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A comparative analyses of microstructures from Late Jurassic diamictic units, near Helmsdale, northeast Scotland and a Pleistocene diamicton from near Milton, southern Ontario, Canada – a differential diagnostic method of sediment *typing* using micromorphology

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Abstract

Micromorphology is used to examine and compare a Late Jurassic diamictite from northeast Scotland with a Pleistocene diamict from southern Ontario, Canada in order to test if a statistical difference between diamicts can be recognized and used to separate differing types of diamicts/diamictites. The diamictites from Scotland have been ascribed to various depositional agencies occurring in several distinctly differing terrestrial and marine palaeoenvironments. In contrast, the Pleistocene diamicton is regarded as a subglacial till. Both diamicts appear remarkably similar visually and contain many corresponding features such as macrostructures, and exotic and fractured subangular to subrounded clasts. Micromorphology is used to re-examine these diamicts/diamictites at the microscopic level to detect if the palaeoenvironments within which they were deposited can be ascertained. In this paper a quantitative assessment of microstructures using micromorphology is developed. Comparative statistical analyses of these diamicts, using micromorphological features, reveals that the Jurassic diamictites are non-glacigenic, non-terrestrial and most likely deposited within a marine environment as a result of subaqueous debris mass movement, while, in contrast, the Pleistocene diamicts were most likely subglacial *tectomicts* deposited beneath the active base of the Laurentide Ice Sheet.

Keywords: diamictites, diamictons, diamicts, till, micromorphology, Jurassic, conglomerates, Pleistocene, statistical analyses

Introduction

Diamicts exist within a very broad range of sediments and sedimentary rocks that can be derived from both terrestrial and subaqueous environments. Diamicts can be classified, in lithified form, as conglomerates or various forms of cataclastics that contain varying proportions of fine-grained matrix within which clasts of a range of sizes and shapes *float* (Pettijohn, 1975; Allen, 1982; Friedman, 2003). The balance between matrix and clast content extends from matrix supported diamicts in which matrix is volumetrically dominant to clast supported diamicts in which clasts dominate the sediment or sedimentary rock and matrix content is volumetrically limited. Some classifications use different terms depending on the percentage of clasts or the degree of fine-grained matrix present (cf. Folk, 1954; Schermerhorn, 1966; Flint, 1971; Pettijohn, 1975), however, essentially all of these types are diamicts. Allaby and Allaby (1999) define a diamict (diamictites if lithified, diamictons if unlithified) as “a nonsorted or poorly sorted, ……, terrigenous (*or marine*) sediment or sedimentary rock that contains a wide range of particle sizes … in a muddy matrix, *and if* lithified, *a* conglomeratic, siliciclastic rock which is unsorted, with sand and/or coarser particles dispersed through a mud matrix” (*present authors’ italics*). As such, diamicts can be derived due to mass movement, glacial, or endogenic processes in terrestrial and subaqueous environments. Diamicts, in many instances, appear remarkably similar in hand-specimen (cf. Price, 1999; Schieber, 2003). However, as yet, the ability to differentiate the various diamictic types remains challenging.

In addition, to the many field and laboratory techniques that can be harnessed to confirm a particular depositional process and environment, micromorphology provides another singularly useful technique to establish formative processes (cf. Van der Meer, 1996; Menzies, 2000a; Lachniet et al., 2001; Van der Meer et al., 2003; Phillips and Auton, 2000, 2007; Phillips et al., 2002; Hart, 2006; Larsen et al., 2006; Menzies et al., 2006;

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Thomason and Iverson, 2006; Menzies and Brand, 2007; Lee and Phillips, 2008). Micromorphology is the microscopic examination of the structural components and constituent elements of earth materials. In the early 20th century micromorphology developed from within Soil Science (cf. Kubiëna, 1938; Stoops, 2003) and since then has spread into diverse fields such as geoscience and geoarchaeology. In sedimentology thin-sections are studied mainly from the objective of composition, whereas in pedology micromorphology is used to "describe, measure and interpret the formation and function of soil materials" (Stoops, 2003). The latter approach is still unusual in sedimentology. However, it is remarkable that the technique is so little used, given that it is the only one that permits the detailed study of sediment or sedimentary rock in situ (Van der Meer, pers. comm., 2007). It is not only possible to know that a particular constituent (e.g. a specific mineralogy, a microfossil) is present, but also where it is present, thus allowing detailed microstratigraphy and micro-structural analyses (cf. O'Brien & Slatt, 1990; Maltman, 1994; Van der Meer at al., 2003). Likewise, as will be demonstrated in the text below, it must be pointed out that the microstructures in both the diamicton and diamictite examined are syndeposi-tional forms developed during sediment emplacement/deposi-tion. Based on the microstructures present in both the Permian and glacial sediments this paper will contrast two known depositional settings and to demonstrate the enormous the potential of microstructure analysis. This paper sets out to differentiate between two geologically, yet visually similar, unrelated diamicts using micromorphology and, in the process, develop a semi-quantitative method of discrimination between diamict origin and type.

