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ORIGINAL PAPER

Rotating micro-structures in Antarctic cold basal ice: implications for glacier flow and its interpretation

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Abstract Structural analyses were conducted in the basal zone of an Antarctic glacier. The studied basal ice sequence was retrieved from a 20-m-long subglacial tunnel dug at the margin of the glacier and is at the temperature of −17°C. For the first time, rotating clast systems embedded within debris-rich ice were thin-sectioned using specially designed cutting techniques. The observed structures reflect the occurrence of pervasive shearing at the base of the glacier, and can be used as shear sense indicators. In addition, some of these structures provide evidence for the presence of thin liquid films at the time of formation despite the marked freezing temperature of the ice. It is showed here that cautious analysis of deformation structures present in debris-bearing ice may bring insights not only into the flow dynamics of the embedding matrix, but also into the behaviour of the interstitial fluid network at the base of cold glaciers and ice sheets.

Keywords Strain figures · Porphyroclasts · Basal ice · Thin liquid films · Ice rheology · Antarctica · Dry Valleys

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Introduction

The basal zone of glaciers and ice sheets is known to display very distinctive properties as compared to the overlying glacier ice. One of its most striking characteristic lies in its generally high debris content and facies heterogeneity (Lawson 1979). When solid particles are present, the basal zone can be composed either of sediments only (glacial till), that form the subglacial bed of the ice body (Dreimanis 1976), or of ice containing particles in variable proportions (‘debris-laden basal ice’). The former is mostly found in the temperate region of glaciers and ice sheets, whereas the latter is mostly found within cold[1] areas of glaciers. Works by Goldthwait (1971), Menzies (1979) and Boulton and Hindmarsh (1987) have brought fundamental insight into the rheological and geological consequences of deformation of glacial till at the bed of temperate glaciers, leading to the recognition that many of these glaciers overlie soft sediments rather than hard bedrock. On the other hand, debris-laden basal ice has been recognized as playing a key role in the dynamics of glaciers and ice sheets in that it is not only a major contributor to the movement of the whole ice body, but also that it is fairly sensitive to environmental changes. For instance, enhanced subglacial ice–water interactions determine the onset of fast-flowing areas such as ice streams (Alley 1989; Tulaczyk et al. 2000), which can have important consequences for the stability of glaciers and polar ice sheets in the context of global change. Recent studies focusing on in situ characterization of basal ice dynamics have also shed light on how basal ice deformation in cold polar regions is

[1] For the remainder of this paper, ‘cold ice’ refers to ice well below its melting point (i.e. <−10°C), as opposed to ‘temperate ice’, that is close to the melting point.

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controlled by debris characteristics and the arrangement of micro-structures (Fitzsimons et al. 1999; Samyn et al. 2008). Characterization of transition flow zones such as the basal zone of flowing ice bodies is thence essential for constraining models of paleo-climates and glaciers and ice sheet (paleo-) flow by adequate boundary conditions.

In this paper, we report results from qualitative structural investigations in cold debris-laden ice excavated from a subglacial tunnel at Taylor Glacier, Antarctica. Different types of small-scale deformation structures were observed throughout the basal part of the glacier. Such deformation structures are common and well documented in mylonitic and metamorphic rocks (Passchier and Simpson 1986; Choukroune et al. 1987). These are the subject of various experimental and theoretical models, some of which describing successfully the building of natural deformation structures within rocks (Idelfonse and Mancktelow 1993; Masuda and Mizuno 1995; McKenzie and Holness 2000; Pennacchioni et al. 2000). However, the existence of small-scale strain structures in basal ice has attracted much less attention. This paucity of information may be explained by the difficulties, first, to excavate basal ice from the glacier bed; and, second, to prepare thin sections from the ice owing to its relatively high debris content. The understanding of deformation structures from the basal zone of glaciers is nevertheless essential for glaciologists and Quaternary geologists since they can provide, like in other rocks, direct information on the genesis and flow kinetics of the modern or past embedding ice matrix.

Ice cores constitute at present the most common and important source of information on the behaviour and history of natural ice bodies. Our interest hence turns on reliable strain indicators that would be available at the scale of an ice core segment. We focus here on rolling structures, of which the (a)symmetry is considered by structural geologists as one of the most powerful rheological markers of the materials containing them (Choukroune et al. 1987; Passchier and Trouw 1996; Passchier and Sokoutis 1993). Quantifying the rotational component of strain is important since the latter can produce distinct flow paths around particles with significantly different kinematic consequences. Building on analogies with structures commonly observed in strained rocks, we propose a new mechanism for the formation of winged structures and the development of foliation within debris-rich ice. Implications for the occurrence of interstitial fluids are also discussed.

