die aktuelle Art ihrer Entwicklung (möglicherweise verbunden mit dem Durchgang einer kinematischen Welle) erkennen. Eine sedimentologische Analyse zeigt, dass ein Grossteil des beteiligten Schuttes von der Oberfläche des Gletschers stammt; er wird entweder direkt vom Fuss der Hänge an den Flanken des Pigne d'Arolla-Eisfalls oder über intraglaziale Scheidewände transportiert, die Sedimente vom Gletscherrand, aufgenommen in der Akkumulationszone, enthalten. Eine Berechnung des Schullvolumens in den Seitenmoränen lässt darauf schliessen, dass der Glacier de Tsidjiore Nouve in letzter Zeit grössere Aktivität beim Transport und bei der Ablagerung oberflächlichen Schuttes entwickelt hat als bei der glazialen Erosion im strengen Sinn.

INTRODUCTION

Lateral moraines are defined by Flint ([^{c}1971], p. 200) as end-moraines built along the lateral margins of glaciers occupying valleys. The implication is that the moraines comprise debris that has slid off the ice-surface into the ablation valley between the glacier and valley wall. This is supported by Boulton and Eyles (1979) who refer to "lateral and latero-frontal dump moraines from supraglacially derived debris". Embleton and King (1975, p. 433) describe lateral moraines that comprise "only a thin covering of surface debris resting on the ice and derived from the rock-walls of the valley". These supraglacial lateral moraines (by contrast with the dump moraines beyond the ice) consist of ice-cored ridges, up to 10 m or more in height, resulting from differential ablation of debris-covered and bare ice. Figure 1a shows the relationship between supraglacial and dump moraines. The latter are progressively built up by successive increments

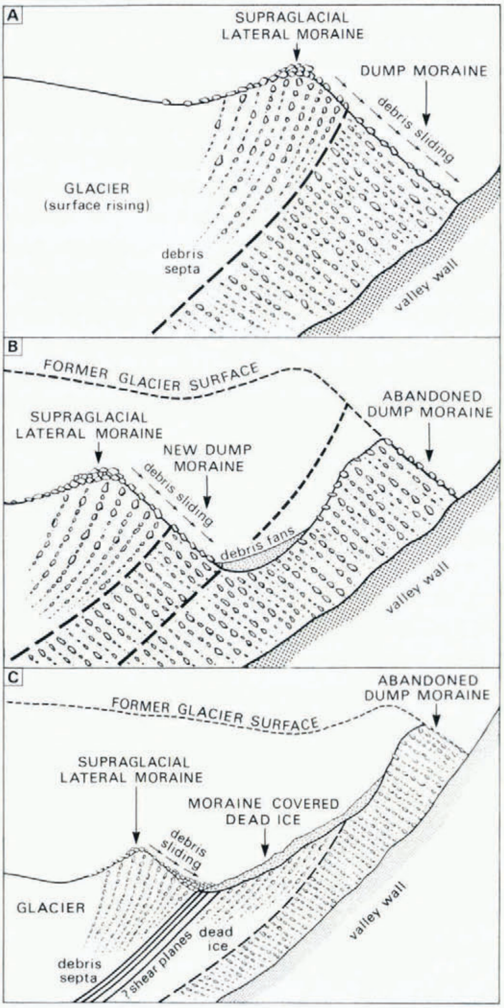

Fig. 1. (a) Formation of lateral dump moraine by sliding of debris from the crest of a supraglacial lateral moraine under conditions of rising glacier surface. (b) Formation of abandoned dump moraine by glacier recession and lowering glacier surface, followed by a limited re-advance and formation of new dump moraine. (c) Formation of abandoned dump moraine and debris covered dead ice mass by a rapid lowering of the glacier surface during the retreat phase of the Little Ice Age (c. 1850–1960). Note the possible formation of shear planes between the dead and flowing ice.

of debris from a rising glacier surface, and display a crude fabric comprising slabby boulders and blade-like clasts dipping towards the valley wall at 10–40°. Sugden and John (1976, p. 241) state that lateral moraines are associated with complex particle movements (contrasting with the more direct "throughput" characteristics of debris transport on medial moraines). Debris on lateral moraines is deposited temporarily and then reincorporated into the glacier any number of times as the glacier margin rises and falls, and expands and contracts, over a period of thousands of years.