Stratigraphy of the Jurassic Diamicts from near Helmsdale, N.E. Scotland

Between Brora and Ord Point, north of Helmsdale in northeast Scotland, a narrow, 1.5 km wide, strip of Late Jurassic (Kimmeridgian) diamictic rocks are exposed (Fig. 1). These diamictites (*termed Boulder Beds in the past*) were first described by Murchison (1827). In the past diverse origins have been ascribed to these rocks. These diamictites have been variously regarded as evidence of ice transport (Ramsay, 1865), river flood deposits (Judd, 1873), subaerial mass movement (Blake, 1902), subaerial mass movement into the sea (*inter alia* Norton, 1917), and a subaquatic debris flow from a submarine fault scarp (Bailey et al., 1928; Bailey & Weir, 1932; Crowell, 1961; Pickering, 1984; MacDonald & Trewin, 1993; Wignall & Pickering, 1993; Hudson & Trewin, 2002). This latter interpretation appears to be the accepted explanation for these Late Jurassic sedimentary rocks based upon detailed macroscopic sedimentological examination (Phillips, pers comm., 2004).

These Jurassic rocks are downfaulted to the east of the Helmsdale Fault against Moinian granulites, Helmsdale granite

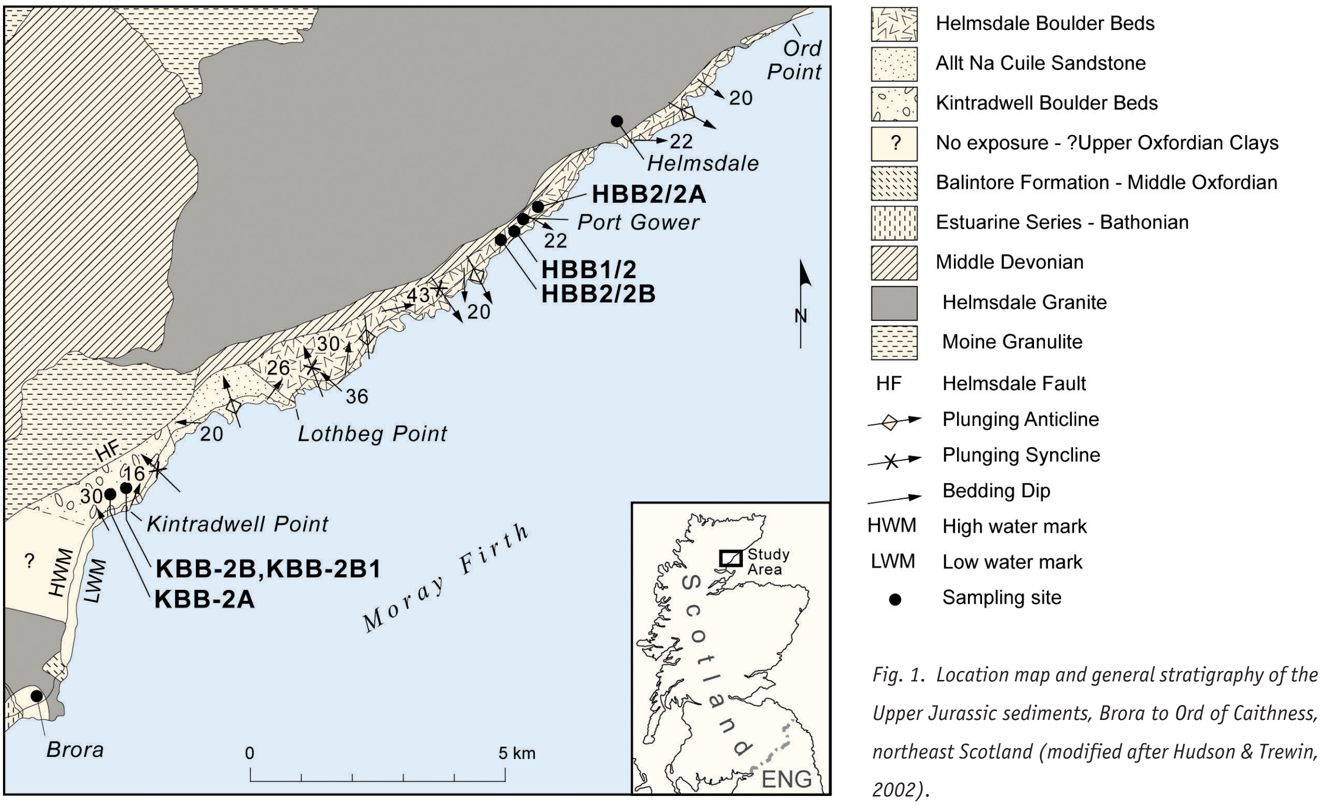

Fig. 1. Location map and general stratigraphy of the Upper Jurassic sediments, Brora to Ord of Caithness, northeast Scotland (modified after Hudson & Trewin, 2002).