Glaciological setting and sampling methods

Taylor Glacier is an outlet glacier from the East Antarctic Ice Sheet and is flowing into Taylor Valley (Dry Valleys, South Victoria Land) (Fig. 1). The ablation zone of the glacier (Fig. 2) can be considered as cold based (Robinson 1984). During the 1999–2000 austral summer, a 20-m-long subglacial tunnel was excavated at the margin of the glacier in order to investigate the deformation mechanisms occurring within the basal zone. The tunnel was oriented parallel to the ice flow and was located on the left side of the glacier, approximately 1.2 km from the terminus. At the end of the tunnel, ice blocks were sampled from a 4-m-deep shaft along a continuous vertical profile (Samyn et al. 2005a). The mean annual temperature measured throughout the basal ice sequence remained close to −17°C. Tunnel and shaft excavations were carried out with the aid of a chain saw and a jackhammer, following the procedure described by Fitzsimons et al. (1999). This way of sampling ice blocks along the basal sequence is particularly convenient to retrieve the initial orientation of samples according to the local glacier flow, as opposed to the case of ice cores, where this relation is generally lost. Strain gauges were placed and surveyed during 1 year along the tunnel walls in order to characterize the type of flow at the margin of the glacier. A pervasive simple shear component was observed at various scales within the basal zone (Fitzsimons et al., in preparation).

A series of debris-bearing ice bands alternating with clean bubbly ice layers was observed in the middle part of the basal sequence for about 2 m (Samyn et al. 2005a, 2008) (Fig. 3). The contact zone between these contrasting ice layers was sharp, as a result of a drastic change in debris concentration. A debris content ranging from less than 0.5% (of ice volume) in the clean ice to more than 30% in the debris-rich bands was observed. In order to investigate the relation between ice crystal properties and debris arrangement, thin sections were prepared from the

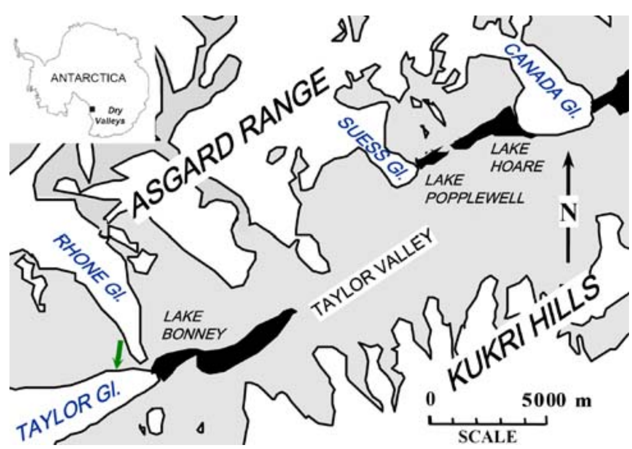

Fig. 1 Location map of the margin of Taylor Glacier, Dry Valleys, Antarctica. The location of the subglacial tunnel is indicated by the *arrow*

Fig. 2 Overview of the terminus of Taylor Glacier. The glacier margin is formed by 18–25-m-high ice cliffs. The subglacial tunnel was located on the left side of the glacier, about 1.2 km upstream from the margin (the direction is indicated by the *arrow*)

ice blocks sampled; mostly by the use of a diamond-wire saw because of the generally high debris concentration (Samyn et al. 2005a). To allow best examination of the strain figures present, most thin sections were cut parallel to the general stretching lineation and normal to the foliation (i.e. parallel to the *X*–*Z* plane of finite strain).

Results and discussion

Morphology of tailed clasts

The core of the deformation structures presented here is made up of a pebble-sized rock clast embedded either within a debris-rich ice layer (Figs. 4, 5) or occasionally within a clean ice layer (Fig. 6). The tails and flow lines departing from these structures extend from each side of the clasts along the lee side of the relative shear motion reported locally. Close to the rigid inclusion, the tails and flow lines show a curved geometry (Figs. 4, 5, 6), indicating that the flow of the ice matrix has been disturbed by interference with the rigid object. Further from the core, the orientation of the tails and flow lines generally becomes subparallel to the ice foliation and—when bubbles are present—to the bubble lineation within a distance of the order of the core diameter (Figs. 4, 5, 6). In addition, the thickness of the tails decreases with the distance to the central rigid core. These observations provide evidence for the occurrence of shearing processes as responsible for the formation of rolling patterns around the rock clasts (Van Den Driessche and Brun 1987). These structures resemble the mantled porphyroclasts often observed in mylonitic rocks and defined as “weakly deformed to undeformed core(s) surrounded by softened material” (Bose and Marques 2004). Wings (or tails), made up of matrix recrystallization products with a variable geometry, may be present around the core of mantled porphyroclasts. The resulting structure is then known as a winged (or tailed) porphyroclast. The tails and deflected flow lines (or drag patterns) observed around the cores in this study are either of σ or δ type, i.e. with a characteristic shape similar to the Greek letters σ or δ (Passchier and Simpson 1986). As illustrated in Fig. 6, tailed clasts are best observable when embedded within clean ice.