Observation of glaciers at Arolla, Valais, Switzerland indicates that a two-fold division into supraglacial and dump moraines is perhaps oversimple. Three broad categories of lateral moraine have been identified on and above the Haut-Arolla, Bas-Arolla, and Tsidjiore Nouve glaciers.

(i) *Supraglacial lateral moraines* occur on all the glaciers, and are in many respects comparable with medial moraines in the area (Small and others, 1979). However, some are more complex in form owing to the presence of large melted-out marginal crevasses. The debris cover of the moraines is derived directly from weathering and collapse of supraglacial rock faces below the firn line (at *c*. 2 900 m) or indirectly from englacial debris septa incorporated well above the firn line (see below).

(ii) *Abandoned dump moraines* (Fig. 1b) consist of sediments standing characteristically 100 m or more above the present glacier (see the western moraine of Bas Glacier d'Arolla). The proximal slopes of the moraines, incised by numerous closely spaced gullies, attain angles of up to 70° or more; the distal slopes are more limited in length, gentler, stable, and partially vegetated. In some instances small debris ridges occur between the supraglacial moraines and the abandoned moraines; these apparently coincide with lines of shear between the moving ice and the margin of the dump moraines. It has been widely assumed that the large abandoned dump moraines were deposited during the Little Ice Age (*c*. 1550–1850) and left in their present positions by the glacial recession since 1850. However, Röthlisberger (1976) and Röthlisberger and Schneebeli (1979) have demonstrated from the evidence of fossil soils and buried tree trunks that the "moraine walls" of this part of Valais were "built up at least by the advances of the last 3 500 years" and probably "during the last 9 000 years" in some instances.

(iii) *Moraines on dead-ice masses* have been observed above the eastern margins of Haut Glacier d'Arolla, in the form of debris covered ice slopes, the ablation of which has been greatly retarded by a 1–2 m debris layer. At some points the dead-ice cores are intermediate between abandoned dump moraines above and supraglacial lateral moraines below (Fig. 1c). Slippage of debris occasionally bares the ice, resulting in locally accelerated ablation. However, ablation rates overall are extremely low, and the ice cores are clearly of considerable age (Østrem, 1959). It can be inferred from the survey of glacier d'Arolla by Mercanton (1910) that the ice masses became detached from the margins of the main glacier during a major recession some 50–70 years ago.

The Tsidjiore Nouve lateral moraines: description and age

These are of exceptional interest for a variety of reasons. To north and south of the glacier the lateral moraines form massive debris embankments, up to 60 m in height on their distal flanks, which in effect confine the glacier like giant levées (Fig. 2). In large measure they are "fossil" features, dating from the Little Ice Age and other Post-Glacial advances, and are therefore apparently classifiable as abandoned moraines. However, at present the summits of the northern moraine ridge are being surmounted by glacier ice, and large quantities of supraglacial debris are being shed from the glacier surface onto the distal slope over a distance of approximately 400 m. This provides an unusual example of dump moraine formation in action, and an opportunity to study the processes that, in the past, contributed to the development of the Tsidjiore Nouve moraines.

