This is a pre-print version of an article in *Sedimentary Geology*:
Weaver, L., Arnaud, E., Polyphase glacigenic deformation in the Waterloo Moraine,
Kitchener, Ontario, Canada, *Sedimentary Geology* (2010),
doi:10.1016/j.sedgeo.2010.07.008
Please go to www.elsevier.com for the finalized manuscript

POLYPHASE GLACIGENIC DEFORMATION IN THE WATERLOO MORaine,
KITCHENER, ONTARIO, CANADA

Laura Weaver¹
AquaResource Inc.
31 Beacon Point Court
Breslau, Ontario, N0B 1M0, Canada

Emmanuelle Arnaud²
School of Environmental Sciences
University of Guelph
Guelph, Ontario, N1E 2K1, Canada

Submitted to *Sedimentary Geology* Special Issue on
Soft Sediment Deformation
February 2, 2010
Revised June 2010

¹ lweaver@AquaResource.ca; Fax: (519) 648-3168

² earnaud@uoguelph.ca; Fax: (519) 824-5730; corresponding author

ABSTRACT

A sedimentological investigation of Quaternary sediments in the Waterloo Moraine was conducted to characterize the nature of deformation in stratified sediments in the Kieswetter Holdings Ltd. aggregate quarry, Kitchener, Ontario. Highly deformed interbedded clay, silt, fine- to very coarse-grained sand and granular to cobble gravel is exposed in two sets of contiguous panels. Analysis of the sediment revealed five recognizable stratigraphic units: 1) climbing ripple cross-laminated silt, 2) normally graded cobble gravel, 3) cross-bedded, fine- to coarse-grained sand, 4) interbedded clay, silt and fine- to very coarse-grained sand with granules and 5) crudely channelized interbedded medium- to very coarse-grained sand and granule to pebble gravel. These units suggest rapid deposition and fluctuating energy in a subaqueous environment prior to deformation.

Deformation structures include normal faults with offsets ranging from 1-50 cm, widespread occurrences of density-driven ductile deformation ranging from 0.5-5 cm, open to closed folds (cm to m scale), as well as an isolated occurrence of overturned fold ranging in size from 0.5 cm to approximately 1.2 m. Abundant reverse faulting with offsets ranging from 0.5-7 cm (average of 2 cm) and widespread occurrences of boudinage and bed attenuation as well as shear folds ranging in scale from 0.5 cm to 1.5 m were also observed. The nature and scale of deformation structures suggest complex polyphase deformation of heterogeneous sediments related to rapid sedimentation, sediment gravity flow, active ice deformation and melting of buried ice in a dynamic subaqueous environment.

Keywords: brittle deformation; ductile deformation; moraines; ice-marginal features; Quaternary

1. Introduction

Deformation in glaciated settings has been the subject of many studies, with a particular focus on structures formed directly by ice in subglacial and ice marginal settings (e.g. Aber et al., 1989; Benn and Evans, 1996; Hart and Watt, 1997; Boulton et al., 1999; Bennett, 2001; Bennett et al. 2004a, 2004b; Phillips et al. 2002). Deformation structures are also common in subaqueous glacial environments (lacustrine or marine) where rapid sedimentation rates lead to the development of unstable density gradients and downslope sediment remobilization as well as ice-contact deformation associated with subaqueous grounding line fans or drifting icebergs (Woodworth-Lynas and Guigné, 1990; Hart and Roberts, 1994; Phillips et al. 2007).

The Waterloo Moraine is a complex deposit consisting of sand, gravel, till and discontinuous units of finer-grained sediments that were deposited between three different ice lobes of the Laurentide Ice Sheet during the Wisconsinan glaciation (Fig. 1; Chapman and Putnam, 1951; Barnett, 1992; Bajc and Karrow, 2004; Bajc and Shirota, 2007). Ice wedge polygons associated with deglaciation have been documented in the Kitchener area (Morgan, 1992; Gao, 2005); deformation structures have otherwise received little attention within the Waterloo Moraine.

A detailed sedimentological investigation was conducted on two successions of highly deformed sediments with three objectives: 1) to characterize the nature of deformation, 2) to determine syn- and post-depositional stresses acting upon the sediment, and 3) to identify the triggers ultimately responsible for the deformation. Analysis of these sections included detailed morphological and sedimentological description of brittle and ductile deformation structures, and interpretation of the timing

and origin of the deformation events. The study sites are located along a regional northwest-southeast trending topographic high that runs through the Waterloo Moraine, thought to have formed as subaquatic coalescing fans along one of the ice margins in the region (Bajc and Karrow, 2004; Bajc and Shirota, 2007). This analysis therefore provides an opportunity to assess the evidence for ice-contact conditions in a stratified interlobate moraine setting, where ice contact, glaciofluvial and glaciolacustrine processes are thought to have varied both spatially and temporally.

2. Study area

The Waterloo Moraine has an irregular shape with several arms, referred to as spurs, branching out from the larger moraine body (Fig. 1). It is bounded by a drumlinized or undulating till plain, outwash plains, kames and isolated eskers (Chapman & Putman, 1951; Karrow and Paloschi, 1996; Bajc and Karrow, 2004). It rises approximately 50 to 100 m above the surrounding plains as a lenticular mass of stratified sediments and till with undulating topography, and is thought to have formed during the Late Wisconsinan Glacial Period (Michigan Subepisode; Karrow et al., 2000; Bajc and Shirota, 2007). Vast quantities of stratified sand and gravel have been mapped at or near the surface and borehole records and geophysical profiling suggest thick sequences of sand also dominate in the subsurface (Chapman and Putnam, 1951; Farvolden et al., 1987; Bajc, et al., 2003; Bajc, 2004; Bajc and Karrow, 2004).

Till units within and along the sides of the moraine are interpreted to record ice advance from different lobes that spread from the present Great Lake basins (Fig 1A: Barnett, 1992; Karrow and Paloschi, 1996), although a recent regional study suggests the

moraine was most affected by the Ontario-Erie lobe, based on paleocurrent and provenance analysis (Bajc and Shirota, 2007). Both the Maryhill and Port Stanley Till crop out near the study sites (Ontario Geological Survey, 2003) and are associated with the Ontario-Erie Ice lobe; the former being associated with the deposition of the moraine sediments during the Erie Phase (Bajc and Shirota, 2007), and the latter found onlapping the moraine primarily to the east and south and recording the last advance in the region during the Port Bruce Phase (Bajc and Karrow, 2004; Bajc and Shirota, 2007). In contrast, the stratified sediments are considered the result of variable depositional conditions during periods of ice retreat (Karrow and Paloschi, 1996; Bajc and Shirota, 2007). These variable depositional conditions include: 1) quiet water basinal, 2) subaquatic fan, 3) deltaic, 4) glaciofluvial and 5) kame/kettle conditions, with ice-bounded glaciolacustrine conditions being the most common (Bajc and Shirota, 2007).

