Interpretation of Glacigenic Sediments

This section is taken from Bethan Davies' PhD thesis.

Multiproxy analysis of glacigenic sediments? | Micromorphological interpretation of glacigenic sediments | References | Comments |

Multiproxy analysis of glacigenic sediments

Lodgement and Deformation tills

Thin-section analysis can be used in conjunction with macroscale sedimentological analysis to identify subglacial processes. Traditionally, tills have been subdivided based on the typical processes assumed to have been dominant in their formation. These were thought principally to be sliding[1], lodgement[2] and deformation[3]. Lodgement till has a long history of research, being originally defined by Chamberlin (1895) as,

> Sediment deposited by plastering of glacial debris from a sliding glacier sole due to the combined effects of pressure melting and frictional drag[4].

This process resulted in massive or fissile tills, with slickensides resulting from shearing (Boulton, 1970). Clasts are lodged into the substrate and have typical bullet-shaped ends and clear stoss-and-lee ends. Alternatively, deformation till[5,6] refers to a,

> Rock or sediment that has largely been homogenised by shearing in the subglacial layer.

Subglacial deformation of soft sediments is considered to account for much of the forward motion by glaciers[3,7]. Massive tills are thought to record evidence of high cumulative strains[8]. Others have argued that massive tills are simply the product of melt-out[9]. Larsen *et al.* (2004) argued that a melt-out / deformation continuum was responsible for thick sequences of massive tills, with vertical accretion of subglacial sediments being melted out at the ice-bed interface, and then deformed[10]. However, if deformation of soft beds is widespread, then deformation tills should be more prevalent (cf.[11]), and macroscopically massive 'deformation' tills often overly undeformed sediments[12].

Glacier motion by sliding and lodgement over soft beds (cf.[13]) was thought to occur by the decoupling of the glacier from its bed due to increased basal water pressures, which would prevent the transmission of stress to the substrate[1]. This theory evolved into an proposal of 'slip-stick' sliding at the ice-bed interface, with areas of high water pressure inducing decoupling[14].

Clay-rich tills are less permeable (cf. sandy tills), encouraging the development of high water pressures; stick-slip behaviour and decoupling may therefore be at least partially lithologically controlled[15,16]. Piotrowski and Kraus (1997) were among the first to propose a mosaic of sliding bed conditions and deforming conditions, where the ice is coupled to the bed. This explains the heterogeneity in tills in Germany[17].

A continuum with lodgement and deformation end-members will lead to progressive changes in bed properties at a particular location[18-20]. This viewpoint highlights the spatial and temporal variability of glacier beds, with ice-bed coupling variability brought about by changes in pore-water pressure. Piotrowski *et al*. (2004) argued that the spatial variability in sliding intensity resulted in a mosaic with sliding conditions and deforming spots. During sliding, ploughing of clasts may take place[21]. ‘Glaciotectonite’ (as originally defined by Banham, 1977[22], and Pedersen, 1988[23]) refers to sheared rocks and sediments, which still retains some of structural characteristics of its parent material[6]. They can display both brittle and ductile deformation, or a combination of the two processes.

Mass flow diamictons (or flow tills) originate from water and sediment released by ablation from debris-rich basal ice. These deposits are typically macroscopically massive. They may have microscopic near-horizontal laminations. Rotational structures, kinking plasmic fabrics, and tile structures form as primary depositional features on a micromorphological scale[24]. Debris flows share many characteristics in common with subglacial sediments, such as pressure shadows, folds, laminations, shears, faults, water-escape structures, and rotational structures[25]. Mass flow diamictons, however, can be distinguished by the presence of ‘tile structures’ in close association with rotational structures[26]. This long and extensive history of thin-section analysis of glacigenic sediments has given rise to a set of well-defined criteria, summarised in Table 1.

A combination of processes

Recently, several researchers have argued that processes at the ice-bed interface are a result of a continuum of processes, including melt-out, lodgement, deformation, and sliding[16,20,27-29]. It is therefore difficult to pin an exact genetic name onto a specific outcrop of diamicton. Evans *et al.* (2006) argued that the subglacial processes of deformation, flow, sliding, lodgement and ploughing all exist contemporaneously at the base of temperate ice.