The "overtopping" of the nothern lateral moraine was first noted in 1970 (as an area of bare ice 10 m long and a maximum of 5 m down-slope), and reported in 1973 (Whalley, 1973) as a singular phenomenon ("I have been unable to find a record of a similar occurrence, either on this glacier or on others"). Whalley suggested that the overtopping was probably related (a) to the sharp turn of the glacier to the right (south), and (b) to the passage of a kinematic wave—though at that time there was no evidence of a wave on the glacier surface. Since 1973 exposures of ice above the moraine have become much more numerous and extensive, as the ice-cored live moraine has grown in height (at some points by several metres) and has thrust onto the moraine

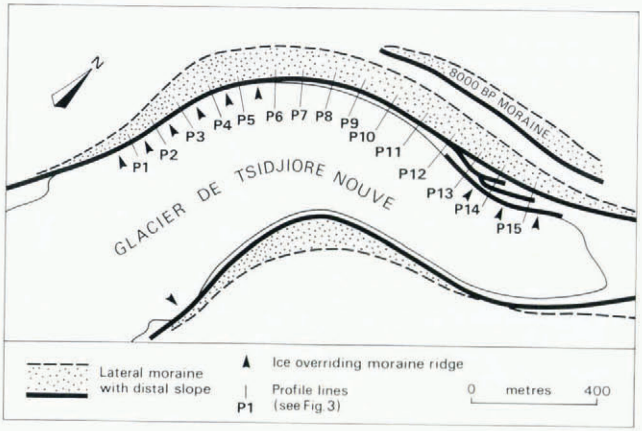

Fig. 2. Glacier de Tsidjiore Nouve, showing moraine embankments, glacial overriding, and the sites of cross-profiles in Figure 3.

summit (photographs taken on 14 June 1981 by I. Beecroft show up-arching of winter snow layers on the moraine crest as the ice has pushed northwards). By September 1981 the glacier margin had risen to the extent that, within the next few years, overtopping of the lateral moraine may extend over a kilometre down-glacier from the initial ice exposure.

(i) *The southern moraine.* This remains largely a fossil feature, though it is being overtopped at its head over a distance of approximately 30 m. The moraine is clearly a composite feature. In its middle section the main ridge is surmounted by a smaller, partly vegetated moraine ridge, forming a "superimposed moraine" (Osborn, 1978). On the proximal side there is a small unvegetated ridge (coincident with the line of shear along the glacier margin) and a much larger ice-cored ridge comparable with that on the northern glacier edge. These moraines combine with the main superimposed ridge to give what Osborn terms a sequence of "nested moraines", successively younger in the direction of the ice.

(ii) *The northern moraine.* Morphologically this is considerably more complex, comprising at least seven superimposed and nested moraine ridges. Figure 3 shows a series of cross-profiles surveyed during July 1981, from the head of the main ridge (P1) to its terminus near the glacier snout (P15). In its upper part the moraine includes two main elements: the main debris ridge, with distal slopes of 31–41°, and the overtopping ice-cored moraine (A) with ice exposures on the distal slope (profiles P2, P3, P4, P6, and P7). It should be noted that the ice-cored ridge (A) becomes progressively narrower up-glacier, owing to the sliding of debris from the distal face and rapid recession of the exposed ice owing to accelerated ablation. In its middle section the moraine consists of several small superimposed and nested ridges (note that moraines C and D are separate on Profiles P5 and P10, but that C obscures the underlying D on profiles P6–P9). Moraine B, a small ridge at the base of the distal face of ice-cored moraine A, coincides with the shear line along the glacier margin. In the lower section of the lateral moraine a series of quite large and well-defined nested ridges is developed (see E, F, and G on profile P15). Moraines C and D are replaced by a major gully formed by stream erosion between ridge E and the glacier edge. Profiles P13–P15 show the continued existence of moraine B, which appears here to be a larger debris accumulation currently being overridden by the glacier from the south. Debris from the crest of moraine A regularly slips down the ice face (at 43–44°), coming to rest on the