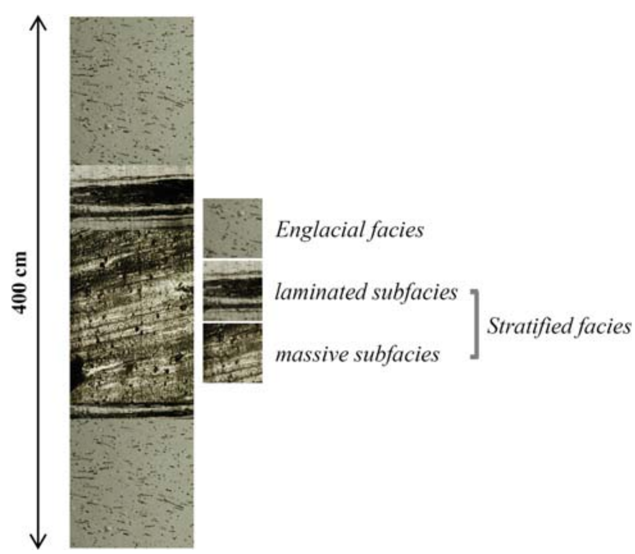

Fig. 3 Schematic of the basal ice sequence sampled at the end of the subglacial tunnel

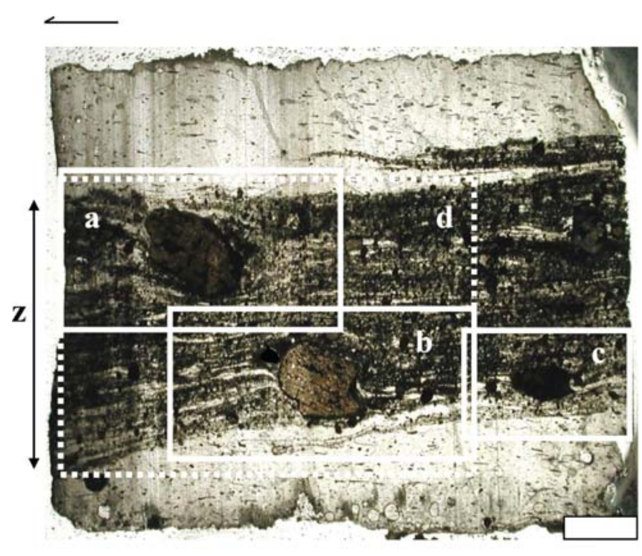

Fig. 4 Photomicrograph of cm-scale σ-shaped clast systems embedded within a debris-rich ice layer. The core of these structures is made up of a rigid granitic clast. Deflected flow lines can be observed in the debris-rich ice matrix past the cores. Shear sense is sinistral. Thin section; transmitted light; *scale bar* 1 cm. *Z* stands for the shear zone width. *Rectangles* tagged from *a* to *d* are magnified in Fig. 5

