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MODELLING GLACIAL EROSIONAL LANDFORM DEVELOPMENT

VOLUME 2

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R. C. A. HINDMARSH

A thesis presented for the degree of Doctor of Philosophy in the University of Durham

Graduate Society

January 1985



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LIST OF FIGURES

Figure 2.1 Development of glacially eroded surfaces by scratching and polishing. Figure 2.2 Derivation of the abrasion equation. Contour plot of surface persistent under Figure 2.3 constant abrasion: a = 1, l = 2, $m_y = m_y = 0$. Contour plot of surface persistent under Figure 2.4 constant abrasion: a = 1, l = 2, $m_r = 0.0$, $m_{y} = -0.5$. Contour plot of surface persistent under Figure 2.5 constant abrasion: a = 1, $\ell = 2$, $m_x = m_y = -0.5$. Figure 2.6 Contour plot of surface persistent under constant abrasion: a = 1, $\ell = 2$, $m_v = m_v = -0.9$. Figure 2.7 Dependence of abrasion on position for persistence of a sine-wave under lowering. Figure 2.8 Evolution of a slope and plateau under constant abrasion using the method of characteristics. Evolution of a bell-shape under constant Figure 2.9 abrasion using the method of characteristics. Figure 2.10 Evolution of a V-shaped valley under constant abrasion using a direct finite-difference formulation of the abrasion equation.

Evolution of a bell-shape under constant

abrasion using a direct finite-difference

formulation of the abrasion equation.

Figure 2.11



- Figure 2.12 Evolution of a V-shaped valley under constant abrasion using the Farmer formulation with a coarse mesh.
- Figure 2.13 Evolution of a V-shaped valley under constant abrasion using the Farmer formulation with a fine mesh.
- Figure 2.14 Evolution of a bell-shape under constant abrasion using the Farmer formulation.

Figure 2.15 Persistence without migration of a bell-shape with lowering.

- Figure 2.16 Persistence with migration of a bell-shape with lowering.
- Figure 2.17 Evolution of a V-shaped valley under constant abrasion using the method of characteristics: no definition of point.
- Figure 2.18 Evolution of a V-shaped valley under constant abrasion using the method of characteristics: smooth definition of point.
- Figure 2.19 Evolution of a V-shaped valley under constant abrasion using the method of characteristics: random definition of point.

Figure 2.20 Evolution of slope and plateau with curvature dependent abrasion rate using the Farmer formulation.

Figure 2.21 Evolution of V-shaped valley with abrasion inhibited by concavity using the Farmer formulation.

| | Figure 2.22 | Evolution of V-shaped valley with abrasion |
|--------|-------------|--|
| | | enhanced by concavity using the Farmer |
| | | formulation. |
| | Figure 2.23 | Evolution of a V-shaped valley with a Gaussian |
| | | abrasion function. |
| | Figure 2.24 | Evolution of a V-shaped valley with rocks of |
| | | different hardness. |
| | Figure 2.25 | Trough persistent under lowering with |
| • • | | a α 1/h: hyberbolic cosine. |
| κ | Figure 2.26 | Troughs persistent under lowering with abrasion |
| | | a function of a curvature. |
| | Figure 2.27 | Abrasion of a weak zone. |
| | | Two element test problem |
| | Figure 4.1 | Two element test problem. |
| | Figure 4.2 | Inclined plane problem-nine nodes. |
| | Figure 4.3 | Inclined plane problem-seventeen nodes. |
| | Figure 4.4 | Rotating Couette flow. |
| | Figure 5.1 | View of finite element mesh showing the |
| | 1 | nesting scheme. |
| | Figure 5.2 | Detail from finite element mesh for modelling |
| | | flow over a semi-cylindrical ridge. |
| | Figure 5.3 | Detail from finite element mesh for modelling |
| - | | flow over a truncated sine ridge. |
| | Figure 5.4 | Schematic diagram of boundary conditions |
| | · · | for plane-strain. |
| | Figure 5.5 | Velocity vector plot for an incompressible |
| | | linear rheology with $v_d = 100 \text{ alu/a}$ (Case 3). |
| | Figure 5.6 | Larger view of velocity vector plot for an |
| | | incompressible linear rheology with |
| | | v _d = 100 alu/a (Case 3). |
| | | |