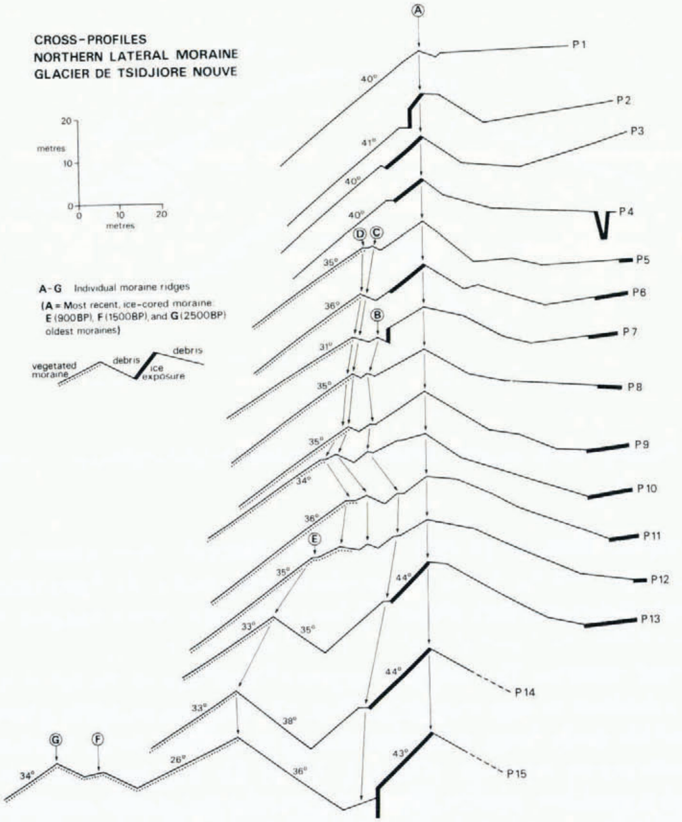

Fig. 3. Cross-profiles of the northern lateral moraine complex, glacier de Tsidjiore Nouve.

summit or distal slope of moraine B. It should be noted that, in addition to ridges A–G, a separate older ridge (H), with a summit elevation below that of ridges G, F, E, and A, is developed farther to the north and is separated from ridge G by a major gully.

On *a priori* grounds it seems safe to assume that moraines G to A are progressively younger. Röthlisberger and Schneebeli (1979) give radiocarbon dates as follows: H 8 000 B.P.; G 2 500 B.P.; F 1 500 B.P.; and E 900 B.P. A preliminary lichenometric investigation, based on *Rhizocarpon geographicum*, indicates possible dates of 825 B.P. for moraine D and 125–100 B.P. for C (that is, the culminating phases of the Little Ice Age). Moraines B and A are unvegetated and "contemporary".

The Tsidjiore Nouve lateral moraines: processes of development

At present, the Tsidjiore Nouve moraine embankments, where actually overridden by ice, are growing by the accumulation of debris dumped on the distal face. This material covers the glacier margins to a thickness of 0.2–0.8 m, giving rise by way of differential ablation to a sharp-crested, ice-cored supraglacial moraine. As the ice margins advance onto the crest of the embankment, debris slides from the outer slope of the supraglacial moraine ridge onto the distal face of the embankment. This creates extensive ice exposures which, during summer, ablate back by 3–5 m, undercutting the proximal slope of the supraglacial moraine and providing additional debris (Fig. 4). Owing to the recession of the ice faces, much of this debris accumulates towards the end of the summer melt season on the crest of the embankment, forming a small nested ridge or individual debris fans. However, with the cessation of ablation during winter and re-advance of the glacier margins, the summer debris is bulldozed onto the outer face of the embankment. This seasonal rhythm in the advance and retreat of the Tsidjiore Nouve ice, and related depositional processes, has been recorded over the past three years. An additional point is that the development of a moraine fabric under present conditions of dumping cannot be observed. Owing to the height (60 m) and steepness of the distal face (*c.* 40°) large boulders released by the glacier gain considerable momentum, and roll and bounce to the base of the embankment. These boulders can cause "erosion" of the embankment slope, though overall there is a net gain of smaller clasts. Melt-water rivulets, fed by the melting ice exposures, develop at some points; these transport finer sediments and wash them into the coarser debris, give rise to small mud flows, and sometimes result in incipient gullying.