These processes result in the mobilisation, transportation and deposition of sediment. This results in stratified or folded to texturally homogenous diamictons. Evans *et al.* (2006) argued that, while specific processes can and should be recognised in the sedimentary record, genetic ‘finger-printing’ of subglacial tills should be less process-specific.

Subglacial tills are polygenetic, and till classification must recognise the range of processes involved by the subglacial till ‘production continuum’[16]. Evans *et al.* (2006) proposed the use of the terms, ‘glaciotectonite’, as defined above, and ‘traction till’, which includes sediments deposited by sliding or deforming at the glacier bed, sediment released by pressure melting, and sediment homogenised by shearing. While ‘traction till’ is a generic term for all these processes, they can still be individually recognised in the geological record. Evans *et al*. (2006) also formally recognise ‘melt-out till’, as a sediment released by melting or sublimation at stagnant or slowly-moving, debris-rich ice, without subsequent transport or deformation.

Laminated diamictons

Glaciotectonic deformation of subglacial sediments can result in tectonic laminations, which are distinct from glaciomarine or subaqueous laminations. Roberts and Hart (2005) identified two types of lamination. Type 1 laminations / stringers typically emanate from soft sediment clasts (e.g. chalk), are discontinuous, subhorizontal, and ungraded. In thin section, Type 1 laminations have sharp, undulatory contacts with silty or sandy stringers. Isoclinal folds are common[30]. Type 2 laminations are laterally continuous, subhorizontal, and poorly sorted with dropstone-like structures and often exhibit reworked soft sediment clasts. Contact boundaries are sharp and unconformable, and dropstone structures are evident. Microfabric birefringence is low, but there are some areas of high birefringence sub-parallel to silty lamination contacts[30]. Type 1 laminations are the result of subglacial deformation by ductile, inter-granular, pervasive shear. Hart and Roberts (1994) argued that this type of lamination occurs as a result of high extensional shear, leading to boudinage. Smaller, less competent perturbations, such as chalk clasts, can become stretched out into a lamination under this high shear strain. The laminations can deform and rotate within the deforming layer, producing tails to appear as sedimentary augens[31].

Type 2 laminations have a subaqueous signal, despite often containing a number of syntectonic ductile deformation structures[30]. At West Runton, Norfolk, the subhorizontal lateral continuity and dropstone structures with down-warped lower contacts and draped upper contacts are indicative of primary subaqueous origin followed by secondary subglacial deformation. The planar, bedded nature of the strata, with sharp contact boundaries, are characteristic of sediments deposited by underflows, overflows, suspension fallout, ice-rafted debris processes and subaqueous debris flows, with each lamination representing a clear separate depositional event[30]. The clear characteristics of these laminations enable easy discrimination of glaciomarine and glaciolacustrine diamictons.