ł

| | Figure 5.7 | v_{τ} against sin γ for an incompressible |
|---|-------------|---|
| | | linear rheology with $v_d = 10 \text{ alu/a}$ (Case 1). |
| | Figure 5.8 | v_{τ} against sin γ for an incompressible |
| | | linear rheology with a cavity and |
| | | $v_d = 400 \text{ alu/a} (\text{Case 7}).$ |
| | Fiugre 5.9 | v_{τ} against sin γ for an incompressible |
| | • • | linear rheology with a cavity and |
| | | $v_d = 10 alu/a (Case 6).$ |
| | Figure 5.10 | v_{τ} against sin γ for a compressible linear |
| | | rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and |
| | | $v_d = 10 alu/a (Case 8).$ |
| | Figure 5.11 | Velocity vector plot for a compressible linear |
| | | rheology with χ = 10 alu ² /bar.a and |
| | | v _d = 200 alu/a (Case 16). |
| | Figure 5.12 | $v_{	au}$ against sin γ for a compressible linear |
| | | rheology with $\chi = 10$ alu ² /bar.a and |
| | | v _d = 200 alu/a (Case 16). |
| | Figure 5.13 | Velocity vector plot for an incompressible |
| • | • | linear rheology with bed of S = 100 alu/bar.a |
| | | and $v_d = 100 alu/a$ (Case 20). |
| | Figure 5.14 | v_{τ} against sin γ for an incompressible |
| | . · · | linear rheology with bed of S = 10 alu/bar.a, |
| | · · | $v_d = 10 alu/a (Case 18)$ |
| | Figure 5.15 | v_{τ} against sin γ for an incompressible |
| | | linear rheology with bed of S = 400 alu/bar.a, |
| | | v _d = 400 alu/a (Case 22). |
| | Figure 5.16 | Velocity vector plot for an incompressible |
| | | Glen rheology with $v_d = 100 \text{ alu/a}$ (Case 25). |

•

Figure 5.17 v_{\perp} against sin γ for an incompressible Glen rheology with $v_d = 10 \text{ alu/a}$ (Case 23). v_{τ} against sin γ for an incompressible Figure 5.18 Glen rheology with $v_d = 400 \text{ alu/a}$ (Case 25). Figure 5.19 Velocity vector plot for an incompressible Glen rheology with a cavity and $v_d = 400 \text{ alu/a}$ (Case 28). v_{\perp} against sin γ for an incompressible Figure 5.20 Glen rheology with a cavity and $v_d = 400 \text{ alu/a}$ (Case 28). Figure 5.21 Velocity vector plot for a compressible Glen rheology with $\chi = 1 \text{ alu}^2 / \text{bar.a}$ and $v_d = 100 \text{ alu/a} (\text{Case 31}).$ v_{τ} against sin for a compressible Glen. Figure 5.22 rheology with $\chi = 1 \text{ alu}^2 / \text{bar.a and}$ $v_d = 200 \text{ alu/a} (\text{Case 32}).$ v_{τ} against sin γ for an incompressible Figure 5.23 Glen rheology with bed S = 10 alu/bar.a and $v_{d} = 10 \text{ alu/a} (\text{Case 34}).$ Velocity vector plot for an incompressible Figure 5.24 Glen rheology over a truncated sine ridge with $v_{d} = 100 \text{ alu/a} (Case 47).$ v, against position for flow over a truncated Figure 5.25 sine ridge (Cases 40 - 49). Regression coefficients from v_{τ} against Figure 5.26 \boldsymbol{v}_d against position for flow over a truncated sine ridge (Cases 45 - 49). Figure 5.27 Pressure contours in bar for an incompressible linear rheology with $v_d = 100 \text{ alu/a}$ (Case 3).

p' against cosy for an incompressible Figure 5.28 linear rheology with $v_d = 400 \text{ alu/a} (\text{Case 1})$. p' against $\cos\gamma$ for an incompressible Figure 5.29 linear rheology with a cavity and $v_{d} = 400 \text{ alu/a} (Case 5).$ Figure 5.30 p' against $\cos\gamma$ for a compressible linear rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and $v_{d} = 400 \text{ alu/a}$ (Case 12). Figure 5.31 Pressure contours in bar for a compressible linear rheology with $\chi = 10 \text{ alu}^2/\text{bar.a}$ and $v_{d} = 400 \, \text{alu} \, / \, \text{a}^{-1}$ (Case 17) Figure 5.32 p' against $\cos\gamma$ for a compressible linear rheology with $\chi = 10 \text{ alu}^2/\text{bar.a}$ and $v_{d} = 200 \text{ alu } / \text{ a}$ (Case 16). Pressure contours in bar for an incompressible Figure 5.33 linear rheology with bed of S = 100 alu /bar.a and $v_d = 100 \text{ alu} / \text{a}$ (Case 20). p' against $\cos\gamma$ for an incompressible Figure 5.34 linear rheology with bed of S = 10 alu /bar.a and $v_d = 10$ alu / are (Case 18). Figure 5.35 p' against $\cos\gamma$ for an incompressible linear rheology with bed of S = 400 alu /bar.a and $v_d = 400$ alu / a (Case 22). Figure 5.36 Pressure contours in bar for an incompressible Glen rheology with $v_d = 200 \text{ alu/a}$ (Case 25). p' against $\cos\gamma$ for an incompressible Figure 5.37 Glen rheology with $v_d = 10 \text{ alu/a}$ (Case 23).