and Middle Devonian sandstone (Bailey, 1928; Bailey & Weir, 1932; Pickering, 1984; MacDonald & Trewin, 1993; Hudson & Trewin, 2002). The succession is composed of lithofacies units that range from coarse conglomerates interbedded with sandstones to shales. Many of the shale units are bioclastic in content, containing ammonites, belemnites, brachiopods, corals, echinoids and thick shelled bivalves (Hudson & Trewin, 2002) (Fig. 1). The rocks young towards the northeast. They are deformed into several northwest to southeast plunging upright folds, and are locally offset by a number of steeply dipping to subvertical normal/reverse faults that in places are displaced several metres to decimetres (Pickering, 1984; Phillips, pers. comm., 2004).

The conglomerates are comprised of the Kintradwell Boulder Beds (KBB) which form the base of the succession in the Brora to Helmsdale area (approximately 85 m in thickness), and the Helmsdale Boulder Beds (HBB) (approximately 530 m in thickness) which lie above the intervening Allt na Cuile Sandstone (Pickering, 1984) (Fig. 2). Both conglomerate beds consist of what Crowell (1999, p. 202) described as "thick breccia beds ... composed of jumbled blocks of various country rock types with a high preponderance of ... Old Red Sandstones within a muddy and limey matrix" (Fig. 3a). These matrix supported, poorly sorted conglomerates are here referred to as diamictites. The diamictites exhibit a wide range of thickness from a few centimetres to several metres. In general, the diamictites contain a range of clast shapes from subangular to subrounded. There is a wide range in clast size and provenance both local and exotic. None of the clasts examined were striated. The matrix, within which these clasts are *suspended*, ranges from medium to very fine-grained sandstones, siltstones and claystones (Fig. 3b). In some places the matrix exhibits laminae and the diamictite becomes distinctly fissile (Fig 3c). In other places bedding planes can be clearly discerned that are warped and, occasionally, folded. In a few locations clasts have the appearance of drop-stones detectable by the downwarped laminated sediments beneath individual clasts (Fig. 3d). In several places thin bioclastic subfacies can be observed sandwiched between clast-rich matrix units.