The study sites lie on the eastern side of a regional northwest-southeast trending ridge of the moraine (Fig. 1B). This ridge is approximately 60 m higher than the surrounding moraine sediments and is approximately ~4 km wide and ~35 km long. It rises to a maximum height of 420 mASL, with ~135 m of Quaternary overburden overlying Paleozoic bedrock. A regional study of deformation throughout the moraine demonstrates that deformed sediments are found on and east of the ridge (Weaver, 2008). Bajc and Shirota (2007) have suggested that this records a series of coalescing subaquatic fans associated with an advance of the Erie-Ontario ice lobe out of the east. The quarry also straddles a local topographic high (1 km long and 275 m wide) superimposed on the larger regional ridge (Fig. 1C). Sediments exposed on the western slope of the local high are characterized by undeformed channelized sand with lesser granule to pebble gravel.

In contrast, sediments east of the local high are characterized by lateral and vertical textural variability and deformation. A unit of laterally persistent sandy silt underlies the entire site, both east and west of the local high. The variations in sedimentary characteristics and deformation east and west of the local topographic high suggest spatially and temporally variable depositional conditions within the aggregate quarry.

This study focuses on two sections of stratified sediments within the Kieswetter Holdings Limited aggregate quarry in southern Kitchener: site KW-1 (73 m of exposure) and site KW-2 (16.5 m of exposure; Figs. 1C; 2 and 3). Each site is divided up into contiguous panels or vertical quarry faces that are broadly oriented E-W (see inset in Figs. 2 and 3). Very limited diamict units are exposed within these two sites, though outcrops of Port Stanley and Maryhill Till occur to the south and north respectively according to regional surficial mapping (Ontario Geological Survey, 2003).

Recorded sedimentary characteristics of deformed and associated undeformed sediments include grain size, sorting and fabric, clast characteristics, sedimentary structures, nature of bounding surfaces, and bed geometry. Lithofacies were described and identified using a modified classification scheme derived from Miall (1977) and Eyles et al. (1983). The deformation at these sites was described using field sketches and photographs. Structural measurements of fold axes and fault planes could not be taken due to restricted access to vertical quarry faces.

3. Sedimentary facies

Analysis of the sediments reveals four recognizable lithofacies at KW-1 and KW-2: common occurrences of mud, abundant sand and gravel as well as minor diamict (Fig. 4).

3.1. Mud

Units of horizontally interlaminated clay, silty clay, clay-rich silt, and silt (Fh) are laterally continuous across exposures of both KW-1 and KW-2. Some discontinuous beds of horizontally bedded mud (1-4 cm thick) interbedded with minor sand rest on low-angle inclined surfaces (approximately 10°) at KW-1. Units of horizontally interlaminated mud are commonly associated with horizontally bedded sand, vary from 10-23 cm thick, and have planar, sharp basal and upper contacts.

At KW-1, a unit of very fine-grained climbing-ripple cross-laminated, sandy silt (Fcr) with a thickness up to 30 cm is observed. Although not exposed at KW-2, this unit is laterally persistent throughout the quarry, with thicknesses reaching 2-3.5 m. Ripple cross-laminations are 3.5 cm in height. The basal contact of this unit is not exposed anywhere in the quarry; its upper contact is erosive and irregular.

3.2 Sand

Units of horizontally bedded sand (Sh) consisting of moderately to well sorted medium- to very coarse-grained sand (Fig. 4A) are exposed at both sites. These are commonly associated with laminated mud. Contacts between sand and mud are sharp and planar, at times erosional. Units of horizontally bedded sand vary from 15-23 cm thick, and have sharp basal contacts and erosional upper contacts.

Cross-bedded medium- to very coarse-grained, moderately sorted sand (St) is laterally continuous over tens of metres at KW-1 and KW-2. Cross-bed sets are 14-30 cm thick (Fig. 4B). Contacts between sets are erosive. Co-sets of cross-beds vary from 0.6-1.7 m thick. Units of cross-bedded sand have a sharp, irregular or erosive basal contact and a sharp upper contact.

3.3. Gravel

Massive, sandy, matrix-supported gravel (Gmm) occurs discontinuously throughout sites KW-1 and KW-2, with localized clast-supported gravel in some sections. Two types of massive gravel exist: finer-grained granule to pebble gravel and coarser-grained pebble to cobble gravel (Fig. 4C); both have a medium- to very coarse-grained, moderately to well sorted sand matrix. Beds of massive gravel are ≤ 1.25 m thick, with lateral exposure of ≤ 9 m. They have sharp, irregular or erosional basal contacts and sharp, irregular upper contacts.

Normally coarse-tail graded, matrix-supported pebble to boulder gravel (Gmg; avg. 2 cm diameter) is discontinuously exposed throughout KW-1 in panels 8, 9 and 12 (Fig 2) and not observed at KW-2. This gravel has a medium- to very coarse-grained, moderately to well sorted sand matrix (Fig. 4D). These graded gravel units are approximately 1m thick, and have an erosive or irregular basal contact (where exposed) and sharp, irregular upper contacts.

Trough cross-bedded, matrix-supported granule to pebble gravel (Gmt) has a coarse- to very coarse-grained, moderately sorted sand matrix. This facies is exposed at KW-1 (panels 5, 10, 11, Fig. 2). Sets of cross-beds are 30 cm to >1 m thick from the basal scree to the upper contact. Based on limited 3-dimensional paleocurrent data measured at KW-1, foresets have a mean dip direction of 284° ($n = 6$; corrected for magnetic declination). Co-sets of cross-bedded gravel tend to have erosional basal contacts (where exposed) and sharp, irregular upper contacts.

3.4. Diamict

Thin, discontinuous beds of massive, matrix-supported, sandy diamict (Dmm) outcrop at KW-1; no diamict was observed at KW-2. The diamict has a sandy clay or clayey silt matrix with common to very abundant clasts (avg. 1 cm diameter). The diamict beds are 2-15 cm thick and are laterally discontinuous over a distance of several metres. Diamict beds commonly have sharp, irregular basal and upper contacts.

3.5. Lateral and vertical distribution of sedimentary facies

Analysis of the sedimentary facies exposed at KW-1 (Fig. 2) and KW-2 (Fig. 3) reveals five stratigraphic units, which are laterally continuous and relatively tabular in geometry. Contacts between stratigraphic units tend to be sharp. A fining-upwards trend is present from Stratigraphic Unit II (SU II) to Stratigraphic Unit IV (SU IV).