The provenance of the debris being dumped onto the Tsidjiore Nouve embankments poses interesting questions. At present, the glacier surface receives large increments of debris from rock walls on either side of the Pigne d'Arolla ice fall, which links the firn basin with the lower glacier tongue. This debris, the product of frost weathering and slope failure, is characteristically coarse and angular. Little of the debris cover appears to be derived from erosion of previously formed morainic ridges (see the comments of Sugden and John above); on the contrary these appear to be remarkably stable and resistant features which, as they have grown over time, have increasingly constricted the glacier. The debris already on the ice surface is, however, continually being recycled, by falling into marginal crevasses and then slowly melting out down-glacier. Crevasse fillings, of loosely compacted sediments, are clearly visible along the exposed northern flank of the glacier, particularly close to the snout where they feed debris fans on the crest of

Fig. 4. Ice exposure at the crest of the northern moraine embankment, Profile 4. Note the recession of the face due to summer ablation, and the melting out of englacial debris.

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moraine B. In view of the large contributions of debris from supraglacial sources below the firn line, the Tsidjiore Nouve moraines seem at first sight to be equatable with the *below-firn-line* type of medial moraine recognized by Eyles and Rogerson (1978).

Sedimentological analysis of samples taken from the surface of ridge A supports the hypothesis of supraglacial derivation of the moraine debris. The particle-size graph (Fig. 5: top left) shows the predominantly coarse nature of the material (which would have been greatly emphasized had the abundant fragments in excess of 32 mm been included) and the relative paucity of fine sand and silt. The graph is similar to those produced by Boulton (1978) for sediment "in high level transport" on glacier d'Argentière and Breiðamerkurjökull.

However, detailed field examination of the northern Tsidjiore Nouve lateral moraine has revealed an additional source of sediment, in a series of debris layers *within* the ice. These are steeply dipping or vertical, and either run roughly parallel to the glacier margin or meet it at an acute angle. The layers are best exposed on ice faces within transverse crevasses, or on ice exposures where the glacier is overriding the embankment. In appearance the layers often closely resemble the englacial debris bands feeding the medial moraines of glacier de Tsidjiore Nouve (Small and Gomez, 1981).

Samples taken from six of the lateral moraine debris bands exposed in July 1981 were subjected to particle-size analysis, and the results are shown in Figure 5, top right. When compared with the graph of 24 medial-moraine debris-band samples, that for the lateral-moraine layers seems also to have a predominantly "supraglacial" character, though there is some lack of material in the -3 to -1 ϕ range. This conclusion is reinforced by a comparison with graphs for "shear plane" (= subglacial) debris from the Bas Glacier d'Arolla and "zone of traction" sediment from glacier d'Argentière and Breiðamerkurjökull (Boulton, 1978). It is inferred that the debris layers within the ice core of ridge A of the northern Tsidjiore Nouve lateral moraine are, like those of the medial moraines (Small and Gomez, 1981), probably composed of material released by weathering of supraglacial faces *above the firn line* and incorporated along the glacier edges, possibly by way of marginal crevasses. The resultant infillings of crevasses became buried by younger ice, compressed and rotated by glacier flow, and exposed by ablation on the lower glacier tongue. Here they make a substantial (though as yet unquantifiable) contribution to the surface debris cover of the ice-cored supraglacial moraine. The latter cannot therefore be strictly regarded as a *below-firn-line* type, but is a combination of *above-firn-line* (*ablation dominant*) and *below-firn-line* types (Eyles and Rogerson, 1978).