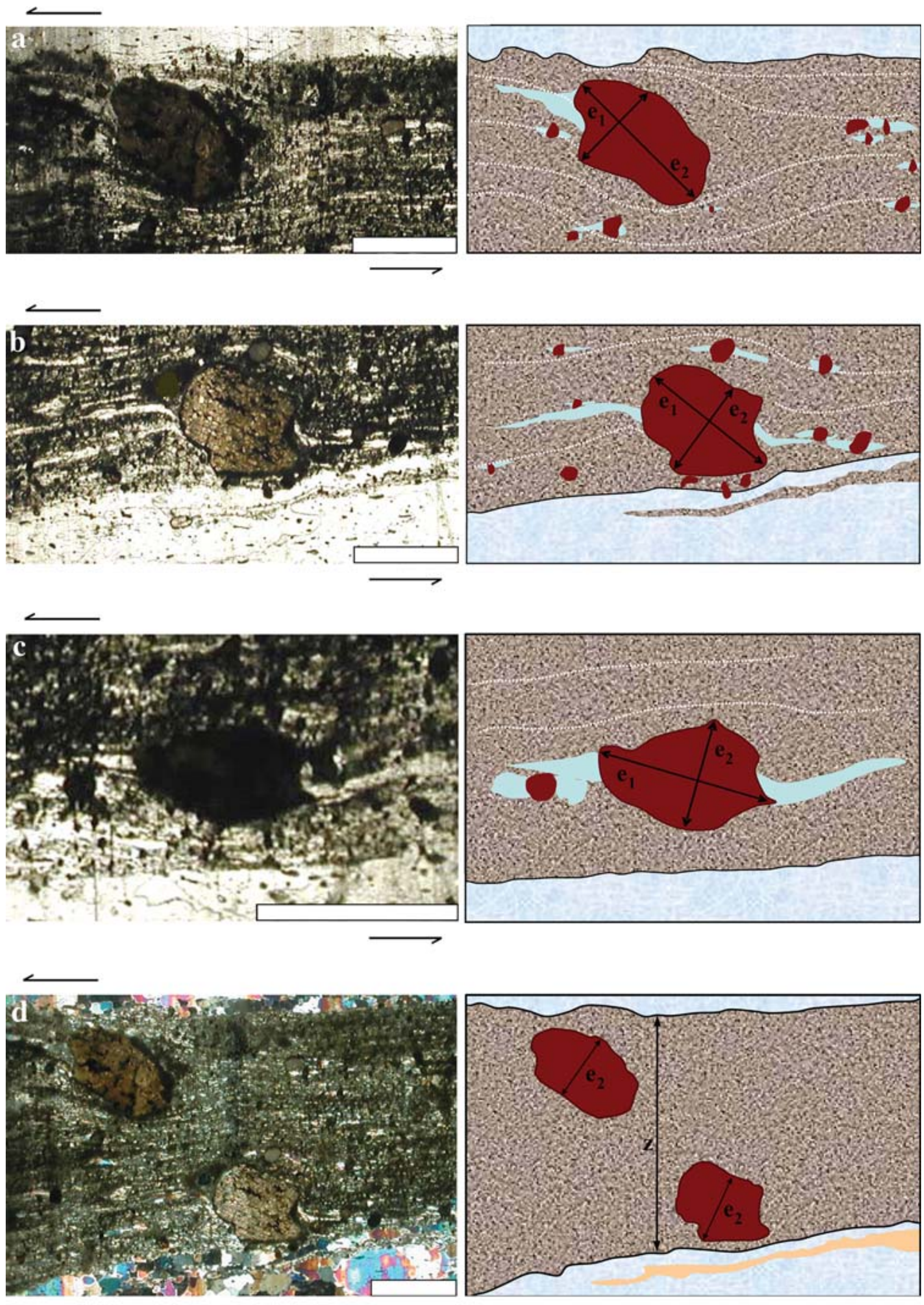

Fig. 5 **a–c** Distinctive drag patterns around centimetre-scale rigid rock clasts indicated in Fig. 4; transmitted light. **d** Flow confinement around the two centimetre-scale rigid rock clasts indicated in Figs. 4, 5a, b. Shear sense is sinistral. Thin sections; crossed polars; *scale bar* 1 cm. Distinctive drag patterns are indicated with *dotted white lines*; distinctive rock clasts and ice lenses are indicated in *dark brown* and *light blue*, respectively. The *dotted grey* and *blue* textures represent debris-rich and clean ice layers respectively. e_1 and e_2 stand for the principal axes of the ellipse embodying the centimetre-scale clasts

When present in debris-rich ice (Figs. 4, 5); however, the tails become difficult to distinguish because they are composed of the same material as the embedding matrix.

Similarities with mylonitic rocks

Van Den Driessche and Brun (1987), Passchier (1994), and Ten Brink and Passchier (1995) showed that, during deformation of mylonitic rocks, the core of porphyroclasts may reduce in size due to the storage of dislocations and to subsequent dynamic recrystallization. According to these authors, this would lead to the input of new material around the core, which would then contribute to the development of tails or wings around it as deformation proceeds. Although the tailed clasts described in the present study show strong morphological similarities with the referred mantled structures in rocks, they cannot result directly from the same process. This is attributed both to structural and environmental reasons. The structural reasons are threefold: (1) the granulometry of the debris in the ice matrix is too fine (silt to