- Figure 5.38 p' against cosy for an incompressible Glen rheology with $v_d = 400 \text{ alu/a}$ (Case 27). Pressure contours in bar for an incompressible Figure 5.39 Glen rheology with a cavity and $v_d = 10 \text{ alu/a}$ (Case 27).
- Figure 5.40 p' against $\cos\gamma$ for an incompressible Glen rheology with a cavity and $v_d = 10 \text{ alu/a}$ (Case 27).
- Figure 5.41 Pressure contours in bar for a compressible Glen rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and $v_{d} = 100 \text{ alu/a} \text{ (Case 29)}.$
- Figure 5.42 p' against $\cos\gamma$ for a compressible Glen rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and $v_{d} = 200 \text{ alu/a} \text{ (Case 30)}.$
- Figure 5.43 p' against $\cos\gamma$ for an incompressible Glen rheology with bed of S = 10 alu/bar.aand $v_d = 10 \text{ alu/a} (\text{Case } 34)$
- p' against position for flow over a truncated Figure 5.44 sine ridge (Cases 40 - 49).
- Figure 5.45 Pressure contours in bar for an incompressible Glen rheology with $v_d = 100 \text{ alu/a}$ for flow over a truncated sine ridge (Case 47). $\dot{\epsilon}$ in a^{-1} for a compressible linear Figure 5.46 rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and v_d = 400 alu/a (Case 12). $\dot{\epsilon}$, in a^{-1} for a compressible linear Figure 5.47
 - rheology with $\chi = 10 \text{ alu}^2/\text{bar.a}$ and $v_d = 200 \text{ alu/a} (\text{Case 16}).$

| Figure 5.48 | $\dot{\epsilon}_v$ in a ⁻¹ for a compressible Glen |
|-------------|---|
| | rheology with $\chi = 1 \text{ alu}^2$ /bar.a and |
| | v _d = 10 alu/a (Case 29). |
| Figure 5.49 | $\dot{\epsilon}_v$ in a ⁻¹ for a compressible Glen |
| | rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and |
| | $v_{d} = 400 \text{ alu/a}$ (Case 33). |
| Figure 5.50 | Regression exponent for $\dot{\epsilon}_v$ against v_d |
| : | for a compressible Glen rheology with |
| | χ = 1 alu ² /bar.a (Cases 29 - 33). |
| Figure 5.51 | μ in bar.a for an incompressible Glen |
| | rheology with $v_d = 10 \text{ alu/a}$ (Case 23). |
| Figure 5.52 | μ in bar.a for an incompressible Glen |
| | rheology with $v_d = 400 \text{ alu/a}$ (Case 26). |
| Figure 5.53 | μ in bar.a for an incompressible Glen |
| | rheology with a cavity and $v_d = 10 \text{ alu/a}$ |
| | (Case 27). |
| Figure 5.54 | μ in bar.a for a compressible Glen |
| | rheology with $\chi = 1 \text{ alu}^2/\text{bar.a and}$ |
| | $v_d = 10 alu/a$ (Case 29). |
| Figure 5.55 | μ in bar.a for a compressible Glen |
| | rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ with |
| | $v_{d} = 400 \text{ alu/a} (Case 33).$ |
| Figure 5.56 | μ in bar.a for an incompressible Glen |
| | rheology with $S = 10 \text{ alu/bar.a and}$ |
| | v _d = 10 alu/a (Case 34). |
| Figure 5.57 | μ in bar.a for an incompressible Glen |
| | rheology with v _d = 10 alu/a for flow over |
| | a truncated sine ridge (Case 45). |

•

Figure 5.58

Figure 5.59

rheology with $v_d = 400$ alu/a for flow over a truncated sine ridge (Case 49). Regression exponent of μ against v_d for flow over a truncated sine ridge (Cases 45 - 49).

μ in bar.a for an incompressible Glen

Semi-analytic interfacial stress for

incompressible linear rheology with

Semi-analytic interfacial stress for

compressible linear rheology with

 $v_d = 10 \text{ alu/a.}$

modelling.

Figure 5.60

Figure 5.61

Figure 5.62

Figure 5.63

Figure 5.64

 $\chi = 1 \text{ alu}^2/\text{bar.a and } v_d = 10 \text{ alu/a.}$ Semi-analytic interfacial stress for compressible linear rheology with $\chi = 10 \text{ alu}^2/\text{bar.a and } v_d = 10 \text{ alu/a.}$ Semi-analytic interfacial stress for incompressible Glen rheology with $v_d = 10 \text{ alu/a.}$ Semi-analytic interfacial stress for compressible Glen rheology with $\chi = 1 \text{ alu}^2/\text{bar.a and } v_d = 10 \text{ alu/a.}$

Finite element mesh for uni-axial flow

Figure 5.65

Figure 5.66

Velocity contours in alu/a for $v_d = 10$ alu/a and a bed of S = 0.002 alu/bar.a, wide-hummocked case.

