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The Structural Glaciology of a Temperate Valley Glacier: Haut Glacier d'Arolla, Valais, Switzerland

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Abstract

This paper describes the structural glaciology of Haut Glacier d'Arolla, a small valley glacier fed by two distinct accumulation basins in the Swiss Alps. A considerable body of field data is presented alongside observations from ground and aerial photographs. Suites of structures identified in the field and from aerial photographs are first described in nongenetic terms before being assigned regular structural terms. Haut Glacier d'Arolla is dominated by primary stratification, which is progressively folded and eventually transposed into longitudinal foliation as it moves into the glacier tongue. Crevasses and crevasse traces cross-cut and in places displace primary stratification and longitudinal foliation. Crevasse traces are formed by the closure of crevasses or may represent tensional veins. On their journey downglacier, crevasse traces become increasingly rotated. Close to the snout, some crevasse traces become reactivated as thrust faults. Strain ellipses, derived from the velocity field, show progressive deformation downglacier (cumulative strain). The shapes of the strain ellipses agree with inferences made concerning the orientation and magnitude of strain from observations of structures in the field. Independent modeling of cumulative strain shows good agreement with the development of longitudinal foliation in a simple shear regime. However, there are inconsistencies in the relationship between modeled cumulative strain and other structures.

Introduction

The aim of this paper is to determine how structures in a temperate alpine valley glacier (Haut Glacier d'Arolla) have evolved. The structure of glaciers has been the subject of numerous previous studies, many of which are summarized in Hambrey and Lawson (2000). The structure of a glacier has important wider implications, for example controlling debris transport and landform development (e.g., Hambrey et al., 1999). Understanding the link between structure and strain allows a glacier's flow regime to be predicted from, for example, the identification of structures from aerial photographs (e.g., Allen et al., 1960; Meier, 1960; Hambrey and Milnes, 1977) or satellite imagery (e.g., Hambrey and Dowdeswell, 1994). The specific objectives of this paper are to:

- define the structural evolution of Haut Glacier d'Arolla, emphasizing the difference between structures and how these structures might be interpreted;
- calculate cumulative strain from field-based velocity measurements and link patterns of cumulative strain to the structural evolution of the glacier;
- compare the structural evolution of Haut Glacier d'Arolla with that of other glaciers with contrasting geometries and thermal regimes; and
- compare this remote sensing and field based derived structural evolution of Haut Glacier d'Arolla with one based on numerical modeling of glacier flow at high resolution (Hubbard and Hubbard, 2000).

This study complements the large portfolio of previous research carried out at Haut Glacier d'Arolla.

Study Area

Haut Glacier d'Arolla is a north-flowing valley glacier at the southern end of the Arolla valley, which forms the western branch of

Val d'Hérens in the Canton of Valais in Switzerland. Haut Glacier d'Arolla (Fig. 1) is approximately 4 km long, with a wide composite accumulation area feeding a narrower tongue area. The glacier tongue is fed by two main basins; the larger Mont Brulé basin (approximately 2.5 km²) to the southeast, and the second a smaller (approximately 1 km²) La Vierge basin between La Vierge and L'Évêque to the southwest, which feeds into the main basin via the La Vierge tributary.

There is a substantial literature on many aspects of Haut Glacier d'Arolla, for example sediment transfer (e.g., Gomez and Small, 1985; Small, 1987), glacial melt-water chemistry (e.g., Brown et al., 1994), glacier geometry (Sharp et al., 1993), subglacial hydrology (e.g., Hubbard et al., 1995; Nienow et al., 1998), interactions between glacier hydrology and dynamics (e.g., Mair et al., 2001), and high-resolution glacier flow modeling (Hubbard et al., 1998; Hubbard and Hubbard, 2000).

Methods

The structure of Haut Glacier d'Arolla was determined in two ways: (1) observations from aerial photography, allowing the overall structural pattern and cross-cutting relationships to be determined, and (2) the identification and three-dimensional measuring of structures in the field during the summer of 2000. Initial nongenetic terms and later interpretational names assigned to each structure are provided in Table 1.

AERIAL PHOTOGRAPHY

A structural map of Haut Glacier d'Arolla was produced by tracing features from two overlapping black and white vertical aerial photographs. The photographs were taken from ~1000 m above the surface of the glacier on 17 October 1992 (Willis et al., 1998). Structures were

TABLE 1
The identification of structures from aerial photographs and field observations. Both nongenetic and interpretational names are provided.

Nongenetic name	Interpretation	Identification on aerial photograph	Identification in the field
Systematic layering	Primary stratification	Parallel layering usually found in the upper glacier basin, sometimes parallel to snowline.	Thin darker layers between thicker lighter layers of firm often found parallel to receding snowline late in summer season. Cross-section sometimes observed in crevasses in upper reaches of glacier.
Discontinuities in layering	Unconformity	A break in the normal systematic layering of the primary stratification.	Difficult to observe close-up. Can be identified as a break in the normal layering when viewed from a distance or from height.
Structural discontinuity	Flow unit boundary	A junction that separates structures rotated in one orientation from structures rotated in a different orientation.	Difficult to identify close up, but can sometimes be recognized by structures oriented at different angles on either side of an area of intense foliation.
Crevasses	Crevasses	Structures may be "smeared" along the junction. Either as straight white lines (snow filled) or straight dark lines (non-snow filled or water filled), which cross-cut other features.	A crack with a visible opening.
Transverse/arcuate structures	Crevasse traces	First found in areas of crevassing as straight dark lines, can be followed downglacier as deforming dark lines, cross-cutting previously formed structures.	Linear or arcuate features, usually <20 cm width, which can be followed laterally for tens of meters, cross-cutting other structures.
Steeply dipping longitudinal structure	Longitudinal foliation	Long linear pervasive layered structure parallel to ice movement, which can be traced discontinuously for several hundred meters.	Alternating, discontinuous layers of bubble-rich and bubble-free white and blue ice, parallel or sub-parallel to surface ice movement.
Small-scale steeply-dipping structure	Axial planar foliation	Not observed on aerial photographs.	Fine, small-scale, near-vertical compositional layering found downglacier of folds, roughly parallel to fold axes.
Folding	Folding	Large-scale folding is identified as curves in linear features which do not follow surface topography.	Isolated folds are identified by linear features which can be followed in one direction before turning through an angle (the fold hinge) and being followed in a different direction. The fold hinge may be rounded or sharp.
Prominent arcuate structures near snout	Thrusts	Not observed on aerial photographs.	A step in the glacier surface, parallel to crevasse traces near the snout of the glacier. Displacement of marker horizons. Associated with basally derived debris.
Circular/elliptical crystal structures	Crystal quirks	Not observed on aerial photographs.	Coarse ice crystals infilling or progressively growing into a water-filled circular or elliptical void.