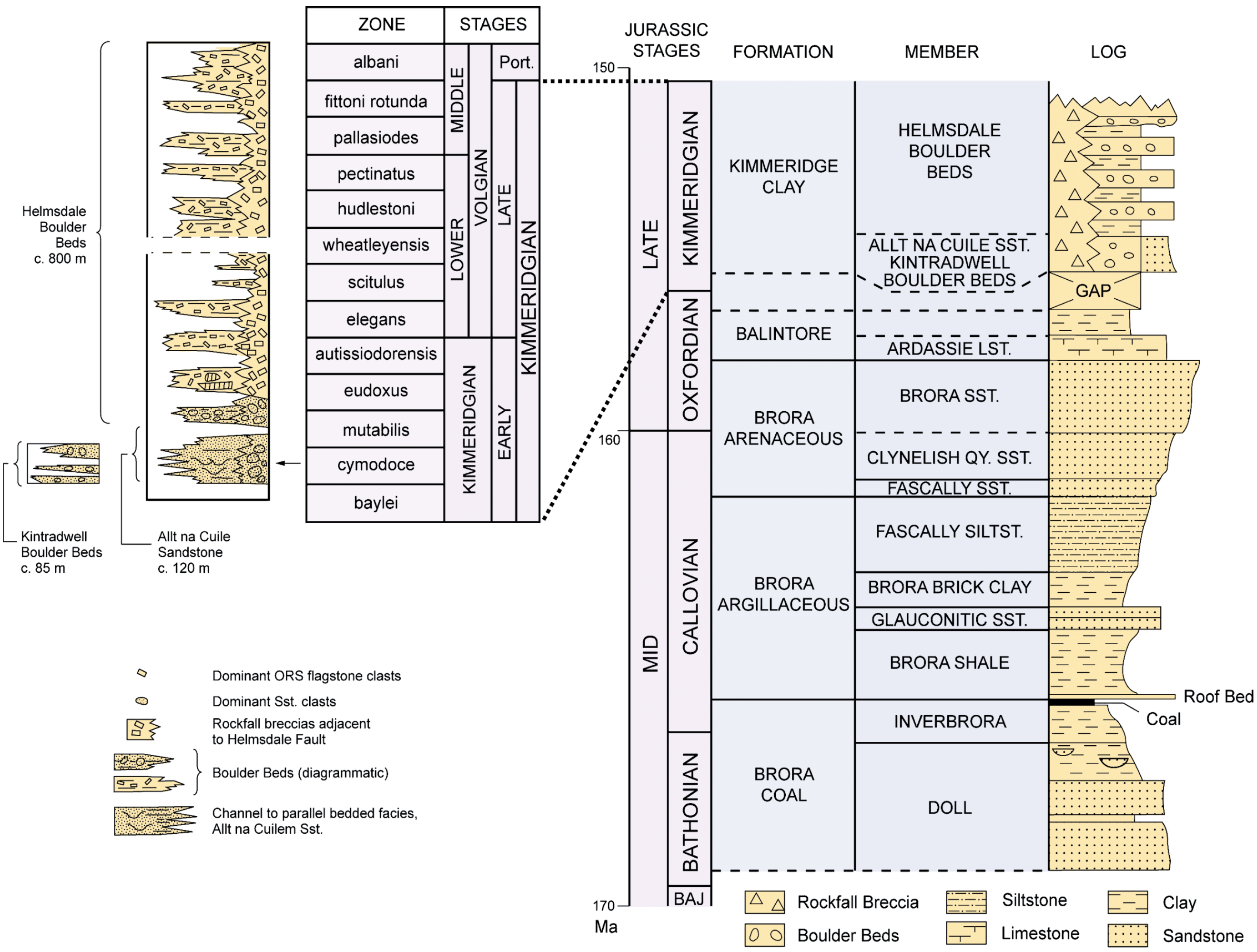

Fig. 2. Stratigraphic succession Brora to Helmsdale (modified after Hudson & Trewin, 2002, figs 11.7 and 11.19).

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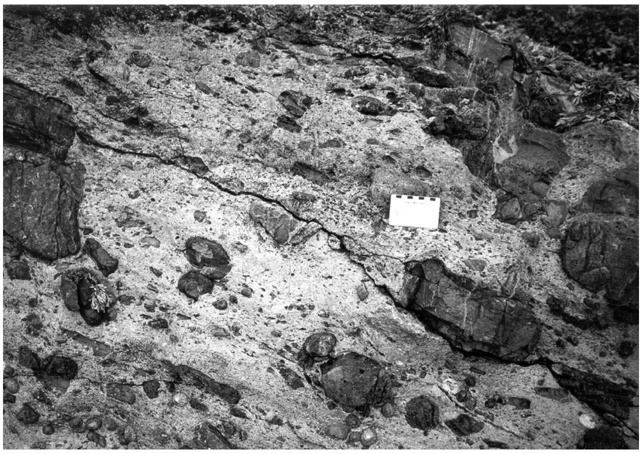
a.



c.

b.

Fig. 3. a. Typical example of the Kintradwell Boulder Beds. (Scale card is 8.5 cm long); b. Example of the matrix-rich boulder beds close to Kintradwell Farm; c. Laminated bioclastic-rich sediments below Kintradwell Boulder Beds; d. Downwarped laminated shales with loadstones below Kintradwell Boulder Beds. Scale is given by 2.6 cm diameter coin; e. Helmsdale Boulder Beds with intercalated laminated shales.

d.

e.

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Palaeogeographical Context of the Brora-Helmsdale Site within the North Sea Basin

Within the context of the North Sea Basin, the sites examined between Brora and Helmsdale are part of a northwestern fringe of Kimmeridgian Late Jurassic sediments that extend across parts of the northern half of the North Sea Basin (Figs 2 and 4) (Ziegler, 1990). The conglomerates (boulder beds) of the Kimmeridgian that extend eastward into the Moray Firth Basin appear, however, to be relatively localized extending out into the basin only a few kilometres east from the downfaulted edge of the Helmsdale Fault (HF) (Fig. 1) (Hudson & Trewin, 2002). Farther eastward the Kimmeridgian sediments can be found to considerable depths within the Viking Graben and possibly almost as far south as the North Netherlands Trough (Fig. 4) (Ziegler, 1990). Late Jurassic Oxfordian age sediments are found within the southern portion of the North Sea extending across the central and eastern part of England and there is some infill within the West Netherlands Trough through the central part of the Netherlands where these Late Jurassic sediments are generally limited to local calcareous and sandy shales. There is no evidence in the Netherlands, for example, of Kimmeridgian age sediments (Ziegler, 1990). The palaeogeographical data show that over the Jurassic and Early Cretaceous periods, the North Sea region occupied a mid-latitudinal position (Ziegler, 1990; Abbink et al., 2001). This late period within the Jurassic, however, exhibits localized and regional basin subsidence across the basin (Ziegler, 1990). Such instability in the form of faulting and localized basin subsidence resulted in thick clastic sediment packages often confined to small areas adjacent to faults and the edges of sinking troughs.