Figure 5.67

Velocity contours in alu/a for $v_d = 10 \text{ alu/a}$ and bed of S = 0.01 alu/bar.a, wide-hummocked case.

| | Figure 5.68 | Velocity contours in alu/a for |
|--------|-------------|---|
| | | $v_d = 10 a lu/a and a bed of S = 0.02 a lu/bar.a,$ |
| | | wide-hummocked case. |
| | Figure 5.69 | Velocity contours in alu/a for |
| | | $v_d = 10$ alu/a and a bed of S = 0.1 alu/bar.a, |
| | | wide-hummocked case. |
| | Figure 5.70 | Velocity contours in alu/a for |
| | •. | $v_d = 10 \text{ alu/a and a bed of S = 0.2 alu/bar.a,}$ |
| | | wide-hummocked case. |
| | Figure 5.71 | Velocity contours in alu/a for |
| | | $v_d = 10 \text{ alu/a}$, and a bed of S = 1 alu/bar.a, |
| | | wide-hummocked case. |
| | Figure 5.72 | Velocity contours in alu/a for |
| | | $v_d = 10$ alu/a and a bed of S = 2 alu/bar.a, |
| | | wide-hummocked case. |
| | Figure 5.73 | Velocity contours in alu/a for |
| | | $v_{a} = 50$ alu/a and a bed of S = 0.01 alu/bar.a, |
| · · | | wide-hummocked case. |
| | Figure 5.74 | Velocity contours in alu/a for |
| | - | $v_{,}$ = 100 alu/a and a bed of S = 0.01 alu/bar.a, |
| | · · · | a wide-hummocked case. |
| | Figure 5.75 | Velocity contours in alu/a for |
| • | | $v_1 = 200 \text{ alu/a and a bed of } S = 0.01 \text{ alu/bar.a},$ |
| | | a wide-hummocked case. |
| | Figure 5.76 | Velocity contours in alu/a for |
| | | $v_{,}$ = 10 alu/a and a bed of S = 0.02 alu/bar.a. |
| | | d narrow-hummocked case |
| | · . | |
| | • | |
| | | |

•

.

| Figure 5.77 | Velocity contours in alu/a for |
|-------------|--|
| | $v_d = 10 \text{ alu/a}$, bed of S = 0.002 alu/bar.a, |
| | narrow-hummocked case. |
| Figure 5.78 | Velocity contours in alu/a for |
| | $v_d = 400 \text{ alu/a}$, bed of S = 0.02 alu/bar.a, |
| | narrow-hummocked case. |
| Figure 5.79 | Velocity contours in alu/a for |
| | $v_d = 10 \text{ alu/a, bed of minimum}$ |
| | S = 0.02 alu/bar.a, smoothed-crested case. |
| Figure 5.80 | Crestal velocities in alu/a for the |
| | wide-hummocked case. |
| Figure 5.81 | Crestal velocities in alu/a for the |
| - · · | narrow-hummocked case. |
| Figure 5.82 | Crestal velocities in alu/a for the |
| | smooth-crested case. |
| Figure 5.83 | Trough velocities in alu/a for the |
| | wide-hummocked case. |
| Figure 5.84 | Trough velocities in alu/a for the |
| | narrow-hummocked case. |
| Figure 5.85 | Trough velocities in alu/a for the |
| | smooth-crested case. |
| Figure 5.86 | Crest/trough velocity ratios for the |
| | wide-hummocked case. |
| Figure 5.87 | Crest/trough velocity ratios for the |
| | narrow-hummocked case. |
| Figure 5.88 | Crest/trough velocity ratios for the |
| | smooth-crested case. |
| Figure 5.89 | Crestal viscosity in bar.a for the |
| | wide-hummocked case. |
| Figure 5.90 | Crestal viscosities in bar.a for the |
| | narrow-hummocked case. |

.