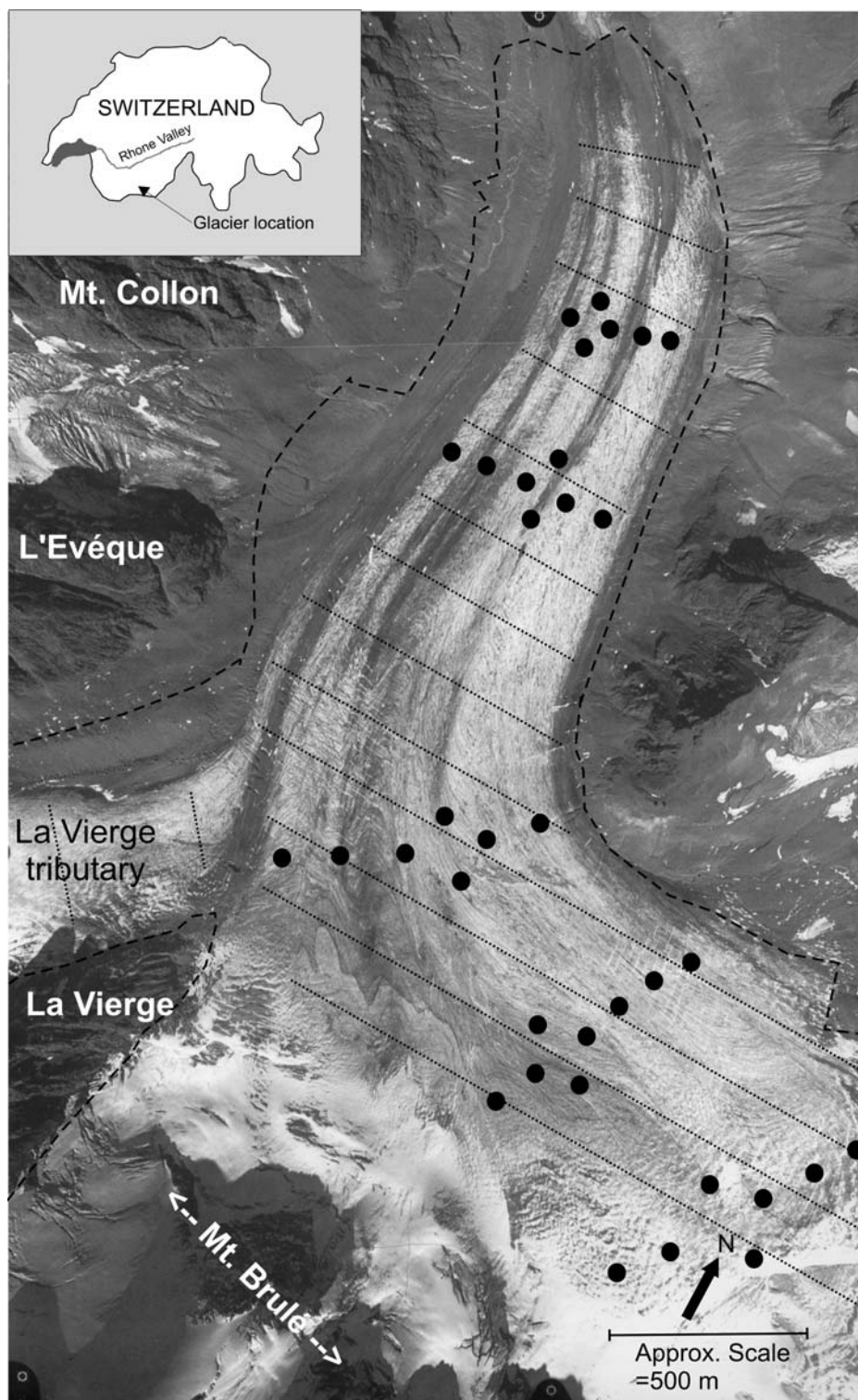


FIGURE 1. Vertical aerial photograph of Haut Glacier d'Arolla, supplied by Grande Dixence SA, used to produce the structural map in Figure 2. The approximate relationship between the aerial photograph and Sharp et al.'s (1993) DEM outline is represented as a dashed line. The approximate positions of velocity stakes used for strain analysis are marked as large black dots. The positions of the transect lines along which structural measurements were made are marked as dotted lines.

identified on the photograph according to their dimensions, orientation, and cross-cutting relationships, using the criteria outlined in Table 1.

FIELD OBSERVATIONS

In the field, structures were identified using the criteria outlined in Table 1. Prominent features, notably primary stratification, longitudinal foliation, crevasses and crevasse traces, were measured and documented along 15 transect lines (Fig. 1). Spacing and direction of transect lines and sample points were measured by a Global Positioning

System (GPS). Less common features, notably folds, axial planar foliation and thrusts, were noted, and located using GPS. Data were collected using the conventional strike/dip technique used in structural geology. Schmidt lower hemisphere equal-area stereographic projections are used to plot the 3-D orientation of structural features. Data were collected in August when the maximum amount of snow-free ice was exposed. In 2000, this allowed measurements on all but the highest reaches of the glacier.

Structural measurements collected in the field are presented using a predefined outline of Haut Glacier d'Arolla, produced by Sharp et al.

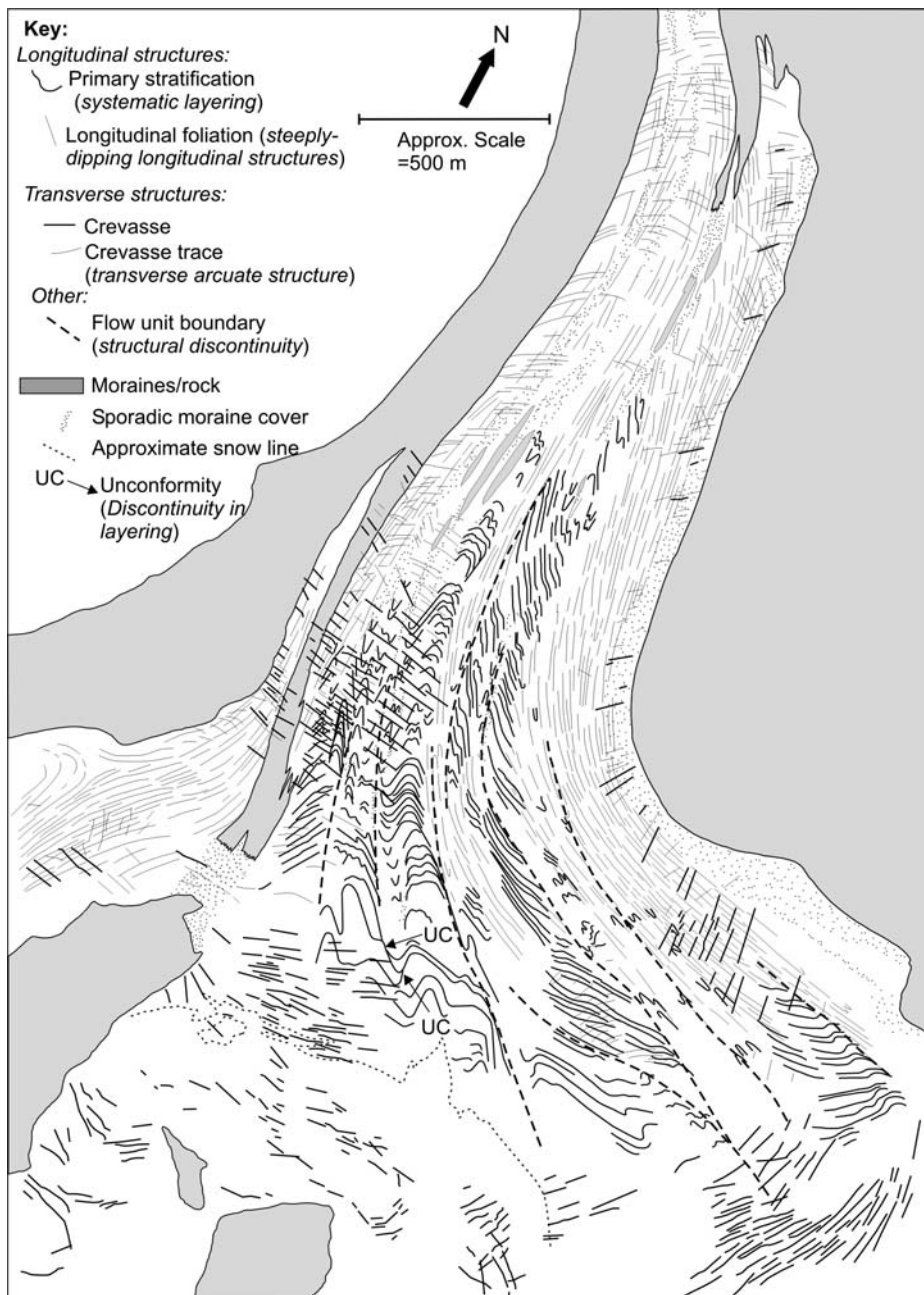


FIGURE 2. Structural map of Haut Glacier d'Arolla, produced from tracings of aerial photograph. Not corrected for edge distortion.

(1993). The approximate relationship between the aerial photograph used in this study and the outline is presented in Figure 1.

METHOD USED TO DETERMINE CUMULATIVE STRAIN AT HAUT GLACIER D'AROLLA

Calculation of cumulative strain is based on the changing dimensions of triangles according to the method described by Milnes and Hambrey (1976). The path of nine points, forming four equal triangles, was traced through an interpolated velocity field. The velocity field was interpolated from the field-measured movement of 35 stakes in five rows across the glacier (Fig. 1) over a 365-d period between 3 September 1994 and 3 September 1995. The subsequent position of the four triangles as they traveled through the interpolated velocity field was calculated annually for 300 yr, and plotted every 50 yr. The changes in triangle geometry were used to calculate cumulative strains. Three assumptions were made to simplify calculations:

- (1) ice travels in a constant direction at a constant speed for one year at a time;
- (2) ice-movement direction and velocity are constant across each grid square; and
- (3) the glacier is in a steady state, i.e. the flow of the glacier does not change over time.

The errors involved in this technique can be large, for example up to 0.021 a^{-1} error in longitudinal strain as measured by Mair et al. (2001, Appendix 1).