Stratigraphic Unit I (SU I) consists of climbing ripple cross-laminated sandy silt (Fcr). SU I sediments are only visible at the base of Panel 9 at KW-1 (Fig. 2), but are laterally persistent throughout the quarry. SU II consists of normally graded gravel (Gmg) at KW-1 (base of panels 8, 9 and 12) and crude to well-bedded cross-bedded gravel (Gmt) at KW-2 (base of panels LW-12 and LW-13; Figs. 2 and 3).

Cross-bedded fine- to very coarse-grained sand (St) and gravel (Gmt) with minor interbeds of mud (Fh) and horizontally bedded sand (Sh) characterize Stratigraphic Unit III (SU III) sediments. SU III can be traced across all the panels at KW-1 and KW-2 (Figs. 2 and 3) and is laterally persistent throughout the quarry, with thicknesses of 1-4 m. An intraformational unconformity occurs between SU III and SU IV east of Panel 3 at KW-1 (Fig. 2)

Finer-grained SU IV sediment consisting of interbedded mud and sand with minor gravel can be traced across all panels at both sites. Thin, discontinuous beds of diamict (Dmm) are present at KW-1 (at the top of SU IV in panels 5 and 6 and at the bottom of SU IV in panels 11 and 3; Fig. 2). At KW-1, a local, relatively coarse-grained massive gravel lens disrupts and is onlapped by the interbedded mud and sand of SU IV (panels 3 and 10; Fig. 2). The gravel lens is ≤ 1.5 m thick, has a tabular geometry, is found above a shear zone and has a flow nose at its western boundary.

Interbedded medium- to very coarse-grained sand (St) and granular to pebble gravel (Gmm) characterize Stratigraphic Unit V (SU V) sediments. At KW-1, SU V is exposed at the top of panels west of Panel 1, whereas it is exposed along the top of all panels at KW-2 (Figs. 2, 3).

3.6. Depositional setting

A number of depositional settings are possible in a moraine influenced by multiple lobes, including glaciolacustrine, subaquatic fan, delta, glaciofluvial, subglacial, and ice marginal (c.f. Barnett et al., 1998). The association of mud, sand and gravel, as well as the occurrence of climbing ripples in sandy silt, graded gravel and load structures (ball-and-pillow and associated flame structures; see below) suggest a glaciolacustrine to subaquatic fan setting with rapid sedimentation and variable sediment supply, discharge and/or sediment delivery (Rust, 1977; Nemec et al., 1984; Nemec and Steel, 1984; Nemec and Steel, 1988). The ice may have been close to the site, but the relatively limited presence of diamict in the section suggests an ice marginal or subglacial origin for these deposits is unlikely. The fining-upward trend observed from SU II to SU IV

suggests a waning of flow energy or fluctuations in the supply of coarse-grained sediments to the system. The proposed depositional model for these study sites is consistent with existing depositional models of Waterloo Moraine sediments (Bajc and Karrow, 2004; Bajc and Shirota, 2007; Russell et al. 2007).

4. Deformation structures

Deformation affects most stratigraphic units and occurs over a range of scales (centimetres to several metres). Deformation structures are characterized as both brittle (normal and reverse faulting) and ductile (various types of folding, attenuated bedding, ball-and-pillow structures or load structures), although the large majority of faults are localized (affecting one or two beds) and with relatively minimal offsets (< 10 cm).

4.1 Site KW-1

Although highly complex and variable throughout the outcrop at KW-1, the deformation structures can be characterized from East to West as predominantly brittle and relatively simple (panel 12, 11), predominantly ductile associated with a thick lens of gravel (panels 10, 3 and 1), transitional with relatively more abundant ductile and brittle deformation (panels 2-4), and lastly, increasingly complex and predominantly shear deformation with minor brittle deformation (panels 5-9) to the west (Fig. 2).

In the East, Panels 12 and 11 consist of relatively tabular deposits of SU II through SU IV. The deformation is best developed in the sand and minor gravel of SU III as well as the interbedded sand and mud of SU IV; SU II gravels are undeformed (Fig. 2, 5). Deformation in SU III sediments consists of broad and open to recumbent folding, attenuated bedding, shear folds and minor normal faults. A tight fold is attenuated and

truncated by the overlying relatively planar contact with SU IV sediments (Fig. 6). Folding ranges over 10's cm to several metres in scale. The minor faults have 1-5 cm offsets and are restricted to SU III sediments; they coincide with a broad open convex fold at the base of Panel 11. The interbedded sand and mud of SU IV are broadly folded with minor asymmetrical anticlinal and synclinal folds (Fig. 5). These folded units are offset by numerous small-scale reverse faults and minor normal faults (displacement of 0.5 to 4.5 cm; dip angles ranging from 60° to near vertical; Fig. 6). The faults can be traced throughout the whole thickness of SU IV and are associated with both the minor asymmetrical folds and the relatively tabular beds (Fig. 5).

Panels 10, 3 and 1 are dominated by partial exposure of SU III sand and gravel, a thick lens of gravel (Fig. 4C), and partial exposure of SU V sand and gravel in the westernmost portion of panel 1. The gravel lens is considered part of SU IV as it is overlapped by middle and upper SU IV sediments in adjacent Panel 11. SU III sediments at the base of these panels are folded (shear, recumbent, highly contorted and convoluted, open: Fig. 2). Faults (1-32 cm offsets) affect both SU III sediments and the base of the SU IV gravel lens (panel 10). The lens itself is predominantly undeformed. A thin (4-20 cm) shear zone (180 cm lateral extent) occurs underneath the gravel lens and consists of diamict (fine sandy clay matrix with clasts < 2 cm) with discontinuous beds of clay, and discontinuous attenuated sand and gravel beds. One of the sand beds has rooted shear folds (cm scale) extending into the diamict with an apparent tangential stress direction of SSW (Fig. 7).

The gravel lens has a clearly defined flow nose at its SSW end with recumbent folded sand and mud in its forefield. SU IV and SU V sediments to the west of the gravel

lens are both affected by asymmetric and symmetric, anticlinal and synclinal folding (cm to 10's cm scale), minor shear folds and attenuated bedding (Panel 1, Fig.2). Steeply dipping reverse and normal faulting (< 5cm offsets) affects all three stratigraphic units at the western end of Panel 1 (Fig. 2).

Panels 2 and 4 consist of deformed stratigraphic units III through IV.