| Figure 5.91 | Crestal viscosities in bar.a for the |
|--------------|---|
| | smooth-crested case. |
| Figure 5.92 | Trough viscosities in bar.a for the |
| | wide-hummocked case. |
| Figure 5.93 | Trough viscosities in bar.a for the |
| | narrow-hummocked case. |
| Figure 5.94 | Trough viscosities in bar.a for the |
| | smooth-crested case. |
| Figure 5.95 | Crest/trough viscosity ratios for the |
| | wide-hummocked case. |
| Figure 5.96 | Crest/trough viscosity ratios for the |
| | narrow-hummocked case. |
| Figure 5.97 | Crest/trough viscosity ratios for the |
| | smooth-crested case. |
| Figure 5.98 | Crestal viscosity x velocity in bar.alu |
| | for the wide-hummocked case. |
| Figure 5.99 | Crestal viscosity x velocity in bar.alu |
| | for the narrow-hummocked case. |
| Figure 5.100 | Crestal viscosity x velocity in bar.alu |
| | for the smooth-crested case. |
| Figure 5.101 | Trough viscosity x velocity in bar.alu |
| | for the wide-hummocked case. |
| Figure 5.102 | Trough viscosity x velocity in bar.alu |
| | for the narrow-hummocked case. |
| Figure 5.103 | Trough viscosity x velocity in bar.alu |
| | for the smooth-crested case. |
| Figure 5.104 | Crest/trough viscosity x velocity ratio |
| | for the wide-hummocked case. |
| | |

| Figure 5.105 | Crest/trough viscosity x velocity ratio |
|--------------|---|
| | for the narrow-hummocked case. |
| Figure 5.106 | Crest/trough viscosity x velocity ratio |
| | for the smooth-crested case. |
| Figure 6.1 | Clast at the base of a temperate glacier. |
| Figure 6.2 | Ice-clast contact geometries. |
| Figure 6.3 | The effect of ice-clast contact geometries |
| | on the water pressure beneath the clast. |
| Figure 6.4 | The effect of a generalised normal velocity |
| · · · | on water pressure. |
| Figure 6.5 | The effect of having pressure turning-points |
| | away from the clast edge. |
| Figure 6.6 | The effect of having a pressure turning |
| | point away from the clast-edge when a |
| | cavity exists. |
| Figure 6.7 | Sub-clast water pressures when the upstream |
| | end is less transmissible. |
| Figure 6.8 | Sub-clast water pressures when the downstream |
| | end is less transmissible. |
| Figure 6.9 | Sub-clast water pressures when the boundary |
| | pressure decline is slower than linear. |
| Figure 6.10 | Sub-clast water pressures when the boundary |
| | pressure decline is faster than linear. |
| Figure 6.11 | Dependence of abrasion rate on velocity |
| | and pressure. |
| Figure 8.1 | Three species mass-balance analysis |
| Figure 8.2 | Four species mass-balance analysis. |
| Figure 8.3 | Four species mass-balance analysis with |

tool supply independent of abrasion rate.

LIST OF OVERLAYS

Overlay 1 Scaling lines for uniaxial flow.

FIGURE 2.1 DEVELOPMENT OF GLACIALLY ERODED SURFACES BY SCRATCHING AND POLISHING







(b) 1 scratch/unit area/unit time

FIGURE 2.2 DERIVATION OF THE ABRASION EQUATION



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Contour plot of surface persistent under constant abrasion: a = 1, $\ell = 2$, $m_x = m_y = 0$.

8.75 4.2

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Figure 2.4 Contour plot of surface persistent under constant abrasion: a = 1, l = 2, $m_x = 0.0$, $m_y = -0.5$.



constant abrasion: a = 1, $\ell = 2$, $m_x = m_y = -0.5$.



Dependence of abrasion on position for

persistence of a sine-wave under lowering.



Evolution of a slope and plateau under constant abrasion using the method of characteristics.



Evolution of a bell-shape under constant abrasion using the method of characteristics.



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Evolution of a V-shaped valley under constant abrasion using a direct finite-difference formulation of the abrasion equation.

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Evolution of a bell-shape under constant abrasion using a direct finite-difference formulation of the abrasion equation.



Evolution of a V-shaped valley under constant abrasion using the Farmer formulation with a coarse mesh.



Evolution of a V-shaped valley under constant abrasion using the Farmer formulation with a fine mesh.

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Figure 2.14 Evolution of a bell-shape under constant abrasion using the Farmer formulation.



Figure 2.15 Persistence without migration of a bell-shape

with lowering.



Figure 2.16 Persistence with migration of a bell-shape

with lowering.

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Evolution of a V-shaped valley under constant abrasion using the method of characteristics: no definition of point.



Evolution of a V-shaped valley under constant abrasion using the method of characteristics: smooth definition of point.



Evolution of a V-shaped valley under constant abrasion using the method of characteristics: random definition of point.



Evolution of slope and plateau with curvature dependent abrasion rate using the Farmer formulation.



Evolution of V-shaped valley with abrasion inhibited by concavity using the Farmer formulation.


Evolution of V-shaped valley with abrasion enhanced by concavity using the Farmer formulation.



Figure 2.23 Evolution of a V-shaped valley with a Gaussian abrasion function.