Structures Identified at Haut Glacier d'Arolla

SYSTEMATIC LAYERING

Systematic layering can be observed on the aerial photograph, best seen in the upper-western areas of Mount Brulé basin (Figs. 1, 2), where individual layers can be followed for hundreds of meters. The layering is less obvious in the eastern area of Mount Brulé basin because recent

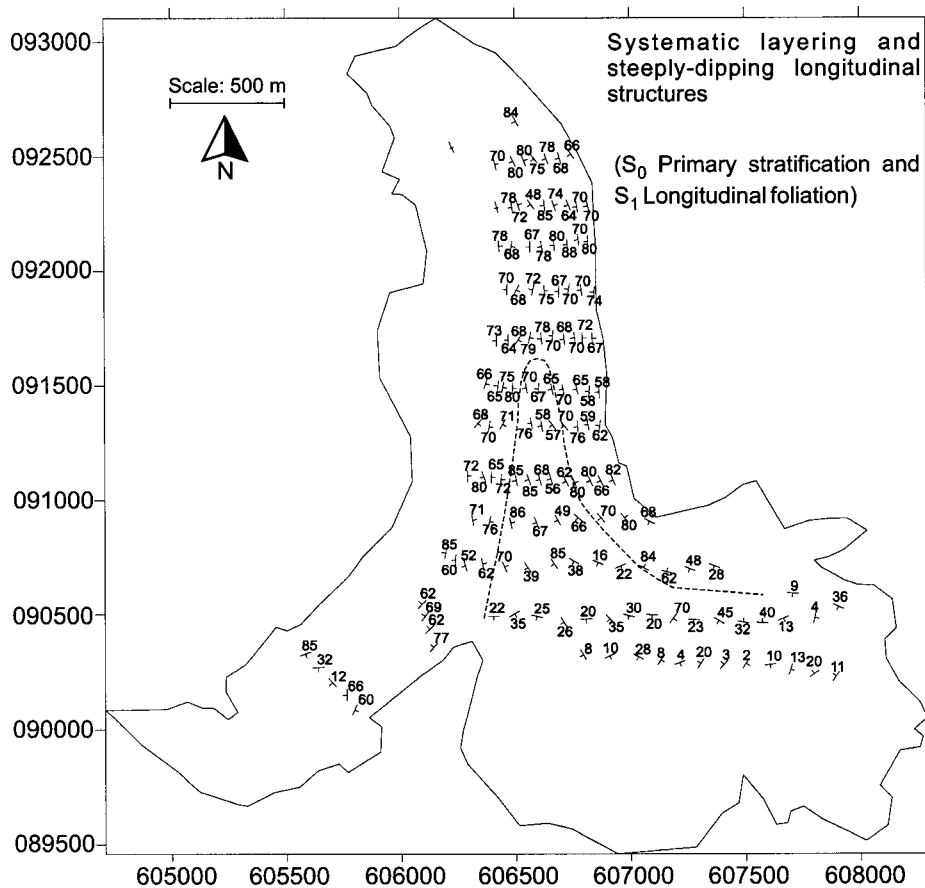


FIGURE 3. Field measurements of systematic layering (interpreted as primary stratification) and the steeply-dipping longitudinal structure (interpreted as longitudinal foliation) from Haut Glacier d'Arrolla presented as a structural field map. Dashed line represents approximate boundary between primary stratification and longitudinal foliation.

snowfall covered features shortly before the photograph was taken. In the field, systematic layering is identified as gently dipping ($<40^\circ$), fairly regular layers of white firn or ice striking perpendicular or oblique to ice-movement direction, broken by continuous thinner, dirty dark layers. In the field, systematic layering can be followed for tens of meters below the headwalls of Mont Brulé at the uppermost reaches of the glacier. Layering is approximately parallel to the snowline in the upper-western area of the Mont Brulé basin. In turn, the snowline followed the outline of large avalanches from Mount Brulé, which had fallen earlier in the summer. The phenomenon of the layering following the outline of avalanche debris is less obvious but still observable on the 1992 aerial photograph (Figs. 1, 2). Systematic layering determined from field mapping is plotted in Figure 3.

DISCONTINUITIES IN LAYERING

In some places minor discontinuities can be identified in the normal systematic layering described above. Examples are identified on the aerial photograph (Figs. 1, 2), but are too subtle to identify in the field.

STRUCTURAL DISCONTINUITIES

Structural discontinuity is the name given to a junction between neighboring areas of structures, in which each area has its own pattern of layering/orientation. Close to these junctions, structures often appear stretched, deformed or folded (Figs. 1, 2).

CREVASSES

Crevasses are vertical and their widths vary from a few centimeters to ~ 1 m and had a vertical dip. Some crevasses grade

laterally into transverse arcuate features (see below). Four main areas of crevassing are recognized from the aerial photograph and field observations:

- (1) chevron crevasses along the eastern margin of the glacier,
- (2) transverse crevasses in the upper reaches of the glacier,
- (3) transverse crevasses in the area of confluence between the La Vierge tributary and the main glacier tongue (Fig. 4), and
- (4) splaying crevasses dissecting the eastern medial moraine.

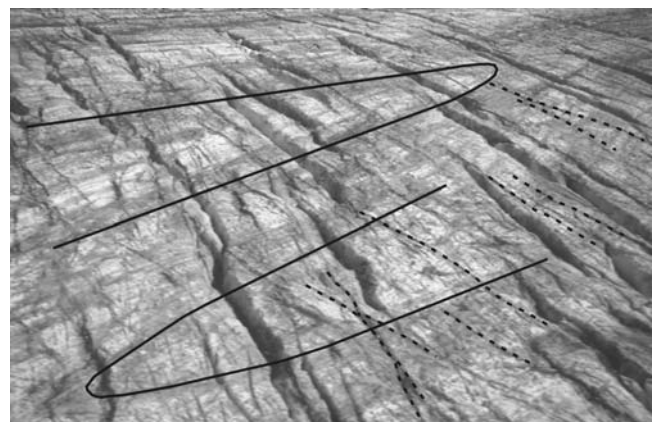
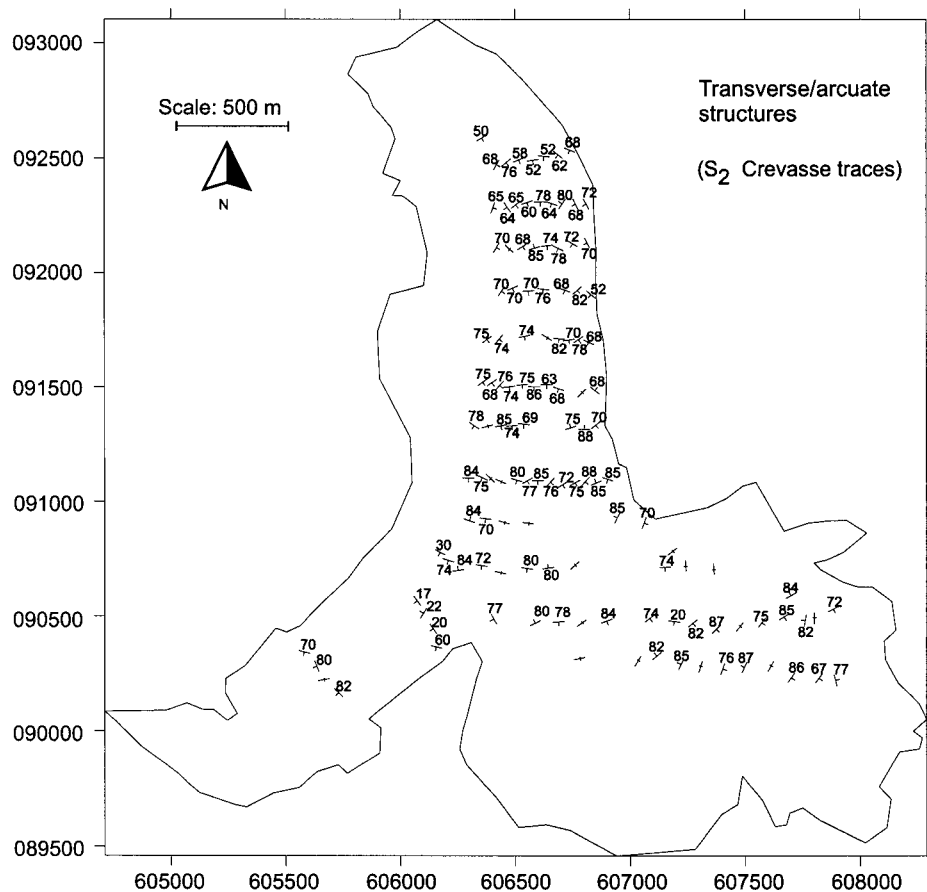


FIGURE 4. Oblique aerial photograph of upper glacier tongue. Crevasses, folded primary stratification (solid lines) and cross-cutting sets of crevasse traces (dashed lines) can be identified. Field of view approximately 100 m wide.