The evidence considered so far indicates the important role of supraglacially derived debris in lateral moraine formation. This is supported by the observations of Boulton and Eyles (1979) on the formation of lateral and latero-frontal moraines. However, these authors postulate that the debris, "derived supraglacially from flanking valley walls, is entrained along foliation planes parallel to the glacier bed and for some distance above it", rather than by open crevasses. Moreover, they state that "although strain within the glacier may considerably alter inter-particle distances, grain contacts are rare and little comminution occurs". This would not necessarily be true of the debris layers of glacier de Tsidjiore Nouve, where limited comminution is not only feasible in view of the concentration of the debris but could account for differences between particle-size distributions of surface debris formed in large measure from rock falls below the firn line and debris bands from the firn zone.

Boulton and Eyles additionally draw attention to the accumulation of lodgement till on the lower proximal faces of lateral dump moraines, and to the inclusion of mud flows and water-washed sediments ("the voids within these open-textured bouldery deposits are slowly filled by

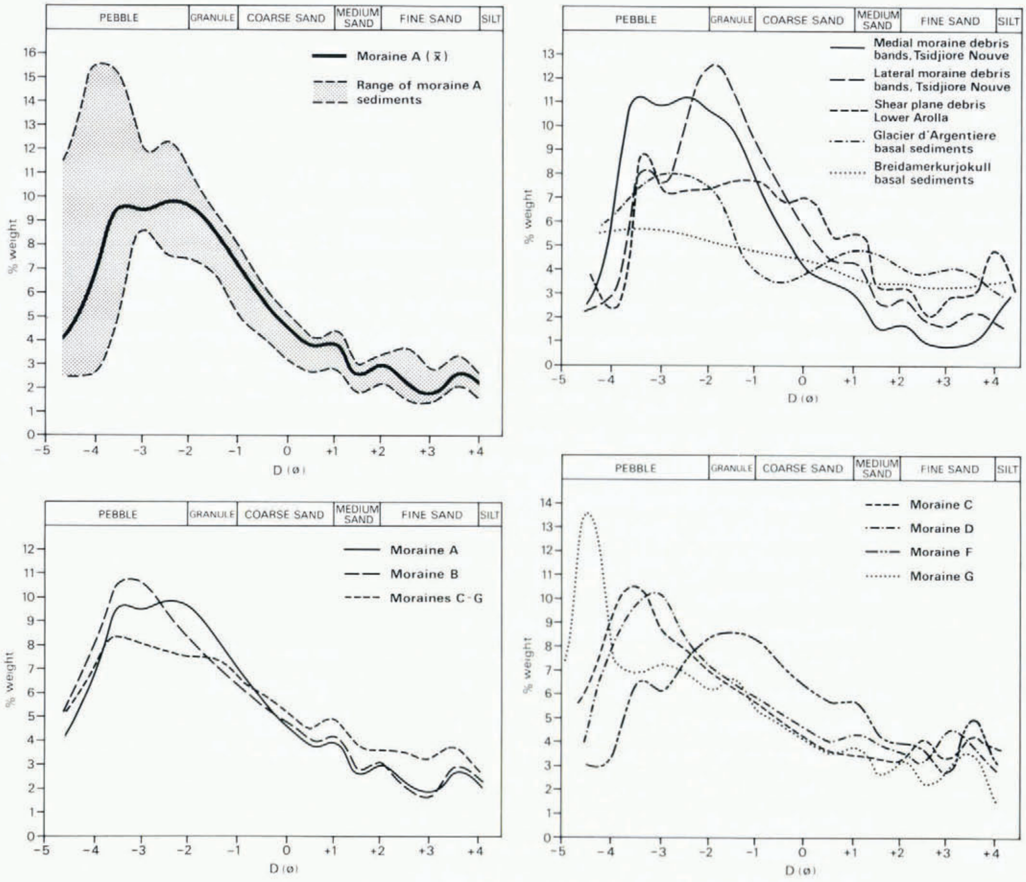

Fig. 5. (Top left) Particle size distribution of debris covering moraine A. (Top right) Particle size distribution of debris from englacial bands, moraine A, compared with debris from englacial bands, main medial moraine (glacier de Tsidjiore Nouve), "shear planes" (Bas Glacier d'Arolla), and basal sediments from glacier d'Argentière and Breiðamerkurjökull (after Boulton, 1978). (Bottom left) Particle-size distribution of debris covering moraines A and B and from moraines C–G (average), northern lateral moraine, glacier de Tsidjiore Nouve. (Bottom right) Particle-size distribution of debris from moraine ridges C, D, F, and G, northern lateral moraine, glacier de Tsidjiore Nouve.