Deformation in stratigraphic unit III includes closed recumbent fold (90x 20 cm; Panel 2), shear folds and attenuated bedding in discontinuous beds of gravel and clay (bottom of Panel 4), as well as localized small-scale normal faulting (< 1.5 cm offsets) affecting one sand unit in the lower left of Panel 2. The deformation affecting SU IV and SU V is highly variable in this transition zone: small-scale ball-and-pillow structures (Fig. 8A) and small-scale faults (1 -15cm offsets) affect individual units or several units within Panel 2, whereas a metre-scale shear fold (Fig. 8B), cm-scale highly convoluted folding, broad open folding, attenuation and minor localized faulting affects bedding in Panel 4. It is important to note that the sands in the underlying SU III are also affected by this m scale shear fold.

Panels 5-9 are dominated by m-scale deformation of SU III to SU V sediments, including complex shear structures (folding and attenuated bedding) as well as broad open anticlinal and synclinal symmetrical and asymmetrical folding (Figs. 2, 9). SU II and SU I sediments are undeformed. The interbedded sand and mud of SU IV appear to be the most severely deformed internally. In addition, these panels exhibit a wide range of other deformation structures including a graben-like feature (1-50 cm offsets), which affects all units in the outcrop (Panel 7: Figs. 2, 10A, B), localized normal and reverse small-scale faulting (cm to 10's cm scale offsets), highly convoluted and contorted

bedding (cm- 10's cm scale), abundant attenuated bedding (Fig. 10C), broad open anticlinal and synclinal asymmetrical folding (cm- 10's cm scale), and minor loading (eg. gravel bed in upper right corner of Panel 7, Fig. 2). Both normal and reverse localized faulting occurs in association with folded or sheared sediment; these faults affect individual units (e.g. panels 5 and 9), several units within one stratigraphic unit (e.g. SU IV in upper right corner of Panel 6) or several stratigraphic units (e.g. SU IV and SUV sediments in upper left corner of Panel 6). Fig. 10B shows that units affected by the graben-like feature were previously deformed.

SU III and SU IV sediments are also affected by an overturned fold in panels 5 to 7 at KW-1. Due to the orientation of the vertical faces relative to the fold, the fold is only visible when viewing the outcrop from the west (Fig. 10D). The fold is 1.5 m high and includes mud, sand and gravel units.

4.2 Site KW-2

Deformation at KW-2 is predominantly of a ductile nature and follows a similar pattern to the western end of KW-1, with pervasive shear (cm-m scale) and broad m-scale anticlinal and synclinal folding (Fig. 3). The three panels at this site consist of SU II through SU V sediments. Deformation is most pervasive in SU IV sediments.

Small graben-like features (< 8 cm offsets) occur in SU III sediments of panel LW 13. Additional minor normal faulting (< 2 cm offsets) occurs in the other two panels, affecting individual units. Shear structures primarily affect SU IV sediments and include rooted shear folds, attenuated bedding, and folded inclusions of SU III that have been attenuated (Fig. 11). Inclusions of SU III sediments in SU IV are deformed both

externally and internally (convoluted and contorted internal laminations, irregular and attenuated outer contacts). The upper contact of SU IV is highly irregular, contorted and convoluted with some rooted shear folds and minor load and flame structures (western end of SO-09). SU V sediments are convoluted and contorted.

5.0 Discussion

5.1 Origin of deformation

The most abundant deformation structures at the site are various types of shear structures. Boudinage and bed attenuation are strain responses to bulk sediment extension along a persistent surface (such as an ice-substrate interface; Goscombe et al., 2004), throughout a mass of slumped bedded sediment (e.g. Hubert et al., 1977; Arnaud and Eyles, 2002) or at the base of debris flows (Nardin et al., 1979). The tangential stress required to develop shear folds can be generated at the base of an over-riding subaqueous sediment gravity flow (Mulder and Alexander, 2001), at the base of an over-riding glacier (Hart and Roberts, 1994; Benn and Evans, 1996) or, if the sediment origin is subaquatic, from water waves (e.g. Owen, 1995; Røe and Hermansen, 2006).

The nature, complexity, abundance and small to medium scale of the shear deformation throughout SU IV and in parts of SU III and SU V, coupled with the depth of the section affected and the association with compressional deformation, suggest high shear strain and subglacial to ice-marginal deformation (Hart and Roberts, 1994; Benn and Evans, 1996; McCarroll and Rijdsdijk, 2003; Lee and Phillips, 2008).

A trigger associated with debris flow or slumping sediments is unlikely as simple shear structures associated with sediment gravity flows tend to be of low shear strain,

found in basal zones of individual units, and overall are associated with vertical deformation (loading, water-escape structures; Hart and Roberts, 1994, McCarroll and Rijdsdijk, 2003). There is also no evidence of shearing by strong wave action as none of the sediments associated with the shear folds show well developed sedimentary structures indicative of such high-energy conditions (e.g. cross-bedding).

In contrast, deformation observed adjacent to a lens of coarse gravel (Panel 3, site KW-1) is interpreted to record compressional and basal shear stress associated with the deposition of a subaqueous sediment gravity flow. The massive gravel lens with its flow nose is interpreted as a localized hyperconcentrated density flow (Postma et. al., 1983; Mulder and Alexander, 2001), which is common in subaqueous fan settings (Nemec et al., 1984). Compressional stresses in the flow forefield likely led to the recumbent fold around the flow nose of the gravel lens, as well as the small-scale folds and convolutions in the adjacent sediments of Panel 1. The shear folds in sand and diamict underneath the coarse gravel lens in Panel 3 are considered a basal shear zone (Figs. 2, 7) and interpreted to result from the tangential stresses associated with the deposition of that flow.

Load structures were observed where a coarser-grained material was underlain by a finer-grained material. These are interpreted as resulting from reversed density gradients, with rapid sedimentation being the trigger for the deformation (Anketell and Dzulynski, 1968; Anketell et al., 1970). The graben-like structures are best explained as a result of gravitational collapse associated with the melting of buried ice (Aitken, 1998).

The association of the remaining types of folding and faults with shear structures as well as the abundance, intensity and complexity of deformation at this site, suggests glacial ice played a role (McCarroll and Rijdsdijk, 2003). These deformation structures

are interpreted to have been triggered by compressional and shear stresses imparted through SU III to SU IV sediment by encroaching glacial ice (cf. Boulton et al., 1999; McCarroll and Rijdsdijk, 2003; Bennett et al. 2004a; Benediktsson et al., 2008). The large majority of the faulting involves minimal offsets of individual units and is associated with folding or shear structures in coarser grained sediments suggesting localized brittle response related to heterogeneity in sediment texture and pore-water content (c.f. Hart and Watt, 1997). This is in contrast to a study by Bennett et al. (2004) that suggested spatially variable distribution of ductile and brittle deformation structures was related to spatially variable distribution of frozen and unfrozen sediments at the ice margin.