TRANSVERSE ARCUATE STRUCTURES

A suite of structures is recognized on the aerial photograph as having similar characteristics to open fractures; they are relatively short, linear features that cross-cut other structural features (Fig. 2). They are very common structures, second only in number to steeply-dipping longitudinal structures (see below). These arcuate structures first appear transverse to flow close to, or within, areas of open fracturing (e.g., Fig. 4). The transverse structures become increasingly arcuate (convex on downglacier side) with distance downglacier. Transverse arcuate structures are least distinct in the central region of the glacier, but they become prominent arcuate features once again near the glacier snout, in particular for the last 500 m of the glacier.

On the glacier tongue, differential weathering of the transverse arcuate structures often results in a minor (<5 cm) step, which acts as a sediment trap; many such structures have accumulations of fine debris along this break in slope. Towards the glacier snout, in particular for the last 500 m of the glacier, approximately 10% of transverse arcuate structures form a step down in the downglacier direction of up to 20 cm in the glacier surface; their dip is between 30 and 50° upglacier. Close to the snout, debris emerges along some of these structural features (Fig. 6). The debris is poorly sorted diamicton dominated by subrounded and subangular clasts.

Folding on the glacier is seen on a variety of scales:

- (1) large-scale open folding (tens to hundreds of meters amplitude) of systematic layering in the upper Mount Brulé basin;
- (2) isoclinal folding within the steeply-dipping longitudinal structures found in the tongue (up to ~ 10 m);
- (3) transposed fold hinges within steeply-dipping longitudinal structures (1 to 2 m); and
- (4) smaller parasitic folding around fold hinges (tens of centimeters). Large-scale folding is identifiable on the aerial photograph as curved systematic layering (Figs. 1, 2).

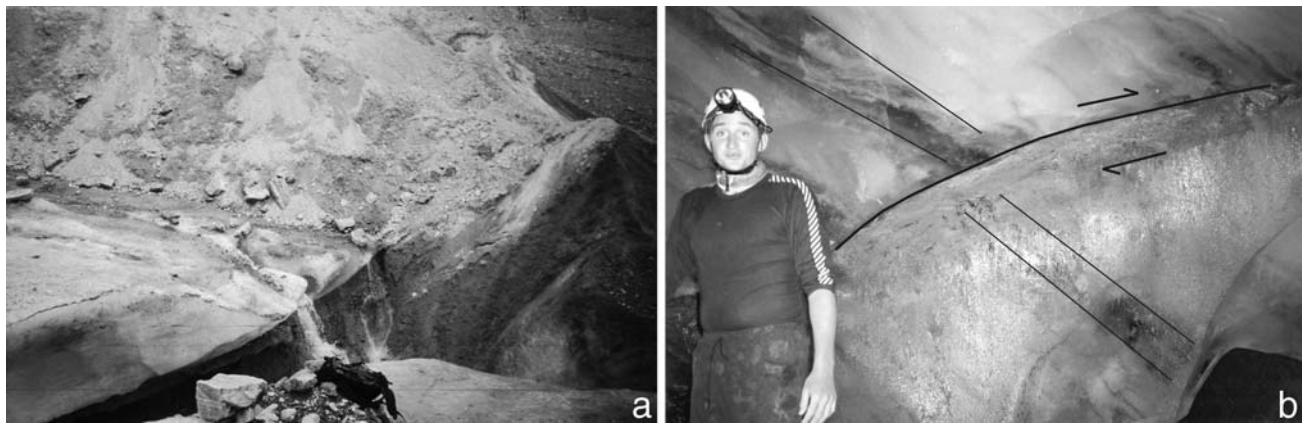


FIGURE 6. Examples of reactivated crevasse traces interpreted as a thrust fault near the snout of Haut Glacier d'Arolla. Ice movement from left to right in both photos. (a) Surface expression of thrust fault. Backpack for scale. (b) Coarse, clear band of ice displaced by reactivated crevasse trace displayed within ice cave at snout of glacier.

Some tighter folding is also identifiable on the aerial photograph, for example on the western side of the Mont Brulé basin (Fig. 2).

In the upper parts of the glacier, the most commonly observed folds are parasitic folding on the large-scale folds within the primary stratification, with open to normal interlimb angles (Fig. 7). On the glacier tongue, isoclinal folding is more common, with limbs comprising the surrounding steeply dipping longitudinal structures (Fig. 4). Some isoclinal folds had parasitic folding around the main fold axis (Fig. 8). On the glacier tongue, fold axes are oriented parallel to flow direction and are generally gently dipping up and downglacier (Fig. 9).

SMALL-SCALE STEEPLY DIPPING PLANAR STRUCTURE

Associated with some isoclinal and parasitic folds is a steeply dipping longitudinal structure comprising centimeter-scale, near-vertical or vertical layers whose strike is roughly parallel to fold axes (Fig. 9). This structure differs from the steeply dipping longitudinal structure described above in that they are only a small-scale, locally formed, nonpervasive feature within granular ice, found up to 1 m downglacier of folds. Excavation of the surface weathered granular ice removed all trace of the structure. The relationships are difficult to

photograph, but they can be seen in Figure 8, picked out by dirt accumulating along the structures.

CIRCULAR/ELLIPTICAL CRYSTAL STRUCTURES

There are several examples of circular or elliptical areas of columnar, coarse crystalline ice growing orthogonally from walls into a void, or towards a central point (e.g., Fig. 10). The size of these circular/elliptical crystal structures varies typically from 50 cm to 2 m in diameter. They are commonly (~70%) positioned on a crevasse trace, but in other cases they appear to have no relationship with the surrounding ice structure.

Structural Interpretations

SYSTEMATIC LAYERING; PRIMARY STRATIFICATION

Systematic layering is interpreted as primary stratification, representing annual layers of snowfall (cf. Allen et al., 1960). The whiter layers are winter accumulation; the darker, thinner layers are ablation surfaces formed by accumulation of wind-blown debris during the subsequent summer season and possibly as a result of the refreezing of melt water. Because the snowline and subsequent primary



FIGURE 7. Photograph of an open fold in primary stratification (S_0) in the upper basin of Haut Glacier d'Arolla. Lower part of left hand fold limb has been off-set by a small crevasse. Parasitic folding is present on the right hand limb. Ice movement from bottom to top of photograph.



FIGURE 8. An example of isoclinal folding of stratification (S_0) in the tongue of Haut Glacier d'Arolla. The fold also has smaller parasitic folds around its axis. It also shows a good example of axial planar foliation (S_1), picked out by dirt below the fold (dashed lines show direction). Ice movement is top to bottom of photograph.