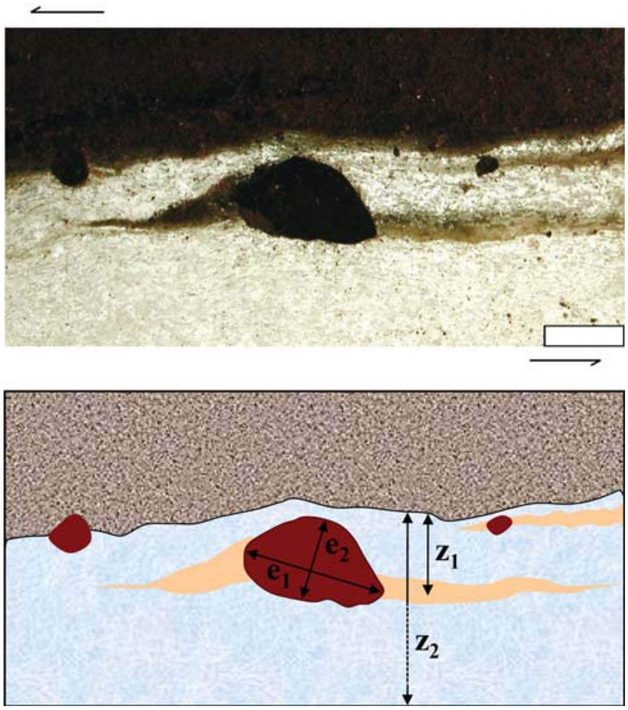

Fig. 6 Photomicrograph of a δ-shaped coated clast within debris-free ice. The left tail is curved and shows stair-stepping, whereas the right one is flat and does not cross the clast reference plane. Shear sense is sinistral. Thick section; transmitted light; *scale bar* 1 cm. Distinctive rock clasts and debris lenses are indicated in *dark* and *light brown*, respectively. The *dotted grey* and *blue* textures represent debris-rich and clean ice layers, respectively. e_1 and e_2 stand for the principal axes of the ellipse embodying the centimetre-scale clast

sand), (2) the embedded debris particles are too worn, and (3) the viscosity contrast between the rigid core of the clast system and the surrounding debris-rich ice matrix is too large, to account for the softening of the outer rim of the rigid cores. The environmental reasons we see are twofold: (1) the basal strain rates measured in the glacier are too low (max. 10^{-5} s^{-1}), and (2) the in situ temperature is too cold (<−15°C), to allow detectable erosion and further recrystallization of the outer rim of the cores.

The question then becomes one of how tails consisting of debris-rich ice laminations could form around rigid cores (as e.g. in Fig. 6). We suggest that the observed rolling systems require in this case the pre-existence of a thin debris layer coating rigid rock clasts. Such debris soft rims were observed around millimetre to centimetre scale rock clasts in the studied sequence (examples are provided in Figs. 6, 7). They were made up of clay-to-sand sized particles cemented by interstitial ice, and their existence can be explained by rotation, during shearing, of the rigid clasts within a debris-rich material prior to the tail development. We propose the term coated clast to characterize such structures, thereby making a distinction with porphyroclast systems resulting from direct transformation of the rigid core. Whether the debris coatings formed at a time where the rigid clasts were within the ice or out of it (e.g. within a till) cannot be known here from micromorphological analysis solely. Regardless of circumstances, their presence around rigid clasts points to the occurrence of substantial amounts of fluids at the time of formation. In case the debris coatings were formed within the basal zone, it seems most likely that clay/silt agglomeration occurred around the clasts with minute fluid films acting as a binder.

A mechanism for the building of rolling structures within basal ice

Based on the spatial consistency between various types of shear-induced structural features, Samyn et al. (2005a, 2008) showed that strain partitioning plays a crucial role, at various scales, in the development of compositional and sedimentological layering in Taylor basal zone. We showed above that the tails and drag patterns flanking rotated clasts in this study result from pervasive shearing processes. To

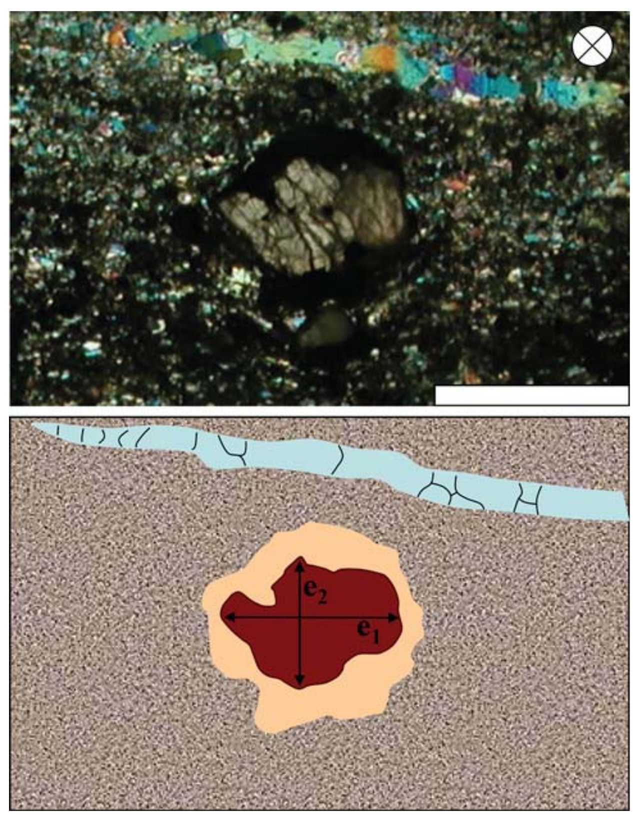

Fig. 7 Photomicrograph of a coated clast within debris-rich ice. The core of the structure is made up of a rigid granitic clast wrapped by a debris envelope. Shear direction is toward the plane of view. Thin section; plane polarized light; *scale bar* 1 cm. Distinctive rock clast, debris coating are indicated in *dark* and *light brown*, respectively, and a distinctive ice lense is indicated in *light blue*. The *dotted grey texture* represents the debris-rich ice matrix. e_1 and e_2 stand for the principal axes of the ellipse embodying the centimetre-scale clast