Glaciomarine and Glaciolacustrine diamictons

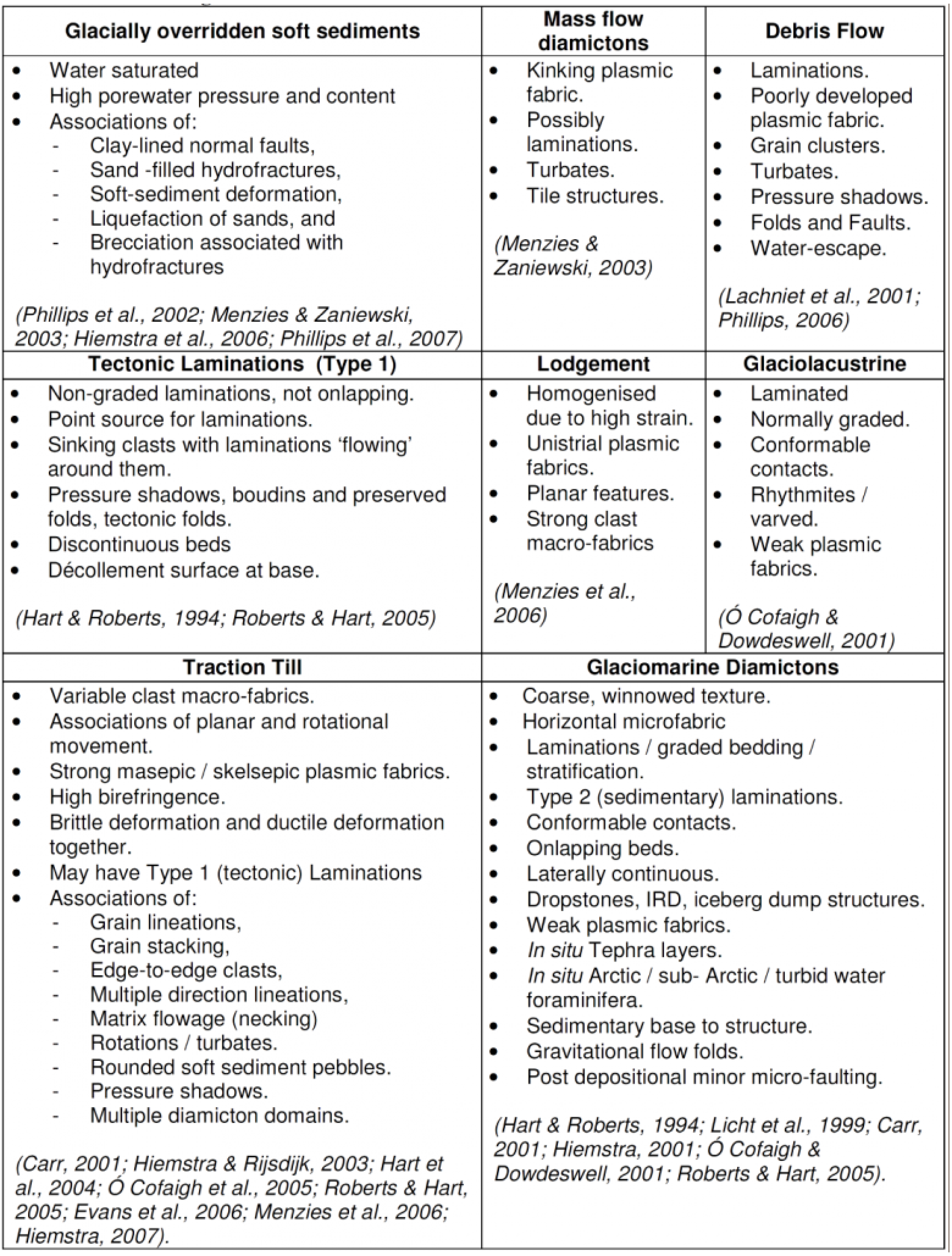
Several additional criteria can distinguish massive and laminated glaciomarine diamictons from subglacial diamictons (Table 1). Glaciomarine diamictons usually have a coarse, winnowed structure with dropstones; common, *in situ* marine microfossils; a lack of deformation structures; laminations, banding, or graded bedding structures; and a lack of plasmic fabric development[30,32,33]. Distal glaciomarine sediments are characterised by their bedding and lamination; a medium to fine matrix; uniform grain shapes; few deformation structures; dropstone features and no plasmic fabric development; and the presence of bioturbation[32].

Glaciolacustrine sediments share many characteristics of glaciomarine diamictons; however, they lack *in situ* marine microfossils and are mostly geographically more limited in extent[34]. Menzies *et al.* (2006) argued that plasmic fabrics indicate the presence of orientated clay particles by strong birefringence. The type of plasmic fabric is indicative of a suite of orientations induced by ductile deformation.