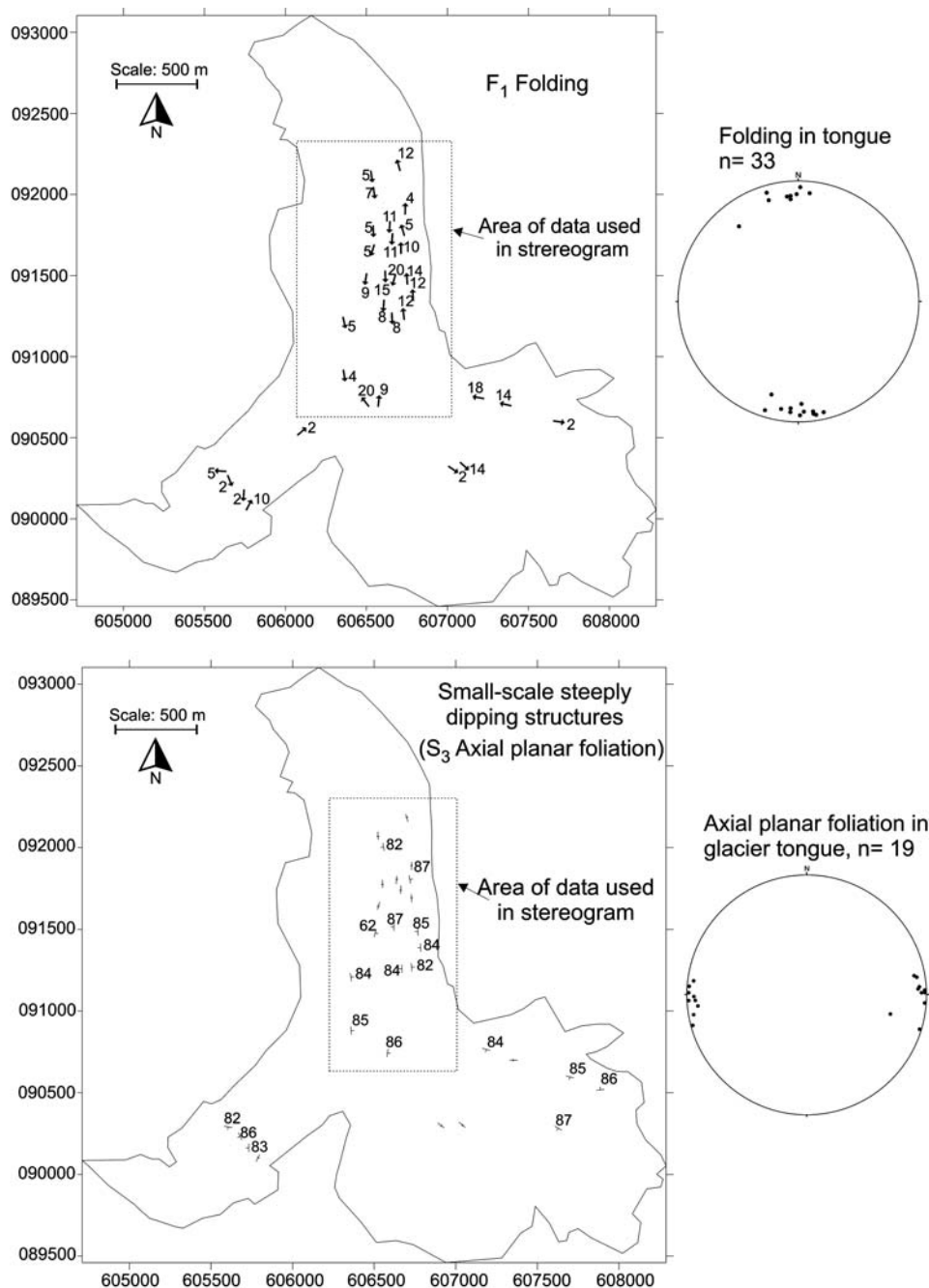


FIGURE 9. Field measurements of fold axes and axial planar foliation at Haut Glacier d'Arolla. Fold axes are linear features, so data in upper stereogram are plotted as "lines" whereas axial planar foliation in the lower stereogram are plotted as "poles to planes" in a Schmidt lower hemisphere equal-area projection.

stratification follow the pattern made by avalanches from Mont Brulé, accumulation from avalanches is a significant factor in the snow accumulation of the Mont Brulé basin.

Both in the field and from the aerial photograph, it is difficult to determine where primary stratification stops and longitudinal foliation starts; the boundary appears to be transitional. It appears that most longitudinal foliation is the result of progressive folding and lateral compression of primary stratification combined with simple shear, during the convergence of flow units, as described below.

DISCONTINUITIES IN SYSTEMATIC LAYERING; UNCONFORMITIES

Discontinuities in the systematic layering of primary stratification are interpreted as angular unconformities, representing a break in the systematic deposition of layers of snow.

STRUCTURAL DISCONTINUITIES; FLOW UNIT BOUNDARIES

Structural discontinuities at Haut Glacier d'Arolla are interpreted as being boundaries between flow units. Each flow unit has its own pattern of primary stratification, suggesting discrete accumulation basins on the flanks of Mount Brulé, which initially act as separate entities before coalescing at the foot of Mount Brulé. Intense folding and deformation of primary stratification and foliation close to the flow unit boundaries suggests that, prior to amalgamation, flow units have different rheological properties and velocities, resulting in the stretching and simple shearing of the primary stratification at the boundary during amalgamation. Hambrey (1976: 1630) described the same features at Charles Rabots Bre (Norway). Previous investigations of velocity at Haut Glacier d'Arolla have not identified separate flow units (e.g., Hubbard et al., 1998), although velocity data have not been collected from the zones where the initial flow units on Mount Brulé may exist.

The observation that some crevasses can be followed laterally into crevasse traces at one end is interpreted as the lateral migration of an open crevasse. The four areas of crevassing on the glacier are interpreted in a similar way to those described by Nye (1952):

- (1) chevron crevasses indicating the role of frictional resistance of valley-side walls along the eastern margin of the glacier,
- (2) transverse crevasses indicating longitudinal extension in the Mont Brulé basin,
- (3) transverse crevasses indicating extension at the confluence of the La Vierge tributary and main flow unit,
- (4) splaying crevasses indicating the lateral expansion of the ice.

Splaying crevasses are not visible on the aerial photograph because they had not yet formed when the photograph was taken. Lateral expansion has been facilitated by the large amounts of ice that have been removed by ablation from the glacier snout, in particular on the eastern margin, during the final decade of the twentieth century. The rapid loss of ice volume and subsequent loss of lateral confining pressures has resulted in the principal tensile stress acting normal to ice-movement direction, and the formation of splaying crevasses.

TRANSVERSE ARCUATE STRUCTURES; CREVASSE TRACES

Transverse arcuate structures are interpreted as crevasse traces, because they are first recognized on the aerial photograph near fields of active open crevassing, and are oriented at similar angles to the open crevasses. On their journey downglacier the crevasse traces become rotated and curved.

Where a crevasse trace occurs within a crevasse field and is parallel to surrounding crevasses, it is interpreted as being close to, or within, its area of origin. Apart from these instances, it is difficult to determine the exact area of origin for any particular crevasse trace, because several sets cross-cut one-another (Figs. 4, 5). However, because crevasse traces become progressively curved and rotated with distance traveled down through the glacier tongue, some inference can be made on the relative distances traveled by crevasse traces.

The population of crevasse traces found at Haut Glacier d'Arolla is high considering that the glacier is now relatively crevasse-free. This could be because:

- (1) crevasses are relict from a time when the glacier was more active and thus had a higher volume of ice, faster velocities and more extensive crevassing, or
- (2) there may be numerous crevasses hidden under snow-cover on the face of Mount Brulé, or
- (3) some crevasse traces have never represented an opening in the ice.

As well as being numerous, crevasse traces are typically far longer than open crevasses on the glacier. Possibly, the open section of a crevasse migrates along the length of the crevasse trace, but it seems more plausible that little of a typical crevasse trace has ever been an open crevasse. This idea has been previously suggested by Hambrey (1976) for Charles Rabots Bre and by Hambrey and Müller (1978) for White Glacier. Both studies suggested that many crevasse traces have never had an opening but are extensional veins forming as the lateral and vertical continuation of open crevasses, similar to tensional veins in deformed rocks (Durney and Ramsay, 1973).

Another observation at Haut Glacier d'Arolla is the fact that crevasse traces extend all the way to the snout of the glacier, which is a considerable distance from any possible source areas. Crevasse traces at the snout are curved and rotated, indicating that they probably traveled long distances. This requires crevasse traces to extend to great

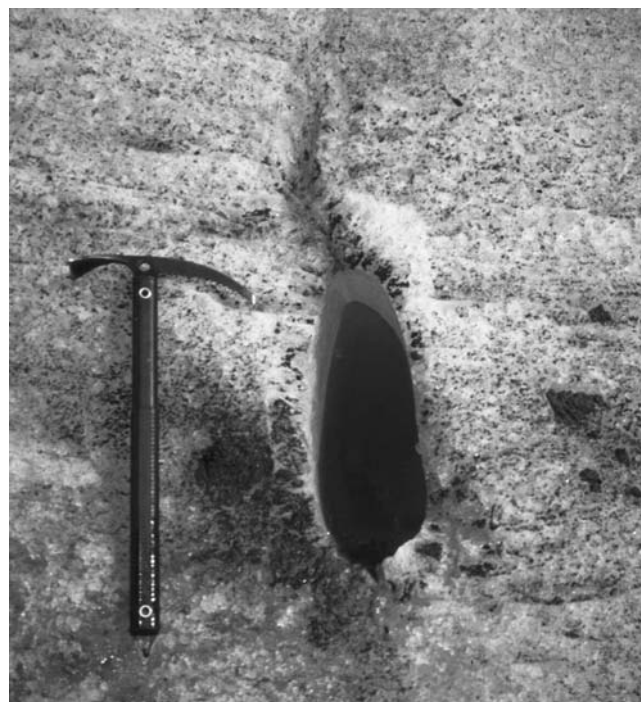


FIGURE 10. An example of an elliptical crystal structure interpreted as a crystal quirk. Large crystals can be identified growing into the water-filled void.

depth, from the surface for at least tens of meters, and even possibly over 100 m if they originally formed in the Mont Brulé basin. No crevasses observed at Haut Glacier d'Arolla were more than 20 m deep. This is further evidence that many crevasse traces at Haut Glacier d'Arolla have never been open cracks, but are more similar to tensional veins.