finer material which is washed in or flows in"). This view may be supported by sedimentological evidence from the older ridges of the northern moraine complex of glacier de Tsidjiore Nouve. The particle-size graphs for sediment samples from ridges C to G show, by comparison with surface debris from the youthful ridges A and B, a relative lack of sediment in the -2 to -4 ϕ range and a greater content of medium to fine sand and silt (Fig. 5, bottom left). However, when graphs for individual morainic ridges are plotted (Fig. 5 bottom right) it is evident that the debris of moraines C, D, and G is characteristically "supraglacial", and that moraine F (with its high content in the $+1$ to -2 ϕ range) has a distorting effect. In this instance samples were taken from both the proximal and distal moraine slopes, and the possibility of inclusion of lodgement till and/or a greater proportion of water-transported sediment must be considered.

Implications

The lateral moraines of glacier de Tsidjiore Nouve (and especially that on the northern glacier flank) provide interesting insights into the mechanisms of dump-moraine formation both at the present day and in the recent past. Moreover, they afford important evidence of the geomorphological activity of this glacier since the "climatic optimum" of the Post-Glacial period. It is likely, to judge from the researches of Röthlisberger and Schneebeli (1979), that these large moraine complexes have—if ridge H is excluded—accumulated largely during the past 5 000 years (and probably during an even shorter period). Calculations of the total volume of the ridges, based on field mapping and a photogrammetric survey made by the Department of Geography, University of Glasgow, give a provisional figure of 9 060 000 m^3. Assuming a void space of 20% and that 80% of the debris is supraglacially derived, an average annual increment to the moraines of 1 160 m^3 is implied. To provide such an amount, recession of rock faces within the Tsidjiore Nouve catchment (which cover approximately 1.55 km^2) must amount to 0.75 mm/year—seemingly a high rate, but one not difficult to reconcile with (*a*) the numerous falls occurring from highly shattered rock exposures above the glacier at the present time, and (*b*) the vast amount of angular surface debris (estimated at 115 000 m^3) resting on the lower glacier tongue. When the supraglacial debris being dumped at the glacier *snout* is also taken into account, it seems probable that the weathering rate within the glacier catchment must be adjusted to nearer 1 mm/annum.

At present a programme of monitoring sediment discharge in the melt-water stream of the glacier is being carried out by research students from Southampton University (initiated by C. R. Fenn and continued by I. Beecroft). Observation by Fenn during the period June–July 1978 revealed a total suspended sediment discharge of 1 313.5 tonnes. It is likely that subglacial sediment sources become somewhat depleted during later summer, so that the sediment discharge from the glacier for the whole of the 1978 melt season may have been no greater than 2 500 tonnes. Converted into rock volume (approximately 800 m^3) and spread over the subglacial surface (estimated to be approximately 3.6 km^2) this could be taken to imply a glacial abrasion rate of 0.24 mm/annum. If this is increased by 30% to allow for bedload discharge (Østrem, 1971) the total erosion rate rises to only 0.31 mm/annum. Observations by Beecroft during 1981 suggest that these figures may be abnormally low. Nevertheless, it does seem possible that glacier de Tsidjiore Nouve has recently been more active in transporting and depositing supraglacial debris than in glacial erosion *sensu stricto*. Such a change of role since the Pleistocene could be due primarily to glacial thinning and increased exposure of valley walls and rock-faces during the Post-Glacial period. It is hoped that a continuing programme of research will shed further light on the problem.

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