Micromorphological interpretation of glacigenic sediments

Lodgement tills, formed in a high-strain environment with considerable shear and deformation, undergo complete homogenisation and demonstrate unistrial plasmic fabrics[35]. Subglacial traction tills can therefore have ductile, brittle, polyphase or intermediate structures (see **Thin-Section Analysis**). Ductile deformation structures include soft sediment pebbles (Type II and III), banding and flow of matrix material, rotational structures with associated skelsepic / masepic plasmic fabrics, and strain caps and pressure shadows. Planar features such as grain lineations are commonly associated with rotational structures, and occur in plastically deforming sediments[36]. Brittle deformation structures include edge-to-edge grain contacts and grain crushing, grain stacking, and brittle faulting and discrete shear zones. Grain stacks form to support stresses developing in a sediment, and form perpendicular to the stress field[36].

Glaciomarine deposits are characterised by graded laminations, iceberg-dump and dropstone structures, and *in situ* marine microfossils. Porewater-induced soft-sediment deformation structures include liquefaction and homogenisation of sands, rafting, and water-escape structures.



Glacially overridden soft sediments	Mass flow diamictons	Debris Flow
• Water saturated • High porewater pressure and content • Associations of: - Clay-lined normal faults, - Sand -filled hydrofractures, - Soft-sediment deformation, - Liquefaction of sands, and - Brecciation associated with hydrofractures *(Phillips et al., 2002; Menzies & Zaniewski, 2003; Hiemstra et al., 2006; Phillips et al., 2007)*	• Kinking plasmic fabric. • Possibly laminations. • Turbates. • Tile structures. *(Menzies & Zaniewski, 2003)*	• Laminations. • Poorly developed plasmic fabric. • Grain clusters. • Turbates. • Pressure shadows. • Folds and Faults. • Water-escape. *(Lachniet et al., 2001; Phillips, 2006)*
Tectonic Laminations (Type 1)	**Lodgement**	**Glaciolacustrine**
• Non-graded laminations, not onlapping. • Point source for laminations. • Sinking clasts with laminations ‘flowing’ around them. • Pressure shadows, boudins and preserved folds, tectonic folds. • Discontinuous beds • Décollement surface at base. *(Hart & Roberts, 1994; Roberts & Hart, 2005)*	• Homogenised due to high strain. • Unistrial plasmic fabrics. • Planar features. • Strong clast macro-fabrics *(Menzies et al., 2006)*	• Laminated • Normally graded. • Conformable contacts. • Rhythmites / varved. • Weak plasmic fabrics. *(Ó Cofaigh & Dowdeswell, 2001)*
Traction Till	**Glaciomarine Diamictons**	
• Variable clast macro-fabrics. • Associations of planar and rotational movement. • Strong masepic / skelsepic plasmic fabrics. • High birefringence. • Brittle deformation and ductile deformation together. • May have Type 1 (tectonic) Laminations • Associations of: - Grain lineations, - Grain stacking, - Edge-to-edge clasts, - Multiple direction lineations, - Matrix flowage (necking) - Rotations / turbates. - Rounded soft sediment pebbles. - Pressure shadows. - Multiple diamicton domains. *(Carr, 2001; Hiemstra & Rijsdijk, 2003; Hart et al., 2004; Ó Cofaigh et al., 2005; Roberts & Hart, 2005; Evans et al., 2006; Menzies et al., 2006; Hiemstra, 2007).*	• Coarse, winnowed texture. • Horizontal microfabric • Laminations / graded bedding / stratification. • Type 2 (sedimentary) laminations. • Conformable contacts. • Onlapping beds. • Laterally continuous. • Dropstones, IRD, iceberg dump structures. • Weak plasmic fabrics. • *In situ* Tephra layers. • *In situ* Arctic / sub- Arctic / turbid water foraminifera. • Sedimentary base to structure. • Gravitational flow folds. • Post depositional minor micro-faulting. *(Hart & Roberts, 1994; Licht et al., 1999; Carr, 2001; Hiemstra, 2001; Ó Cofaigh & Dowdeswell, 2001; Roberts & Hart, 2005).*	

Table 1. Macroscopic and microscopic criteria for interpretation of some typical glacigenic sediments.