A new process probably affects crevasse traces for them to become more prominent towards the glacier snout, with some crevasse traces forming a step in the glacier surface. These reactivated crevasse traces are interpreted as thrust faults (cf. Hambrey and Müller, 1978), in view of their orientation (shallow upglacier dip) and the displacement they sometimes cause (Fig. 6b). The reactivation of crevasse traces as thrust faults may occur at Haut Glacier d'Arolla in response to longitudinal compression at the snout, or flow against a reverse slope associated with an over-deepening measured near the snout (Sharp et al., 1993).

STEEPLY-DIPPING LONGITUDINAL STRUCTURE; FOLIATION

The steeply dipping longitudinal structure is interpreted as longitudinal foliation. Past literature has separated primary stratification from foliation, and described foliation as a completely new structure, on the basis of, for example, foliation cross-cutting original primary stratification (e.g., Allen et al., 1960), whereas other workers recognized that foliation may form from primary stratification (e.g., Ragan, 1969; Hambrey, 1976; Hambrey and Milnes, 1977; Hooke and Huddleston, 1978; Lawson et al., 1994). At Haut Glacier d'Arolla, foliation may still represent the original layering of the glacier, and probably forms by a process similar to that described by Hambrey and Lawson (2000, Fig. 9). In this case, foliation forms by the gradual folding and eventual transposition of the original primary stratification at the same time as recrystallization of the original primary stratification of snow and firn, with crystals preferentially oriented perpendicular to the plane of maximum compressive stress. Evidence for this is:

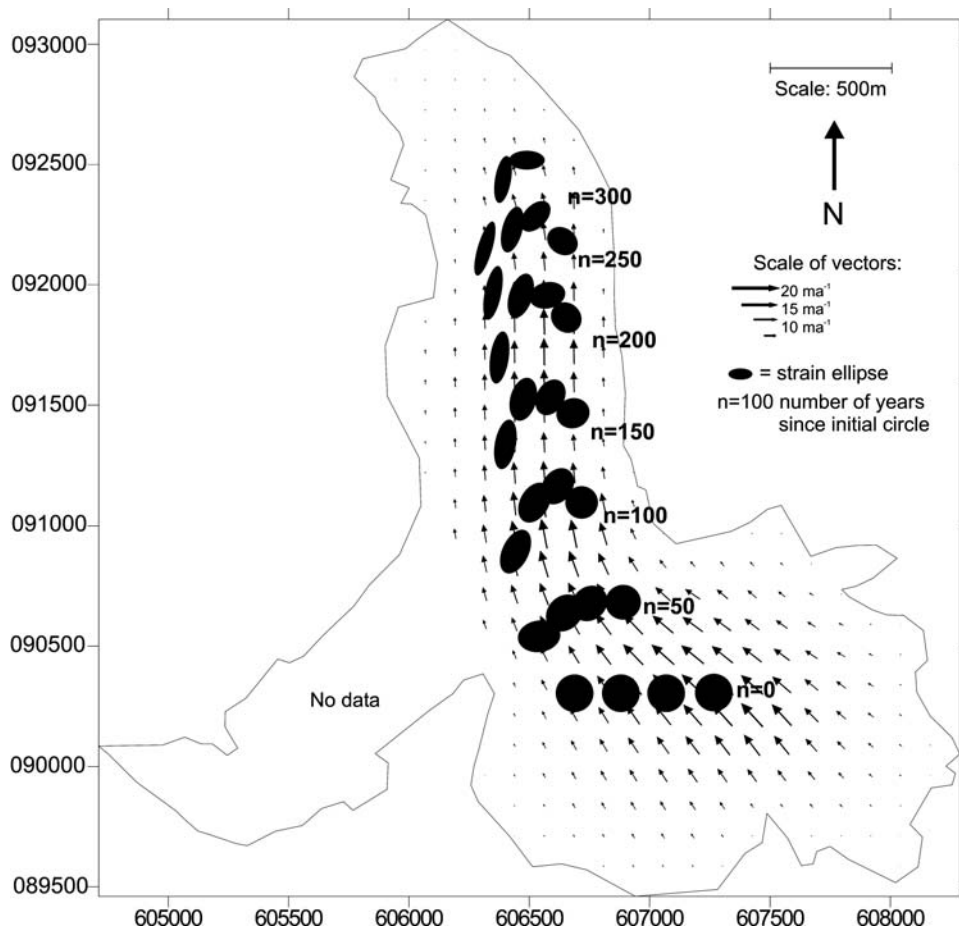


FIGURE 11. Deformation of four strain ellipses at 50-yr intervals according to vector field.

- (1) longitudinal foliation does not cross-cut primary stratification, suggesting one forms from the other,
- (2) primary stratification becomes progressively folded and rotated as it passes from the Mont Brulé basin to the glacier tongue (Figs. 1, 2), and
- (3) it is not possible to place a boundary between the two structures in the field or on the aerial photograph suggesting a transitional relationship.

FOLDING

Folding of the original primary stratification and longitudinal foliation probably occurs in response to lateral compression combined with simple shear as the ice moves from the broad Mont Brulé basin of the glacier into a narrow tongue, a process suggested by Lawson et al. (1994) and Hambrey et al. (1999). The folding process has promoted the formation of longitudinal foliation, by tightly folding and finally transposing the primary stratification. The isolated smaller scale isoclinal folds in the glacier tongue are interpreted as transposed fold hinges and attenuated limbs, which have become stretched and isolated during transposition. As with rocks, smaller scale parasitic folds have formed on the limbs of the larger folds.

SMALL-SCALE STEEPLY DIPPING STRUCTURE; AXIAL-PLANAR FOLIATION

The small-scale steeply dipping structure found downglacier of gently plunging fold axes are interpreted as axial planar foliation.

Similar structures have been described by Lawson et al. (1994: Fig. 4b) at surge-type temperate Variegated Glacier, Alaska, and in polythermal glaciers by Hambrey et al. (1999). They are believed to superficially resemble the folding/slaty cleavage relationship in low-grade metamorphic rocks although the exact mechanism for producing the planar elements in such axial-plane foliation in glacier ice is unknown (Hambrey and Lawson, 2000). It is not clear whether the granular ice in which they are found promotes the formation of axial planar foliation, or if the formation of axial planar foliation results in the recrystallization of the ice.

CIRCULAR/ELLIPTICAL CRYSTAL STRUCTURES; CRYSTAL QUIRKS

At Haut Glacier d'Arolla, circular/elliptical crystal structures are interpreted as crystal quirks (after Stenborg, 1968), which represent the recrystallization of voids that were moulins or other englacial drainage features.

The Relationship between Structure and Cumulative Strain

Structures in ice form in response to deformation operating over several decades in valley glaciers. Cumulative strain ellipses of four triangular areas at 50-yr intervals are presented in Figure 11, which includes the original kinematic data used to calculate strain-rates and ultimately cumulative strains. The highest cumulative strains occur along the western margin of the glacier, where strain ellipses rotate, their long axes becoming parallel to the western margin of the glacier,

indicating a simple shear regime. The easternmost strain ellipse does not deform or rotate as much as the westernmost strain ellipse, suggesting less transverse compression in the east.

There is some similarity between the deformation of the strain ellipses in Figure 11 and the deformation of structures measured in the field. For example:

- (1) The four ellipses become closer together as they move into the glacier tongue, simulating the combined transverse compression and simple shear that results in folding of primary stratification.
- (2) The spatial relationship between the four strain ellipses in the glacier tongue mirrors the general orientation of crevasse traces in the glacier tongue.
- (3) The rotation of the long axis of the westernmost strain ellipse accurately depicts the almost 90° rotation of primary stratification into longitudinal foliation along the western margin of the glacier.

Structural Evolution of Haut Glacier d'Arolla

To help understand the structural evolution of the glacier, an attempt has been made to distinguish between phases of deformation, as first demonstrated by Hambrey and Milnes (1977). Planar structures are termed S_0 to S_3 in order of their formation, and the one identifiable phase of folding, as F_1 . Unconformities and crystal quirks are not included in the structural history of the glacier as their importance is considered to be minimal in terms of the overall structural evolution of the glacier.