5.2. Polyphase deformation model

Overall, the nature and scale of deformation structures suggest complex polyphase deformation of heterogeneous sediments related to sediment gravity flow, rapid sedimentation, active ice deformation, and melting of buried stagnant ice. Deformation at these two sites is considered polyphase because several deformation events occurred over time. A three-stage conceptual model is proposed, where brittle and ductile deformation can be attributed to variable syn- and post-depositional processes (Fig. 12, 13).

Stage 1– Non-glacial deformation

Stage 1 consists of the deposition of SU I through SU V sediment (Fig. 13). Varying grain sizes between and within stratigraphic units suggest variable discharge and variation in supply of coarse-grained sediments, or proximity to sediment source. Deposition appears to have been relatively continuous.

A period of deformation is associated with deposition of SU IV sediments (Fig. 12). Common fluidization and liquefaction related to rapid sedimentation and reversed density loading led to ball-and-pillow structures and associated flame structures in interbedded sand and mud (Fig. 8). Small-scale compressional folding (Panel 1, KW-1) and shear folding within a basal shear zone (Panel 3, KW-1) are also associated with the deposition of a localized subaqueous hyperconcentrated density flow. The influx of coarse-grained sediment represented by this localized hyperconcentrated density flow may represent a distal signal of the advance of ice into the basin (Fig. 13).

Stage 2 – Active ice deformation

Stage 2 is characterized by pervasive simple shear and compressional deformation of SU III to SU V sediments (Figs. 12, 13). The abundance, complexity, and association of simple shear and compressional deformation observed at both sites are typical of ice marginal and subglacial environments (McCarroll and Rijdsdijk, 2003).

The heterogeneous character of the deformed sediment may explain the observed variability in deformation styles and intensity (Phillips et al., 2002; 2007). At the site scale, the deformation east of Panel 3 at KW-1 is predominantly brittle, whereas the deformation west of Panel 3 and at site KW-2 is predominantly ductile. The brittle deformation is found in SU IV sediment and overlies an intraformational unconformity and a thin discontinuous diamict bed. The presence of that thin diamict bed and the relatively sandier SU IV sediments in panels 10-12 (KW-1) compared with the other SU IV sediments to the West may explain the exceptionally abundant reverse faulting in panels 10-12 at KW-1.

It is proposed that SU III and SU IV sediments in panels 10-12 were compressed, leading to an initial phase of broad open folding (low shear strain). The presence of a thin diamict at the interface with underlying SU III sediment and the relatively more competent (sandier) sediment of SU IV, together with further compressional and simple shear stresses, led to extensive reverse faulting in SU IV sediment and the development of a shear or decollement surface at the interface between SU III and SU IV sediments. In contrast, the relatively finer-grained sediments to the West of Panel 3 and at site KW-2 responded to the additional compressional and simple shear deformation by developing more complex and intense deformation structures indicative of high shear strain. Relatively minor faulting occurred in associated sand due to localized brittle deformation in response to the high shear strain. In panels west of Panel 3 at KW-1 and at site KW-2, SU III and SU IV sediments appear to have deformed together under tangential and compressional stresses. The faulting would have developed near the end of the active ice deformation stage, as pore-water pressures decreased and normal effective stress increased, resulting in the overprinting of ductile shear structures with minor offsets and brittle deformation (e.g. Benediktsson et al., 2008).

The complexity and widespread occurrence of deformation on one side of a local topographic high is typical of glacial structures associated with an ice-contact ridge (e.g. Benn and Evans, 1996). As such, the shearing and compressional structures are attributed to a local re-advance of glacial ice (Fig. 13).

Stage 3 –Stagnant ice deformation

Vertical deformation associated with the melting of a buried ice block and collapse of the sedimentary floor led to additional localized extensional faulting of sediments and formation of graben structures (Panel 7 at KW-1; Figs. 12, 13). The large graben feature affects all visible stratigraphic units and other deformation structures in Panel 7; this deformation event is thought to have occurred after all other deformation events (Figs. 2, 10A, B and 11). The study sites are within the interlobate Waterloo moraine—a complex mosaic of depositional environments affected by the fluctuations of multiple ice margins. While the sediments at this site record subaqueous deposition, the buried ice was probably incorporated into the sediment pile during an earlier stage of fluvial or deltaic deposition, when ice margin locations allowed the ice-dammed waters to drain.

5.3 Implications for the regional glacial history

The study sites are situated along a regional ridge that is thought to record coalescing subaqueous fans associated with the margin of the Erie-Ontario ice lobe (Bajc and Shiota, 2007). The lack of deformation in correlative units further to the west within the Kieswetter Quarry (this study) and regionally (Weaver, 2008) suggests that the shear deformation recorded at these two sites resulted from overriding of the area from the East by Erie-Ontario ice. It is interesting to note that this section is primarily dominated by relatively planar tabular units exhibiting shear structures. Although it may be a function of outcrop exposure, there does not appear to be significant displacement of sediment either in imbricate thrust slabs or near-horizontal nappes as is common in the foreland of push or end moraines (Bennett, 2001). This may be a feature of interlobate ice contact features or may suggest that the sites were some distance away from the compressional

deformation zone of this ice contact setting; the latter is likely considering the almost 4 km width of this regional ridge.

The overriding of the sites by Erie-Ontario ice is also consistent with the nearby exposure of Port Stanley Till-a subglacial deposit with dominant clast fabric suggesting flow from the southeast (Karrow, 1963), generally associated with the Erie-Ontario ice lobe. Considering the near-surface exposure of these deformed sediments and the close association of Port Stanley Till immediately to the South of the site, deformation most likely occurred in the late stages of development of the Waterloo moraine-likely Port Bruce phase; this suggests that active ice processes were important in shaping the final morphology of the moraine.

Lastly, it should be noted that the decollement surface identified in panels 11 and 12 may be associated with a previous ice advance, whereby the sediments of SU III were deformed prior to deformation of SU IV and SU V. It is difficult to confirm this, however, due to the thin nature and limited extent of the diamict. In addition, the contact between SU III and SUIV in other panels at site KW-1 and KW-2 is obscured by deep penetration of stage 2 active ice deformation (panels 5-9) and by deformation underneath the gravel lens (panels 10, 3 and 1), making it difficult to find evidence of a previous phase of deformation in those adjacent panels.