Citation

Davies, B.J., 2009. British and Fennoscandian Ice-Sheet Interactions during the Quaternary, Unpubl. PhD Thesis. Department of Geography, Durham University, Durham, 502 pp.

Bethan Davies Thesis (Zipped PDFs – 70MB)

References

1. Brown, N.E., Hallet, B. & Booth, D.B. Rapid soft bed sliding of the Puget glacial lobe. *Journal of Geophysical Research* **92**, 8985-8997 (1987).

2. Dreimanis, A. Tills, their genetic terminology and classification. in *Genetic Classification of Glacigenic Deposits* (eds. Goldthwait, R.P. & Matsch, C.L.) 17-84 (Balkema, Rotterdam, 1989).

3. Alley, R.B., Blankenship, D.D., Bentley, C.R. & Rooney, S.T. Deformation of till beneath Ice Stream B, West Antarctica. *Nature* **322**, 57-59 (1986).

4. Chamberlin, T.C. Recent glacial studies in Greenland. *Bulletin of the Geological Society of America* **6**, 199-220 (1895).

5. Elson, J.A. The geology of tills. in *Proceedings of the 14th Canadian soil mechanics conference*, Vol. 69 (eds. Penner, E. & Butler, J.) 5-36 (Commission for Soil and Snow Mechanics, Technical Memoir, vol. 69, 1961).

6. Benn, D.I. & Evans, D.J.A. *Glaciers & Glaciation*, 802 (Hodder Education, London, 2010).

7. Humphrey, N., Kamb, B., Fahnestock, M. & Englehardt, H. Characteristics of the bed of the Lower Columbia Glacier, Alaska. *Journal of Geophysical Research* **98**, 837-846 (1993).

8. Hart, J.K., Hindmarsh, R.C.A. & Boulton, G.S. Styles of subglacial glaciotectonic deformation within the context of the Anglian ice-sheet. *Earth Surface Processes and Landforms* **15**, 227-241 (1990).

9. Clayton, L., Mickelson, D.M. & Attig, J.W. Evidence against pervasively deformed bed material beneath rapidly moving lobes of the southern Laurentide Ice Sheet. *Sedimentary Geology* **62**, 203-208 (1989).

10. Larsen, N.K., Piotrowski, J.A. & Kronborg, C. A multiproxy study of a basal till: a time-transgressive accretion and deformation hypothesis. *Journal of Quaternary Science* **19**, 9-21 (2004).

11. Piotrowski, J.A., Mickelson, D.M., Tulaczyk, S., Krzyszkowski, D. & Junge, F.W. Were deforming subglacial beds beneath past ice sheets really widespread? *Quaternary International* **86**, 139-150 (2001).

12. Boulton, G.S. & Hindmarsh, R.C.A. Sediment deformation beneath glaciers: rheology and geological consequences. *Journal of Geophysical Research* **92**, 9059-9082 (1987).

13. Clark, P.U. & Hansel, A.K. Clast ploughing, lodgement and glacier sliding over a soft glacier bed. *Boreas* **18**, 201-207 (1989).

14. Fischer, U. & Clarke, G.K.C. Stick-slip sliding behaviour at the base of a glacier. *Annals of Glaciology* **24**, 390-396 (1997).

15. Boulton, G.S. Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. *Journal of Glaciology* **42**, 43-62 (1996).

16. Evans, D.J.A., Phillips, E.R., Hiemstra, J.F. & Auton, C.A. Subglacial till: Formation, sedimentary characteristics and classification. *Earth-Science Reviews* **78**, 115-176 (2006).

17. Piotrowski, J.A. & Kraus, A.M. Response of sediment to ice sheet loading in north-western Germany: effective stresses and glacier-bed stability. *Journal of Glaciology* **43**, 495-502 (1997).

18. Lian, O.B. & Hicock, S.R. Thermal conditions beneath parts of the last Cordilleran Ice Sheet near its centre as inferred from subglacial till, associated sediments, and bedrock. *Quaternary International* **68-71**, 147-162 (2000).