The structural notation used for Haut Glacier d'Arolla is summarized in Table 2. Each of these structures has been fully described in previous sections, but an attempt is made here to describe the sequential development of structures (Fig. 12), and explain how the structural evolution is controlled by the dynamics of the glacier (Fig. 11).

The first event at Haut Glacier d'Arolla is the deposition of snow and its transformation to firn and then glacier ice, to form primary stratification (S_0). Seven sets of primary stratification (S_0) originate on the slopes of Mont Brule, each with recognizable flow-unit boundaries (Fig. 2). The form and orientation of the primary stratification suggest that these separate flow units must initially behave independently in terms of velocity, flow direction and strain in the upper reaches of the glacier, before coalescing to become one main flow unit as they pass down into the narrower tongue.

As the stratification moves downglacier from its place of origin it becomes progressively folded (F_1). Folding at Haut Glacier d'Arolla is interpreted to be the result of compression as the wide upper-glacier area feeds into the narrow tongue (cf. Lawson et al., 1994; Hambrey et al., 1999; Ximenis et al., 2000). The strain ellipses in Figure 11 demonstrate how this compression affects ice structures; initial circles become elongated parallel to ice-movement direction as they pass downglacier into the glacier tongue. The parasitic folding found in the field would have formed in the same F_1 phase of deformation.

Field and aerial photograph observations suggest that longitudinal foliation (S_1) at Haut Glacier d'Arolla forms from the folding (F_1) and eventual transposition of S_0 (Fig. 12). It is also possible that some early crevasse traces are transposed along with S_0 into S_1 . The boundary between S_0 and S_1 is difficult to define. The rotation of S_0 into a longitudinal orientation is demonstrated by strain ellipses in Figure 11. S_0 becomes steeply dipping as it moves towards the glacier tongue. Field observations indicate a gradual transition from S_0 to S_1 . Longitudinal foliation (S_1) continues to evolve while traveling down the glacier tongue in response to continued lateral compression combined with simple shear; folds become increasingly isoclinal and, as a result of continual simple shear and attenuation of fold limbs

TABLE 2

Structural notation used for the Haut Glacier d'Arolla.

Planar structures and fold phases	
Stratification	S_0
Transposed longitudinal foliation	S_1, F_1
Axial planar foliation	S_1, F_1
Crevasse traces ^a	S_2
Thrusts	S_3

^a Main set of several.

during transposition, less obvious with distance downglacier. Axial planar foliation (also termed S_1) is probably formed at the same time as longitudinal foliation, in response to the same processes.

The main set of crevasse traces (S_2) is not folded within, but cross-cuts longitudinal foliation, and so must have formed after F_1 . Crevasse traces are rotated as they travel downglacier (Fig. 12). This rotation is also predicted by the strain ellipses in Figure 11. Rotation is the result of ice moving faster in the middle of the glacier than at the margins.

Finally, thrust faults (S_3) form at the glacier snout by the re-activation of crevasse traces (S_2), probably in response to longitudinal compression as the flow rate decreases towards the snout of the glacier.

The structures observed at Haut Glacier d'Arolla are not unique and have been described elsewhere. The progressive folding of primary stratification as it moves downglacier from a wide upper basin into a thinner glacier tongue is described by Hambrey et al. (1999) and Ximenis et al. (2000) from polythermal glaciers and Lawson et al. (1994) at surge-type temperate Variegated Glacier. Several sets of cross-cutting crevasses at different stages of deformation are described at, for example, Charles Rabots Bre, Norway (Hambrey, 1976). Thrust faults at the snout of valley glaciers have been identified by, for example, Hambrey et al. (1999) at polythermal Svalbard glaciers, and by Herbst and Neubauer (2000) at a temperate Austrian glacier. Axial-planar foliation at Haut Glacier d'Arolla resembles that described from glaciers in Svalbard by Hambrey and Glasser (2003). The similarity with structures described at other valley glaciers suggests that the structural evolution at Haut Glacier d'Arolla is typical of a valley glacier that flows from a wide-upper basin into a narrower tongue. There appears to be little difference between the structures and structural evolution described at temperate Haut Glacier d'Arolla, and those described for similar shaped polythermal glaciers. However, Haut Glacier d'Arolla differs from surge-type glaciers which demonstrate multiple phases of deformation during successive quiescent and surge phases (e.g., Lawson et al., 1994), or glaciers at the base of icefalls, which are dominated by transverse foliation (e.g., Allen et al., 1960; Ragan, 1969; Hambrey and Milnes, 1977; Goodsell et al., 2002).

A Comparison between Field and Numerically Derived Data

Recent developments in glacier modeling have facilitated the prediction of stress and strain fields (Hubbard et al., 1998) and the evolution of structures (Hubbard and Hubbard, 2000) of Haut Glacier d'Arolla. Only a brief comparison between modeled and field-based data is made here as a detailed comparison would involve a comprehensive study in its own right.

Field observations suggest that Hubbard and Hubbard's (2000) modeled data depict the deformation and rotation of primary stratification and crevasse traces in the central and eastern parts of the glacier to a high degree of accuracy. However, Hubbard and Hubbard's (2000) results predict:

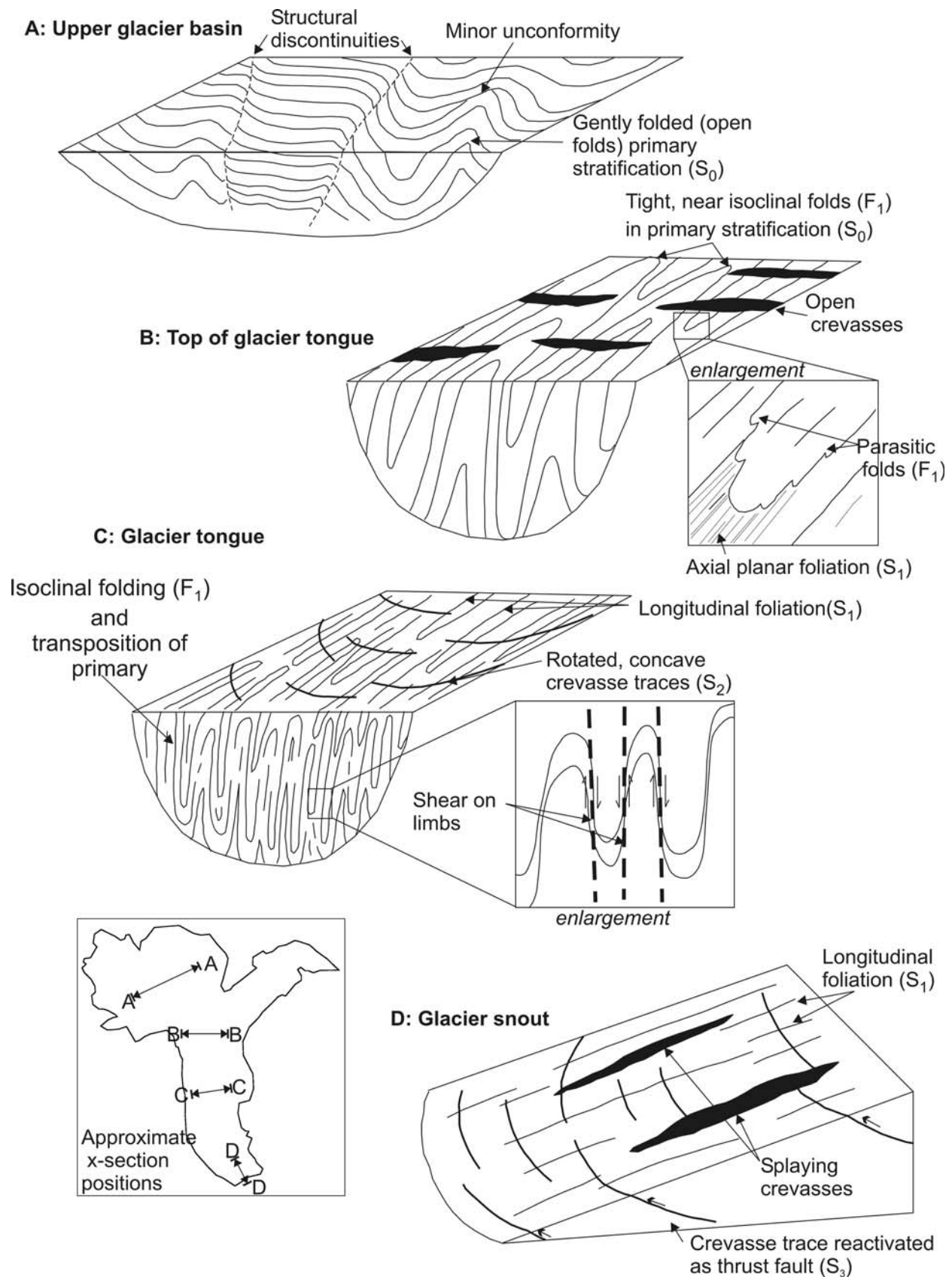


FIGURE 12. Schematic diagram of the structural evolution of Haut Glacier d'Arolla. (A) Flow-units, each with its own pattern of primary stratification, separated by structural discontinuities. (B) Primary stratification gradually folded as it flows into the glacier tongue. Cut by open crevasses. (C) Continued deformation and formation of longitudinal foliation. Closure and rotation of crevasse traces. (D) Reactivation of crevasse traces and opening of splaying crevasses.