6. Conclusion

A detailed investigation of deformed surficial stratified sediments was conducted within the Waterloo Moraine. Highly deformed interbedded mud, sand and gravel are exposed in two series of contiguous panels. Facies analysis reveals five recognizable

stratigraphic units at the two sites that suggest rapid deposition and fluctuating energy in a subaqueous environment prior to deformation.

Deformation (cm to m scale) is stylistically and structurally heterogeneous and affects most stratigraphic units. The sites reveal vertical (normal faults, load structures), compressional (folding and reverse faulting), and simple shear (boudinage, attenuated bedding and shear folding) styles of deformation. The nature and scale of deformation structures suggest complex polyphase deformation related to sediment remobilization and rapid sedimentation (stage 1), active ice deformation (stage 2), and melting of buried ice (stage 3). The deformed sediments occur east of a local topographic high, whereas the sediments to the west consist of undeformed channelized sand and gravel, suggesting this topographic high may have been an ice-contact grounding-line fan.

Acknowledgements: The authors would like to thank Jim Kieswetter of Kieswetter Holdings Ltd. for access to his aggregate operation, Peter Martini for helpful discussions throughout the project, Sarah Ouellette for her assistance in the field and Geraint Owen, Massimo Moretti and Pedro Alfaro for inviting us to contribute to this Special Issue. This research was funded by a Natural Sciences and Engineering Research Council Discovery Grant to Arnaud and a University of Guelph Scholarship and Ontario Graduate Scholarship to Weaver. This financial assistance is greatly appreciated. We are also grateful for the detailed comments and suggestions of Emrys Phillips and an anonymous reviewer.

References

- Aber, J.S., Croot, D.G., Fenton, M.M., 1989. Glaciotectonic landforms and structures. *Glaciology and Quaternary Geology*. Kluwer Academic Publishers, Dordrecht, 200 pp.
- Aitken, J. F., 1998. Sedimentology of Late Devensian glaciofluvial outwash in the Don Valley, Grampian Region. *Scottish Journal of Geology*, 30: 97-117.
- Anketell, J., Dzulynski, S., 1968. Patterns of density controlled convolutions involving statistically homogeneous and heterogeneous layers. *Rocznik Polskiego Towarzystwa Geologicznego*, 38: 401-409.
- Anketell, J., Cegla, J., Dzulynski, S., 1970. On the deformation structures in systems with reversed density gradients. *Rocznik Polskiego Towarzystwa Geologicznego*, 41: 3-30.
- Arnaud, E., Eyles, C.H., 2002. Catastrophic mass failure of a Neoproterozoic glacially-influenced continental margin, the Great Breccia, Port Askaig Formation, Scotland. *Sedimentary Geology*, 151: 313-333.
- Bajc, A.F., 2004. Three-dimensional mapping of Quaternary deposits in Waterloo Region, southwestern Ontario, Ontario Geological Survey, Sedimentary Geoscience Section (24), Open File Report 6145.
- Bajc, A. F., Karrow, P. F., 2004. 3-dimensional mapping of Quaternary deposits in the Regional Municipality of Waterloo, southwestern Ontario, Lake to Lake: GAC-MAC Joint Annual Meeting. Geological Association of Canada/Mineralogical Association of Canada, FT-7, St. Catharines, ON.
- Bajc, A.F., Shiota, J., 2007. Three-dimensional mapping of surficial deposits in the Regional Municipality of Waterloo, southwestern Ontario, Ontario Geological Survey, Groundwater Resources Study 3, 42p.
- Bajc, A.F., Endres, A.L., Hunter, J.A., Pullan, S.E., 2003. An update on three-dimensional mapping of Quaternary deposits in Waterloo Region, southwestern Ontario, Ontario Geological Survey, Sedimentary Geoscience Section (24), Open File Report 6120.
- Barnett, P. J., 1992. Quaternary Geology of Ontario. In: P.C. Thurston, H.R. Williams, Sutcliffe, R.H., Stott, G.M., (Eds.), *Geology of Ontario*. Ontario Geological Survey, Toronto, pp. 1011-1090.
- Barnett, P.J. Sharpe, D. R., Russell, H. A. J., Brennand, T. A., Kenny, F. M., Pugin, A., 1998. On the origin of the Oak Ridges Moraine. *Canadian Journal of Earth Science*, 35: 1152-1167.

- Benediktsson, Í. Ö., Möller, P., Ingólfsson, Ó, van der Meer, J. J. M., Kjær, K. H., Krüger, J., 2008. Instantaneous end moraine and sediment wedge formation during the 1890 glacier surge of Brúarjökull, Iceland. *Quaternary Science Reviews*, 27: 209-234.
- Benn, D. I., Evans, J. A., 1996. The interpretation and classification of subglacially-deformed materials. *Quaternary Science Reviews*, 15: 23-52.
- Bennett, M. R. 2001: The morphology, structural evolution and significance of push moraines. *Earth-Science Reviews* 53, 197-236.
- Bennett, M. R., Huddart, D., Waller, R. I., Midgley, N. G., Gonzalez, S. & Tomio, A. 2004a: Styles of ice-marginal deformation at Hagafellsjökull-Eystri, Iceland during the 1998/99 winter-spring surge. *Boreas* 33, 97-107.
- Bennett, M. R., Huddart, D., Waller, R. I., Cassidy, N., Tomio, A., Zukowskyj, P., Midgley, N. G., Cook, S. J., Gonzalez, S. & Glasser, N. F. 2004b: Sedimentary and tectonic architecture of a large push moraine: A case study from Hagafellsjökull-Eystri, Iceland. *Sedimentary Geology* 172, 269-292.
- Boulton, G. S., van der Meer, J. J. M., Beets, D. J., Hart, J. K., Ruegg, G. H. J., 1999. The sedimentary and structural evolution of a recent push moraine complex: Hølmstrombreen, Spitsbergen. *Quaternary Science Reviews*, 18: 339-371.
- Chapman, L.J., Putnam, D.F., 1951. *The physiography of Southern Ontario*. University of Toronto Press, Toronto, 284 pp.
- Eyles, N., Eyles, C. H., Miall, A. D., 1983. Lithofacies types and vertical profile models; an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences. *Sedimentology*, 30: 393–410.
- Farvolden, R. N., Greenhouse, J. P., Karrow, P. F., Pehme, P. E., Ross, L. C., 1987. Subsurface Quaternary stratigraphy of the Kitchener-Waterloo area using borehole geophysics. Ontario Geological Survey Open File Report 5623.
- Gao, C., 2005. Ice-wedge casts in Late Wisconsinan glaciofluvial deposits, southern Ontario, Canada. *Canadian Journal of Earth Sciences*, 42: 2117-2126.
- Goscombe, B. D., Passchier, C. W., Hand, M., 2004. Boudinage classification: end-member boudin types and modified boudin structures. *Structural Geology*, 26: 739-763.
- Hart, J. K., Roberts, D. H., 1994. Criteria to distinguish between subglacial glaciotectonic and glaciomarine sedimentation, I. Deformation styles and sedimentology. *Sedimentary Geology*, 91: 191-213.