Figure 2.24 Evolution of a V-shaped valley with rocks of different hardness.



Figure 2.25

Trough persistent under lowering with a α 1/h: hyberbolic cosine.

Troughs persistent under lowering with abrasion

a function of a curvature.



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FIGURE 4.1 TWO ELEMENT TEST MODEL

o-Node at which velocity and pressure are solved for ł

x-Node at which velocity only is solved for



Boundary Conditions

ad – Fixed bed or Weertman abcd–Prescribed velocity or traction abd,bcd are the finite elements



Inclined plane problem-nine nodes.



Figure 4.3

Inclined plane problem-seventeen nodes.





Figure 4.4

Rotating Couette flow.

View of finite element mesh showing the

nesting scheme.

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Figure 5.2 Detail from finite element mesh for modelling flow over a semi-cylindrical ridge.



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Detail from finite element mesh for modelling flow over a truncated sine ridge.



FIGURE 5.4 SCHEMATIC DIAGRAM OF BOUNDARY CONDITIONS FOR PLANE-STRAIN



Weertman; if cavity exists, then tractions along ef a,b-Slip velocity at infinity



Larger view of velocity vector plot for an incompressible linear rheology with $v_d = 100 \text{ alu/a}$ (Case 3).



 v_{τ} against sin γ for an incompressible linear rheology with $v_d = 10 \text{ alu/a}$ (Case 1).



SINC GAMMA >



 v_{τ} against sin γ for an incompressible linear rheology with a cavity and v_{d} = 400 alu/a (Case 7).

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 70

 60
 70

 50
 70

 10
 70

 20
 0.4

 10
 0.6

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 0.4

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 v_{τ} against sin γ for an incompressible linear rheology with a cavity and

 $v_d = 10 \text{ alu/a} (\text{Case 6}).$

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-0.4

-0.6

-0.2

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 v_{τ} against sin γ for a compressible linear rheology with $\chi = 1$ alu²/bar.a and $v_{d} = 10$ alu/a (Case 8).





Velocity vector plot for a compressible linear rheology with $\chi = 10 \text{ alu}^2/\text{bar.a and}$ $v_d = 200 \text{ alu/a}$ (Case 16).



 v_{τ} against sin γ for a compressible linear rheology with $\chi = 10$ alu²/bar.a and $v_{d} = 200$ alu/a (Case 16).





Velocity vector plot for an incompressible linear rheology with bed of S = 100 alu/bar.aand $v_d = 100 \text{ alu/a}$ (Case 20).



 v_{τ} against sin γ for an incompressible linear rheology with bed of S = 10 alu/bar.a,

v_d = 10 alu/a (Case 18)





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 v_{τ} against sin γ for an incompressible linear rheology with bed of S = 400 alu/bar.a, v_{d} = 400 alu/a (Case 22).



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Velocity vector plot for an incompressible Glen rheology with $v_d = 100 \text{ alu/a}$ (Case 25).



Figure 5.17 v_{τ} against sin γ for an incompressible Glen rheology with $v_{d} = 10$ alu/a (Case 23).













 v_{τ} against sin γ for an incompressible Glen rheology with a cavity and $v_{d} = 400$ alu/a (Case 28).





Velocity vector plot for a compressible Glen rheology with $\chi = 1 \text{ alu}^2/\text{bar.a and}$ $v_d = 100 \text{ alu/a}$ (Case 31).



 v_{τ} against sin γ for a compressible Glen rheology with $\chi = 1$ alu²/bar.a and $v_{d} = 200$ alu/a (Case 32).





LOGIO SIN(GAMMA)

 v_{τ} against siny for an incompressible Glen rheology with bed S = 10 alu/bar.a and v_{d} = 10 alu/a (Case 34).









 v_{τ} against position for flow over a truncated sine ridge (Cases 40 - 49):Glen rheology



Hummock

Regression coefficients from v_{τ} against v_{d} against position for flow over a truncated sine ridge (Cases 45 - 49).





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p' against $\cos \gamma$ for an incompressible linear rheology with a cavity and $v_d = 400$ alu/a (Case 5).





Figure 5.30 p' against cosy for a compressible linear rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and $v_{d} = 400 \text{ alu/a} \text{ (Case 12)}.$





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Pressure contours in bar for a compressible linear rheology with $\chi = 10 \text{ alu}^2/\text{bar.a}$ and $v_d = 400 \text{ alu/a}$ (Case 17).



p' against $\cos \gamma$ for a compressible linear rheology with $\chi = 10 \text{ alu}^2/\text{bar.a}$ and $v_d = 200 \text{ alu} / \text{a}$ (Case 16).