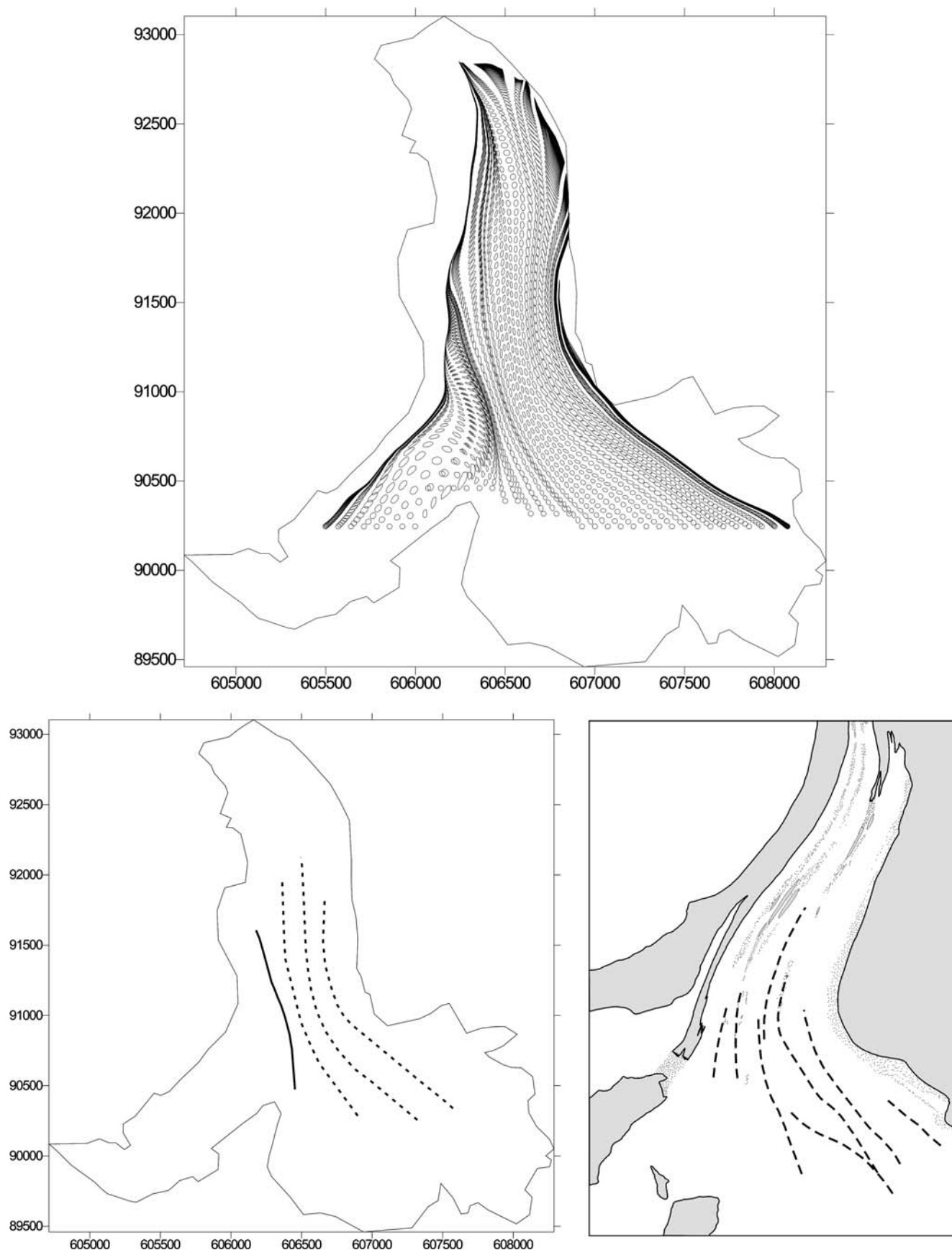


FIGURE 13. The potential presence of flow units within Hubbard and Hubbard's (2000) modeled strain ellipses. Top: Modeled strain ellipses, modified from Fig. 3b in Hubbard and Hubbard (2000). Lower left: Location of four possible flow unit boundaries within Hubbard and Hubbard's modeled data. Solid line represents obvious flow unit boundary between the main glacier and La Vierge tributary. Dashed lines represent suggested other boundaries. Lower right: Location of flow unit boundaries identified from aerial photograph.

- (1) inaccurate deformation and over-rotation of primary stratification and crevasse traces along the western glacier margin (cf. Fig. 2 with Figs. 5 and 7 of Hubbard and Hubbard [2000]), and
- (2) too little deformation at the top of initially vertical structures in cross-section through the glacier centerline (cf. Fig. 5 with Fig. 6 of Hubbard and Hubbard [2000]).

It is suggested here that Hubbard and Hubbard's (2000) modeled strain ellipses (reproduced in Fig. 13 [top]) indicate the existence of separate flow units. Apart from the obvious flow unit boundary between the two glacier basins, Hubbard and Hubbard's (2000) modeled strain ellipses suggest that four regions may exist within the main glacier. Each region is defined by the coherent patterns of strain ellipses within it. (Fig. 13).

Deviations between modeled and measured data may reflect several model assumptions: non-steady-state conditions, constant annual velocity, no basal sliding (not included in model equations), simplifications involved in using basic momentum equations, rheological errors and slope errors (B. Hubbard, pers. comm., 2002). To improve in the accuracy of the numerical model in order to characterize structural evolution of the glacier requires a reduction in these variables. For example, Willis et al. (2003) have demonstrated that basal sliding and plug flow may be significant components of the flow regime of some parts of Haut Glacier d'Arolla throughout the year.

Conclusions

Several conclusions may be drawn concerning the structural evolution of Haut Glacier d'Arolla, based on detailed mapping, cumulative strain analysis, and examination of modeled kinematic data.

- (1) Primary stratification becomes progressively more tightly folded as it moves downglacier, especially in the zone of converging flow where several flow units merge into one. Conceptual models developed for polythermal glaciers of similar morphology apply equally well to Haut Glacier d'Arolla.
- (2) The boundary between primary stratification and longitudinal foliation is gradational, and the former appears to be transposed into the latter.
- (3) Crevasse traces result from crevasse closure, or represent unopened crevasses similar to tensional veins. Crevasse traces are rotated according to flow as they travel downglacier. Their presence at the snout suggests that they extend to near the base of the glacier.
- (4) Following rotation to upglacier dips at the surface of 30 to 50°, some crevasse traces are reactivated as thrust faults at the snout of the glacier.
- (5) Crystal quirks are interpreted as the product of freezing of water-filled englacial drainage features, and therefore provide evidence of former drainage systems.
- (6) The structural evolution of Haut Glacier d'Arolla can be summarized as follows: first, primary stratification (S_0) is progressively folded by F_1 . This facilitates the formation of longitudinal foliation and axial planar foliation (S_1). The main set of crevasse traces (S_2) forms after F_1 . Crevasse traces towards the margins of the glacier tongue rotate on their downglacier journey. Compression at the snout causes the reactivation of crevasse traces (S_2) as thrust faults (S_3).
- (7) There is a strong relationship between cumulative strain and structural evolution, e.g. longitudinal foliation reflects rotation of the strain ellipse towards parallelism with flow

direction, and thus a simple shear regime. Thus, if dynamic data are unavailable, the structural pattern of a glacier can be used to infer past dynamic behavior.

- (8) The structural evolution of Haut Glacier d'Arolla based on high-resolution flow modeling agrees with field data and field observations to varying degrees of accuracy. The best match is in the central and eastern parts of the glacier. The main discrepancies are along the western margin of the glacier.

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