19. Boulton, G.S., Dobbie, K.E. & Zatsepin, S. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. *Quaternary International* **86**, 3-28 (2001).

20. Nelson, A.E., Willis, I.C. & Ó Cofaigh, C. Till genesis and glacier motion inferred from sedimentological evidence associated with the surge-type glacier, Brùarjökill, Iceland. *Annals of Glaciology* **42**, 14-22 (2005).

21. Piotrowski, J.A., Larsen, N.K. & Junge, F.W.F.W. Reflections on soft subglacial beds as a mosaic of deforming and stable spots. *Quaternary Science Reviews* **23**, 993-1000 (2004).

22. Banham, P.H. Glaciotectonites in till stratigraphy. *Boreas* **6**, 101-105 (1977).

23. Pedersen, S.A.S. Glaciotectonite: brecciated sediments and cataclastic sedimentary rocks formed subglacially. in *Genetic Classification of Glacigenic Deposits* (eds. Goldthwait, R.P. & Matsch, C.L.) 89-91 (Balkema, Rotterdam, 1988).

24. Lachniet, M.S., Larson, G.J., Lawson, D.E., Evenson, E.B. & Alley, R.B. Microstuctures of sediment flow deposits and subglacial sediments: a comparison. *Boreas* **30**, 254-262 (2001).

25. Phillips, E. Micromorphology of a debris flow deposit: evidence of basal shearing, hydrofracturing, liquefaction and rotational deformation during emplacement. *Quaternary Science Reviews* **25**, 720-738 (2006).

26. Menzies, J. & Zaniewski, K. Microstructures within a modern debris flow deposit derived from Quaternary glacial diamicton – a comparative micromorphological study. *Sedimentary Geology* **157**, 31-48 (2003).

27. van der Meer, J.J.M., Menzies, J. & Rose, J. Subglacial till: the deforming glacier bed. *Quaternary Science Reviews* **22**, 1659-1685 (2003).

28. Menzies, J., van der Meer, J.J.M. & Rose, J. Till-as a glacial “tectomict”, its internal architecture, and the development of a “typing” method for till differentiation. *Geomorphology* **75**, 172-200 (2006).

29. Menzies, J. Strain pathways, till internal architecture and microstructures – perspectives on a general kinematic model – a ‘blueprint’ for till development. *Quaternary Science Reviews* **50**, 105-124 (2012).

30. Roberts, D.H. & Hart, J.K. The deforming bed characteristics of a stratified till assemblage in north East Anglia, UK: investigating controls on sediment rheology and strain signatures. *Quaternary Science Reviews* **24**, 123-140 (2005).

31. Hart, J.K. & Roberts, D.H. Criteria to distinguish between subglacial glaciotectonic and glaciomarine sedimentation: I – Deformation styles and sedimentology. *Sedimentary Geology* **91**, 191-214 (1994).

32. Carr, S.J. Micromorphological criteria for distinguishing subglacial and glacimarine sediments: evidence from a contemporary tidewater glacier, Spitsbergen. *Quaternary International* **86**, 71-79 (2001).

33. Hiemstra, J.F. Microscopic analyses of Quaternary glacigenic sediments of Marguerite Bay, Antarctic Peninsula. *Arctic, Antarctic and Alpine Research* **33**, 258-265 (2001).

34. Ó Cofaigh, C. & Dowdeswell, J.A. Laminated sediments in glacimarine environments: diagnostic criteria for their interpretation. *Quaternary Science Reviews* **20**, 1411-1436 (2001).

35. Khatawa, A. & Tulaczyk, S. Microstructural interpretations of modern and Pleistocene subglacially deformed sediments: the relative role of parent material and subglacial process. *Journal of Quaternary Science* **16**, 507-517 (2001).

36. Hiemstra, J.F. & Rijsdijk, K.F. Observing artificially induced strain: implications for subglacial deformation. *Journal of Quaternary Science* **18**, 373-383 (2003).