- Hart, J. K. & Watts, R. 1997: Comparison of the styles of deformation associated with two recent push moraines, south Van Keulenfjorden, Svalbard. *Earth Surface Processes and Landforms* 22, 1089-1107.
- Hubert, J.F., Sucheki, R.K., Callahan, R.K.M., 1977. The Cow Head Breccia: sedimentology of the Cambro-Ordovician continental margin, Newfoundland. *Society of Economic Paleontologists and Mineralogists, Special Publication*, 25: 125-154.
- Karrow, 1963. Pleistocene Geology of the Hamilton-Galt Area, P.F. Karrow. (Geological Report No.16). Ontario Department of Mines, Toronto, 68 pp.
- Karrow, P. F., Paloschi, G. V. R., 1996. The Waterloo kame moraine revisited: new light on the origins of some Great Lake region interlobate moraines. *Zeitschrift fuer Geomorphologie N.F.*, 40: 305-315.
- Karrow, P.F., Dreimanis, A., Barnett, P.J., 2000. A proposed diachronic revision of Late Quaternary time-stratigraphic classification in the eastern and northern Great Lakes area. *Quaternary Research*, 54: 1-12.
- Lee, J. R. Phillips, E. R., 2008. Progressive soft sediment deformation within a subglacial shear zone—a hybrid mosaic–pervasive deformation model for Middle Pleistocene glaciotectonised sediments from eastern England. *Quaternary Science Reviews*, 27: 1350-1362.
- McCarroll, D., Rijdsdijk, K. F. 2003. Deformation styles as a key for interpreting glacial depositional environments. *Journal of Quaternary Science*, 18: 473-489.
- Miall, A. D., 1977. A review of the braided-river depositional environment. *Earth Science Reviews*, 13: 1-62.
- Ministry of Natural Resources, 2002. Provincial Digital Elevation Model- Tiled Data Set (DEM); Tiles 81, 82, 85, 86.
- Morgan, A.V., 1992. Late Wisconsinan ice-wedge polygons near Kitchener, Ontario, Canada. *Canadian Journal of Earth Sciences*, 9: 607-617.
- Mulder, T., Alexander, J., 2001. The physical character of subaqueous sedimentary density flows and their deposits. *Sedimentology*, 48: 269-299.
- Nardin, T.R., Hein, F. J., Gorsline, D. S., Edwards, B. D., 1979. A review of mass movement processes, sediment and acoustic characteristics and contrasts in slope and base-of-slope systems versus canyon-fan-basin floor systems. In: Doyle, L.J., Pilkey, O.H. (Eds.) *Geology of Continental Slopes*, Society of Economic Paleontologists and Mineralogists Special Publication, (27): 61-73.

- Nemec, W., Steel, R.J., 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravelly mass-flow deposits. In: Koster, E.H., Steel, R.J. (Eds.), *Sedimentology of gravels and conglomerates*. Canadian Association of Petroleum Geologists, Memoir. Canadian Society of Petroleum Geologists, Calgary, pp. 1-32.
- Nemec, W., Steel, R.J., 1988. What is a fan delta and how do we recognize it? In: Nemec, W., Steel, R.J. (Eds.), *Fan deltas : sedimentology and tectonic settings*. Blackie, Glasgow, pp. 3-14.
- Nemec, W., Steel, R.J., Porebski, S.J., Spinnangr, A., 1984. Domba conglomerate Devonian, Norway: processes and lateral variability in a mass-flow dominated lacustrine fan-delta. In: Koster, E.H., Steel, R.J. (Eds.), *Sedimentology of Gravels and Conglomerates*. Canadian Society of Petroleum Geologists, Memoir, pp. 295-320.
- Ontario Geological Survey 2003. *Surficial geology of Southern Ontario*; Ontario Geological Survey, Miscellaneous Release--Data 128.
- Owen, G., 1995. Soft-sediment deformation in upper Proterozoic Torridonian sandstones (Applecross Formation) at Torridon, Northwest Scotland. *Journal of Sedimentary Research*, A65: 495-504.
- Phillips, E. R., Evans, D. J. A., Auton, C. A., 2002. Polyphase deformation at an oscillating ice margin following the Loch Lomond Readvance, central Scotland, UK. *Sedimentary Geology*, 149: 157-182.
- Phillips, E. R., Merritt, J., Auton, C. A., Golledge, N., 2007. Microstructures in subglacial and proglacial sediments: understanding faults, folds and fabrics, and the influence of water on the style of deformation. *Quaternary Science Reviews*, 26: 1499-1528.
- Postma, G., Roep, T. B., Ruegg, G. H. J., 1983. Sandy-gravelly mass-flow deposits in an ice-marginal lake (Saalian, Leuvenumsche Beek Valley, Veluwe, the Netherlands), with emphasis on plug-flow deposits. *Sedimentary Geology*, 34: 59-82.
- Russell, H.A.J., Sharpe, D.R. Bajc, A.F., 2007. Sedimentary signatures of the Waterloo Moraine, Ontario, Canada. In: Hambrey, M.J., Christoffersen, P., Glasser, N.F., Hubbard, B. (Eds.), *Glacial Sedimentary Processes and Products*. International Association of Sedimentologists Special Publication 39, Blackwell Publishing, pp. 85-108.