Figure 5.33 Pressure contours in bar for an incompressible linear rheology with bed of S = 100 alu /bar.a and $v_d = 100 \text{ alu} / \text{a}$ (Case 20).



p' against $\cos \gamma$ for an incompressible linear rheology with bed of S = 10 alu /bar.a and $v_d = 10$ alu / a. (Case 18).



p' against $\cos\gamma$ for an incompressible linear rheology with bed of S = 400 alu /bar.a and v_d = 400 alu / a (Case 22).





Pressure contours in bar for an incompressible Glen rheology with $v_d = 200 \text{ alu/a}$ (Case 25).



p' against $\cos\gamma$ for an incompressible Glen rheology with $v_d = 10$ alu/a (Case 23).



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p' against $\cos\gamma$ for an incompressible Glen rheology with $v_d = 400 \text{ alu/a}$ (Case 27).





Pressure contours in bar for an incompressible Glen rheology with a cavity and $v_d = 10 \text{ alu/a}$ (Case 27).



p' against $\cos\gamma$ for an incompressible Glen rheology with a cavity and $v_d = 10$ alu/a (Case 27).





Pressure contours in bar for a compressible, Glen rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and $v_d = 100 \text{ alu}/\text{a}$ (Case 29).



p' against $\cos \gamma$ for a compressible Glen rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and $v_d = 200 \text{ alu}/\text{a}$ (Case 30).



LOGIO COS(GAMMA)

p' against $\cos \gamma$ for an incompressible Glen rheology with bed of S = 10 alu/bar.a and v_d = 10 alu/a (Case 34)



p' against position for flow over a truncated sine ridge (Cases 40 - 49).



Hummock

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Pressure contours in bar for an incompressible Glen rheology with $v_d = 100 \text{ alu/a}$ for flow over a truncated sine ridge (Case 47).



Figure 5.46 ε_v in a⁻¹ for a compressible linear rheology with $\chi = 1$ alu²/bar.a and $v_d = 400$ alu/a (Case 12).



Figure 5.47 $\dot{\epsilon}_v$ in a^{-1} for a compressible linear rheology with $\chi = 10 \text{ alu}^2/\text{bar.a}$ and v_d = 200 alu/a (Case 16).



 ε_v in a⁻¹ for a compressible Glen rheology with x = 1 alu²/bar.a and $v_d = 10$ alu/a (Case 29).



Figure 5.49 $\dot{\epsilon}_{v}$ in a^{-1} for a compressible Glen rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ and $v_{d} = 400 \text{ alu/a} \text{ (Case 33)}.$



Figure 5.50 Regression exponent for $\dot{\epsilon}_v$ against v_d for a compressible Glen rheology with $x = 1 \text{ alu}^2 / \text{bar.a}$ (Cases 29 - 33).



Figure 5.51 μ in bar.a for an incompressible Glen rheology with $v_d = 10 \text{ alu/a}$ (Case 23).



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Figure 5.52 μ in bar.a for an incompressible Glen rheology with $v_d = 400 \text{ alu/a}$ (Case 26). ----



Figure 5.53 μ in bar.a for an incompressible Glen rheology with a cavity and $v_d = 10 \text{ alu}/\text{a}$ (Case 27).



Figure 5.54 μ in bar.a for a compressible Glen rheology with $\chi = 1 \text{ alu}^2/\text{bar.a and}$ v_d = 10 alu/a (Case 29).



Figure 5.55 μ in bar.a for a compressible Glen rheology with $\chi = 1 \text{ alu}^2/\text{bar.a}$ with v_d = 400 alu/a (Case 33).

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Figure 5.56 μ in bar.a for an incompressible Glen rheology with S = 10 alu/bar.a and $v_{d} = 10 \text{ alu/a} (Case 34).$



 μ in bar.a for an incompressible Glen rheology with $v_d = 10$ alu/a for flow over a truncated sine ridge (Case 45).



Figure 5.58 µ in

 μ in bar.a for an incompressible Glen rheology with $v_d = 400$ alu/a for flow over a truncated sine ridge (Case 49).



Regression exponent of μ against v_d for flow over a truncated sine ridge (Cases 45 - 49).



Semi-analytic interfacial stress for incompressible linear rheology with

 $v_d = 10 alu/a$.



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r R m N N D R m / m < K

Semi-analytic interfacial stress for compressible linear rheology with

 $\chi = 1 \text{ alu}^2/\text{bar.a and } v_d = 10 \text{ alu}/\text{a.}$



r R m N N D R m / m < R

Semi-analytic interfacial stress for compressible linear rheology with

 χ = 10 alu²/bar.a and v_d = 10 alu/a.



Semi-analytic interfacial stress for

incompressible Glen rheology with

 $v_d = 10 alu/a$.