investigate the kinematical conditions under which such structures can form within basal ice, we rely on pioneering experimental modelling of rotating objects conducted by Passchier and Sokoutis (1993). An important notion in fluid dynamics to introduce at this stage is the concept of separatrix in deforming rocks (Ottino 1989). The latter defines a sharp boundary between open and closed flow lines around a given porphyroclast (Fig. 8). Passchier and Sokoutis (1993) showed that, in the case of low viscosity contrast between the clast mantle material and the embedding matrix, part of the mantle may transect the separatrix and may then become free to move away from the rigid core by differential deformation. After a certain amount of finite strain, local flow perturbations begin to occur past the rigid core, giving rise to progressive core rotation. In such circumstances, tails can form, which is achieved by stretching and wrapping of the mantle around the core. If the mantle thickness is relatively large as compared to the diameter of the core, part of the mantle may continually stay outside the separatrix. This would lead to the formation of tails with a σ-type geometry (Passchier and Trouw 1996; Bose and Marques 2004). If the mantle then becomes thin enough to reside inside the separatrix at some point, enhanced dragging of the wings would occur as a result of increased vorticity, and typical embayment of δ-type would finally develop (Passchier and Sokoutis 1993; Bose and Marques 2004). Accordingly, the separatrix would play a crucial role in controlling the shape of drag patterns around the embedded clasts. We believe that an analogy can be drawn with the above model to account for the formation of the tailed, coated clasts observed in the basal ice studied here. The core of the latter structures appears to have behaved as a rigid object that could rotate in the ice matrix, thereby disturbing the flow pattern of the matrix itself in the immediate vicinity of the cores. The occurrence of tailed coated clasts within debris-free ice layers of the sequence, as exemplified in Fig. 6, is consistent with our view above that the presence of a coating around a rigid core is a requisite for the production of tailed clasts within basal ice. Figure 6 also clearly illustrates the fact that tailed coated clasts can participate in the building of foliation in the ice: when differential deformation occurs in the vicinity of coated cores, debris-rich laminations are produced and quickly become subparallel to the main foliation. This provides strong evidence for a new mechanism for the inception or consolidation of foliation within a deforming material.

Occurrence of antithetic rotation

As already noted, it is well accepted in structural geology that the fabric asymmetry of winged porphyroclasts can be considered as a reliable shear sense indicator (Choukroune et al. 1987; Passchier and Sokoutis 1993). However, kinematic interpretation must be made with caution since

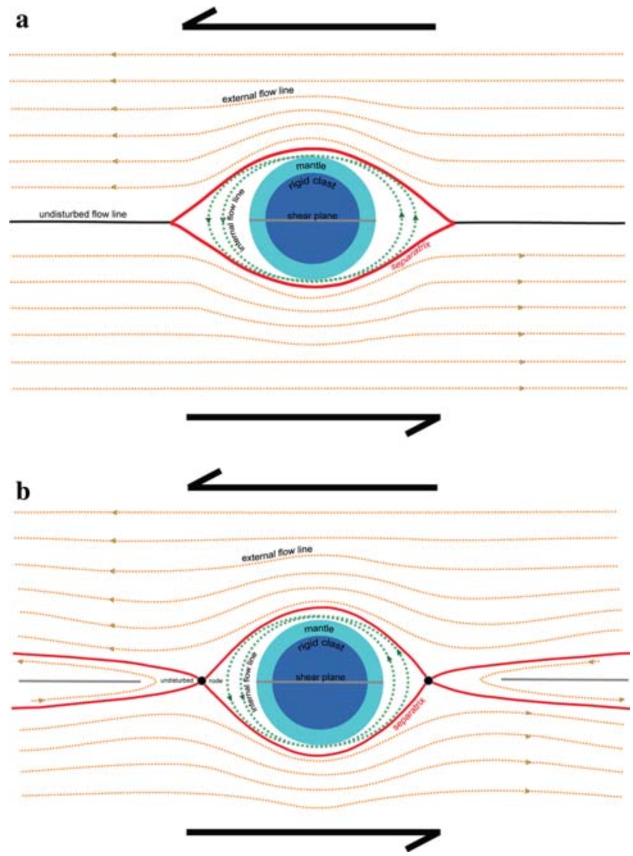

Fig. 8 Schematics of the separatrix concept, illustrating the deflection of flow lines around rigid clasts: **a** Eye-shaped flow pattern; **b** bow-tie flow pattern. Cross-sections are represented in the direction of flow. The reference plane of the clasts corresponds here to the shear plane