- Rust, B.R., 1977. Mass flow deposits in a Quaternary succession near Ottawa, Canada; diagnostic criteria for subaqueous outwash. *Canadian Journal of Earth Sciences*, 14: 175-184.
- Røe, S-L., Hermansen, M., 2006. New aspects of deformed cross-strata in fluvial sandstones: Examples from Neoproterozoic formations in northern Norway. *Sedimentary Geology*, 186: 283-293.
- Statistics Canada, 2007a. *Ontario Hydrology, Rivers 2006 Census* (cartographic boundary file, ghy_035d06a_e.zip). Arc Info Edition. System requirements: Arc Info Interchange for Windows. These data are available at no additional charge to Canadian educational institutions participating in the [Data Liberation Initiative](#).
- Statistics Canada, 2007b. *Ontario Hydrology, Lakes 2006 Census* (cartographic boundary file, ghy_035c06a_e.zip). Arc Info Edition. System requirements: Arc Info Interchange for Windows. These data are available at no additional charge to Canadian educational institutions participating in the [Data Liberation Initiative](#).
- Statistics Canada, 2007c. *Provinces and Territories, 2006 Census* (cartographic boundary file, gpr_000b02_e.exe). Arc Info Edition. System requirements: Arc Info Interchange for Windows. These data are available at no additional charge to Canadian educational institutions participating in the [Data Liberation Initiative](#).
- Statistics Canada, 2007d. *Ontario Dissemination Areas, 2006 Census* (cartographic boundary file, gda_035b06a_e.zip). Arc Info Edition. System requirements: Arc Info Interchange for Windows. These data are available at no additional charge to Canadian educational institutions participating in the [Data Liberation Initiative](#).
- Weaver, L., 2008. Soft sediment deformation in the Waterloo Moraine, Southwestern Ontario. M.Sc. thesis, University of Guelph, Guelph, 146 pp.
- Woodworth-Lynas, C.M.T., Guigné, J.Y., 1990. Iceberg scours in the geological record: examples from glacial Lake Agassiz. In: Dowdeswell, J.A., Scourse, J.D. (Eds.), *Glaciomarine Environments: Processes and sediments*. Geological Society of London Special Publication, pp. 217-223.

Figure captions

Fig. 1: A) Overview map of southwestern Ontario showing location of the Waterloo Moraine and the distribution of the Laurentide ice lobes (modified from Barnett, 1992; moraine outline taken from Bajc and Karrow, 2004); B) Regional map showing topography, extent of the Waterloo moraine and location of Kieswetter Holdings Ltd. Quarry relative to the moraine. Note the northwest-southeast trending ridge (arrows); C) Site map of Kieswetter Holdings Limited property showing local topography and part of the local topographic high, relative E-W position of study sites and extent of nearby tills. Note the change in elevation scale between (B) and (C). Note maps (B) and (C) were produced by L. Weaver using base map data from Statistics Canada (2007a-d), DEM data from Ministry of Natural Resources (2002) and surficial geology data from Ontario Geological Survey (2003) under License with the Ontario Ministry of Northern Development and Mines © Queen's Printer for Ontario, 2010.

Fig. 2: Annotated photomosaic (A) and interpretive diagram (B) showing the distribution of facies, deformation and stratigraphic units in contiguous panels or vertical faces of highly deformed sediments exposed at site KW-1. Inset map shows orientation of panels. See Fig. 1 for location of site KW-1 relative to the Waterloo Moraine and regional ice lobe configuration. Exposure of SU I is very limited but is otherwise found throughout the pit. Thin beds of diamict occur rarely. Note extensive small-scale reverse faulting in panels 11 and 12. See text for discussion.

Fig. 3: Contiguous panels or vertical faces of deformed sediments exposed at site KW-2 showing the distribution of facies, deformation and sedimentary units. Inset map shows

orientation of panels. See Fig. 1 for location of site KW-2 relative to the Waterloo Moraine and regional ice lobe configuration.

Fig. 4: Photographs of common sedimentary facies. A) Faulted horizontally bedded medium- to very coarse-grained sand (Sh) overlain by fine-grained mud (Fh), Panel 2, KW-1. Ruler shows increments in centimetres (right) and inches (left); B) Cross-bedded medium- to very coarse-grained sand (St) with occasional clasts overlain by moderately deformed horizontally-laminated mud, Panel 9, KW-1. Metre stick shows 10 cm increments; C) Lens of coarse-grained massive matrix-supported gravel (Gmm), Panel 3 and 10, KW-1; D) Normally-graded matrix-supported cobble to boulder gravel (Gmg) with clast-supported sections, Panel 8, KW-1.

Fig. 5: Detailed diagram of Panel 12 showing widespread reverse faulting associated with open asymmetrical folding in SU IV sediments, simple shear structures in SU III sediments and an unconformity interpreted as a decollement surface (arrow) between deformed SU III and SU IV sediments. See text for discussion and Fig. 2 for extent of stratigraphic units.

Fig. 6: Photograph of extensively faulted SU IV sediments and underlying attenuated tight fold in SU III sediments (centre of photo), Panel 11, Site KW-1. Metre stick shows 10 cm increments.

Fig. 7: Shear zone with shear folds of sand (Sm) in diamict (Dmm) underneath gravel lens (see Fig. 2C), Panel 3, KW-1.

Fig. 8: A) Ball-and-pillow structures (arrow) and associated flame structures in mud, Panel 2, KW-1. Ruler shows increments in centimetres (bottom) and inches (top); B) Shear fold (arrow), Panel 4, KW-1. Metre stick shows 10 cm increments.

Fig 9: Detailed diagram of Panel 6. Extensive simple shear and compressional deformation affect both SU IV and SU III sediments. See Fig. 2 for extent of stratigraphic units.

Fig 10: A) Graben-like feature, panels 6 and 7, KW-1; B) Close-up of graben-like feature in (A), showing pre-existing shear folding within sediments, suggesting faulting occurred after shearing. See text for discussion; C) Attenuated bedding (arrows) in lower left of Panel 6, KW1. Ruler shows increments in centimetres (bottom) and inches (top). D) Photograph of large overturned fold, panels 5 to 7, KW-1. Handle of shovel is 30 cm; Handle of trowel in A) and B) is 12 cm.

Fig. 11: A) general view of shearing in SU IV sediments, Panel LW-12, Site KW-2; B) close-up of sediments shown in (A). Note inclusions of underlying SU III sediments (arrows).

Fig. 12: Summary diagram outlining the nature, origin and timing of the polyphase deformation.

Fig. 13: Schematic diagram of the three stages of the polyphase deformation model showing the overall depositional setting, the extent of ice cover and the distribution of sediment types.

E

Panel 12

Panel 11

Panel 10

Panel 3

Panel 1

Panel 2

Panel 4

Panel 5

Panel 6

Panel 7

Panel 8

Panel 9

W

Mud layer (silt, clay)

Very fine- to very coarse-grained sand

Granule to cobble gravel

Scree

Fault

SU II

SU III

SU IV

Mud layer (silt, clay)

Very fine- to very coarse-grained sand

Granule to cobble gravel

Scree

Fault

SU III

SU IV

SU V

1 m

Glacial ice

Mud (silt and clay)

Sand

Granule to cobble gravel

Diamict

Faults

Relative
Location
of Sites
KW-1,
KW-2
to Ice
Margin

W

①

KW-1, KW-2

E

W

②

KW-1, KW-2

E

W

③

KW-1, KW-2

E