Semi-analytic interfacial stress for compressible Glen rheology with

 $\chi = 1 \text{ alu}^2/\text{bar.a and } v_d = 10 \text{ alu}/\text{a.}$

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Figure 5.65 Finite element mesh for uni-axial flow modelling.



Velocity contours in alu/a for $v_d = 10$ alu/a and a bed of S = 0.002 alu/bar.a,

wide-hummocked case.

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Velocity contours in alu/a for $v_d = 10$ alu/a and bed of S = 0.01 alu/bar.a,

. .. .

wide-hummocked case.



Velocity contours in alu/a for

 $v_d = 10 \text{ alu/a and a bed of } S = 0.02 \text{ alu/bar.a},$

wide-hummocked case.





Velocity contours in alu/a for

 $v_d = 10$ alu/a and a bed of S = 0.1 alu/bar.a, wide-hummocked case.



Velocity contours in alu/a for

 $v_d = 10 \text{ alu/a and a bed of } S = 0.2 \text{ alu/bar.a},$ wide-hummocked case.



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Velocity contours in alu/a for $v_d = 10$ alu/a, and a bed of S = 1 alu/bar.a, wide-hummocked case.



Velocity contours in alu/a for

 $v_d = 10$ alu/a and a bed of S = 2 alu/bar.a, wide-hummocked case.



Velocity contours in alu/a for

 $v_d = 50 \text{ alu/a and a bed of S = 0.01 alu/bar.a,}$ wide-hummocked case.



Velocity contours in alu/a for

 $v_d = 100 \text{ alu/a}$ and a bed of S = 0.01 alu/bar.a, wide-hummocked case.



Velocity contours in alu/a for $v_d = 200 \text{ alu/a}$ and a bed of S = 0.01 alu/bar.a, wide-hummocked case.



Velocity contours in alu/a for

 $v_d = 10 \text{ alu/a}$ and a bed of S = 0.02 alu/bar.a, narrow-hummocked case.



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Velocity contours in alu/a for

 $v_d = 10 \text{ alu/a, bed of } S = 0.002 \text{ alu/bar.a,}$

narrow-hummocked case,



Velocity contours in alu/a for

 $v_d = 400 \text{ alu/a}$, bed of S = 0.02 alu/bar.a, narrow-hummocked case.



Velocity contours in alu/a for

 $v_d = 10 \text{ alu/a, bed of maximum}$

S = 0.02 alu/bar.a, smoothed-crested case.





smooth-crested case. . ..

narrow-hummocked case.

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Figure 5.84 Troug

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Trough velocities in alu/a for the narrow-hummocked case.

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Figure 5.85

Trough velocities in alu/a for the . smooth-crested case.

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Figure 5.90

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1.8



Figure 5.91

Crestal viscosities in bar.a for the narrow-hummocked case.

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Crestal viscosities in bar.a for the smooth-crested case. . 1



LOGIO DISTAL VELOCITY/ALU/A

. .. Trough viscosities in bar.a for the Figure 5.92

wide-hummocked case.

Figure 5.93

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Figure 5.94

Trough viscosities in bar.a for the

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Figure 5.100

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Figure 5.99 Crestal viscosity x velocity in bar.alu for the narrow-hummocked case.

Crestal viscosity x velocity in bar.alu; for the smooth-crested case.





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Figure 5.101 Trough viscosity x velocity in bar.alu for the wide-hummocked case.

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Figure 5.102 for the narrow-hummocked case.

Trough viscosity x velocity in bar.alu



Trough viscosity x velocity in bar.alu for the smooth-crested case.

Figure 5.103



for the wide-hummocked case.

ure 5.105 Crest/trough viscosity x velocity ratio for the narrow-hummocked case. Crest/trough viscosity x velocity ratio for the smooth-crested case.



Clast at the base of a temperate glacier.



FIGURE 6.2 ICE-CLAST CONTACT GEOMETRIES



ICE FLOW DIRECTION

STABLE, DISCONTINUOUS WATER PRESSURE Ο \odot Ο Ο Ο - O Ο Ο О, Ó Ο Ο Ο Ο О





The effect of ice-clast contact geometries

on the water pressure beneath the clast.



The effect of a generalised normal velocity

on water pressure.





Distance

The effect of having pressure turning-points

away from the clast edge.



The effect of having a pressure turning point away from the clast-edge when a cavity exists.





Distance

Sub-clast water pressures when the upstream

end is less transmissible.



Sub-clast water pressures when the downstream

end is less transmissible.



Sub-clast water pressures when the boundary pressure decline is slower than linear.



Transverse distance

Sub-clast water pressures when the boundary pressure decline is faster than linear.





'DISTAL PRESSURE' 2 8 ç D 1

Dependence of abrasion rate on velocity and pressure.

Figure 6.11


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Distance

Four species mass-balance analysis with

tool supply independent of abrasion rate.





Distance