problems such as non-ideally oriented sections or overprinting deformation events may bring into confusion (Van Den Driessche and Brun 1987; Passchier and Williams 1996). Of particular interest in this context is the sense of rotation undergone by the centimetre-scale elliptic rock clasts shown in Fig. 5. In spite of the uncertainty on the original orientation of the rigid cores, the deflection of flow lines around the cores with respect to the effective shear motion suggests the occurrence of antithetic rotation of the cores, whereas most of the structures observed in the basal sequence show synthetic rotation. In addition, and as observed by Marques and Bose (2004) in analogue experiments, a stable preferred orientation is suggested by the backward tilt position of the largest cores (e.g. $\sim 20°$ in Fig. 5d). If the hypothesis of antithetic rotation is valid, its occurrence is best explained here by the coalescence of two determining conditions, namely, (1) the presence of a lubricating phase (i.e. a slipping mode, as opposed to an adherent mode) and (2) geometrical confinement. The occurrence of a fluid phase around the rotated clasts in question is implied from the presence of pressure shadows departing from their wedges and filled with clean ice, as exemplified at millimetre and centimetre-scales in Fig. 5b, c. It is worth noting that the elongated aspect of the largest pressure shadows, which can give a clue on the intensity of shearing undergone (>100%). Such a fluid phase at the time of formation of porphyroclast systems in rocks has been shown to induce a velocity discontinuity across the inclusion/matrix boundary because of interfacial lubrication (Idelfonse and Mancktelow 1993; Bjørnerud and Zhang 1995; Marques and Coelho 2001). Consequently, the kinematics as well as the finite geometry of the porphyroclast system differs from the case of coherent interface. Marques and Bose (2004) and Marques et al. (2005) even argued that, despite leading to an overall flow pattern similar to the adherent mode, the slipping mode would exclude the existence of both a separatrix and closed flow lines around an inclusion.

The second factor that could explain the antithetic rotation of the rigid cores, namely geometrical confinement, can be modelled as the ratio between the shear zone width (z) and the shortest principal axis (e_2) of the ellipse embodying the inclusion. According to Marques and Coelho (2001), this ratio controls the repartition of pressure anomalies within the shear zone. These authors showed from shear flow experiments that, when the environment is confined, i.e. when z/e_2 approaches unity, and when lubrication of the inclusion/matrix interface is allowed, antithetic rotation is favoured. This phenomenon is assumed to stem directly from the prevalence of clast rotation driven by pressure variations at the clast wedges (pressure-gradient-driven rotation) over clast rotation driven by the shear-induced vorticity (vorticity-driven rotation). In Fig. 5d, the ratio between the width of the embedding debris-rich ice layer and the e_2 dimensions of the largest rigid clasts is found to be close to 3, which is in the order of magnitude reported by Marques and Coelho (2001) for the cases where antithetic rotation occurred. In addition, the relatively close proximity between the two centimetre-scale rigid clasts in Fig. 5d may have brought further flow confinement within the debris-rich ice layer, and therefore have enhanced the phenomenon. Figure 6 also illustrates the effect of flow confinement on the outline of the core tails. The tail at the left-hand side of the larger clast is δ-curved and shows embayment (i.e. it has crossed the clast elongation axis e_1), whereas the tail at its right is flat and does not show embayment. This type of asymmetry as well as the back tilting of the clast can be explained by strong confinement of the flow between the top of the clast and the lower boundary of the debris-rich ice band (i.e. the flow is confined in a shear zone where $z/e_2 \ll 1$), which caused the observed tail deflection. Below the clast, however, the absence of confinement in the clean ice did not produce any significant flow distribution around the clast, but led instead to flat-shearing of the tail concurrently to its formation.

Slipping, or non-slipping interface?

From the above, it follows that a potentially important variable in the formation of coated tailed clasts is the presence of a lubricating phase at the interface between rigid inclusions and the surrounding matrix. This is supported by experimental and numerical modelling (Bjørnerud and Zhang 1995; Pennacchioni et al. 2000; Bose and Marques 2004), where the lubricating phase has been shown to control the degree of coupling between the inclusion and the matrix. A slipping interface can, in fact, be compared in its effect to a decrease of the inclusion competence with respect to the matrix (Bjørnerud 1989), thereby leading to a reduction of the interference between the matrix flow and the rigid inclusion.

Thin liquid (or quasi-liquid) films are known to persist within polycrystalline ice, down to temperatures well below the pressure-melting point (i.e. $<-20°C$). This phenomenon, called premelting, is due to a change in chemical potential of water molecules at the boundary surface between entities, and originates from various physico-chemical mechanisms, mostly including intercrystalline (Nye 1989; Mader 1992a, 1992b) and interfacial phenomena (Gilpin 1979; Dash et al. 1995; Ishizaki et al. 1996; Cuffey et al. 1999; Souchez et al. 2004). The thickness of these films is of the order of a few micrometers at $-30°C$ (Rempel and Worster 2001) and increases exponentially with temperature and impurity content (Mader 1992a; Dash et al. 1995; Wettlaufer 1999). These interstitial fluid bodies are known to play an important role in the dynamics of cold basal ice (Cuffey et al. 1999; Souchez et al. 2004; Samyn et al. 2005b). In the basal ice of Taylor Glacier, geochemical and crystallographic evidences for the presence of quasi-liquid bodies were provided by Samyn et al. (2005a, 2008), who suggested that subtle changes in the gas content and in the grain boundary kinetics of ice layers at structural interfaces were typical of phase changes involving slight changes in fluid content. These authors also argued that these phase changes should be due to changes in debris content and strain dynamics across the basal zone rather than to significant temperature changes during basal ice formation. But did the fluid phase play an effective role in the formation of the tailed coated clasts observed in this study? Idelfonse and Mancktelow (1993) found that δ-type tails form in a non-Newtonian material only when the coherence between the rigid core and the matrix is high, that is, when interfacial fluid water is limited. In other conditions, σ-type or symmetrical clast systems are likely to form. Results from Bjørnerud and Zhang (1995) and Bose and Marques (2004) suggest that the same is true for Newtonian materials. Accordingly, since we mostly observed σ-shaped clast systems within debris-rich ice layers and δ-shaped clast systems within clean bubbly ice layers, we infer that the nature of flow at the interface between the rigid cores and the embedding matrix is not only related to the lubrication mode at the interface, but is also partly a function of the matrix debris content, which is itself a major control on the interfacial fluid content: the higher the debris content, the larger the depression of the pressure melting point, and thus the higher the fluid content (Dash et al. 1995; Rempel and Worster 2001). This reinforces the idea that the presence of interstitial fluid bodies is an important factor governing the geometry of the coated clasts observed. It can be further argued that the fluid phase, given its decoupling effect around the rigid clasts, is also likely to contribute significantly to the rheological softening, and hence to the overall horizontal motion, of the basal zone of flowing ice bodies.

An important aspect that might be worth investigating in this regard to improve our understanding of rolling structure kinematics would be the thermodynamical interdependency between the embedding matrix, the coating, the clast surface and the fluid phase behaviour at the interface. To our knowledge, this dependence, known to be mostly determined by temperature, roughness and compositional gradients (Gilpin 1979; Mader 1992a; Dash et al. 1995; Rempel and Worster 2001), has not been critically considered yet in structural geology and glaciology. Analogue experimental modelling is indeed generally conducted with materials that are rather unreactive between each other thermodynamically speaking, which is clearly not the case in natural geological and glacial conditions. In addition, there is now a growing body of evidence, at least for the case of debris-bearing ice, that the intermolecular forces leading to premelting also exert a repulsive force at the interface between foreign materials (Gilpin 1979; Rempel and Worster 2001). The resulting thermo-molecular and buoyancy gradients localized at the outer and inner surfaces of the clast mantles observed might consequently have rheological and kinematic consequences that should be taken into account in order to explain variations in the morphology of basal ice and till microstructures.

Conclusion

We conducted a morphological and kinematical qualitative study of coated clast systems observed in thin sections from cold Antarctic basal ice. These thin sections were made using specially designed cutting techniques, setting a precedent by which similar combinations of analyses can be used to describe the dynamics of the basal zone of past and modern flowing ice bodies. We proposed a new mechanism based on the presence of a preliminary debris coating around rigid clasts to account, first, for the building of tailed coated clasts and, second, for the inception or consolidation of foliation within debris-rich ice. We showed that the study of internal symmetry of strain figures in basal ice provides diagnostic information on the kinematics of shearing processes occurring at the base of glaciers and ice sheets. Tails and drag patterns around rigid clasts are of particular interest in this context since they can be used as reliable shear-sense indicators in the vicinity of the clast systems if the conditions for basal ice formation are known. This type of study is of potential importance for the following research perspectives: (1) the processing of the basal parts of deep ice cores, as it might help for instance to re-orient ice cores retrieved from deep drilling, or to assess the basal flow paths necessary for glacier modelling, and (2) the reconstruction of (de)glaciation events from tills, or the study of permafrost dynamics, both of which requiring a clear distinction between depositional and tectonic processes. Finally, our work emphasizes the fact that treating debris-rich ice based on polyphase and polymineralic rock deformation theory provides a suitable framework to improve our understanding of basal ice rheology and kinematics. In this perspective, research is underway to assess the contribution of interstitial meltwater in the formation of strain indicators found within debris-rich ice and in the rheological softening of debris-rich basal layers. Further work is also needed to determine to which extent rotating clast systems can be used, in addition to as shear-sense indicators, as rheology indicators.

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