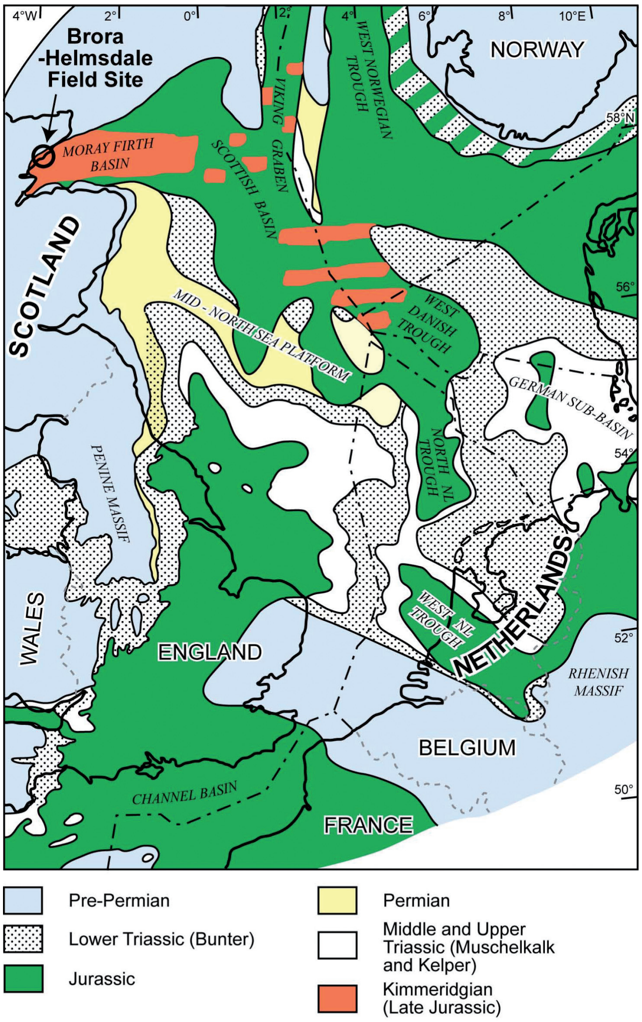


Fig. 4. Palaeogeographic map of the North Sea Basin showing Jurassic sediment distribution and the location of the Brora-Helmsdale field site in relation to Kimmeridgian Upper Jurassic sediments (modified from Ziegler, 1990).

Stratigraphy of the Pleistocene Diamicts from near Milton, southern Ontario, Canada

The diamicts from Ontario were deposited during the Pleistocene by the Laurentide Ice Sheet during the Late Wisconsinan within the Trafalgar Moraine. The moraine, trending approximately southwest to northeast, is located approximately 10 km to the southeast of Milton, in southern Ontario, Canada (Fig. 5). These sediments have been mapped as being part of the Halton Till complex (Barnett, 1992) within the Trafalgar Moraine deposited from an ice lobe advancing northwest out of the Lake Ontario. As the ice moved to the northwest it seems likely that the basal ice scavenged both glaciolacustrine proglacial sediments and coarser outwash glaciofluvial sediments. This diamicton (QDmm) contains a wide range of clast sizes and sub-lithofacies units. The matrix is fine grained, reddish brown in colour, with evidence, in hand specimen, of folded units, dropstone-like clasts and, in places, strong fissility. The diamicton is dominated by Palaeozoic clasts of local origin (86%) with a small percentage of exotic clasts typically from the Precambrian Shield to the north and northeast. This diamicton has previously been classified as a subglacial lodgement till (cf. Karrow 1987, 1989) and later re-interpreted as part of the Halton Till Complex but still a lodgement till (Barnett, 1992). More recently it has again been re-examined and interpreted as a deformation diamicton or tectomict (cf. Menzies et al, 2006; Eyles et al., submitted).

Sampling and Thin-section Production

Representative samples were obtained from both Jurassic diamictites (KBB, HBB) at locations shown on Figure 1. The diamictite samples were removed from in situ rock faces and

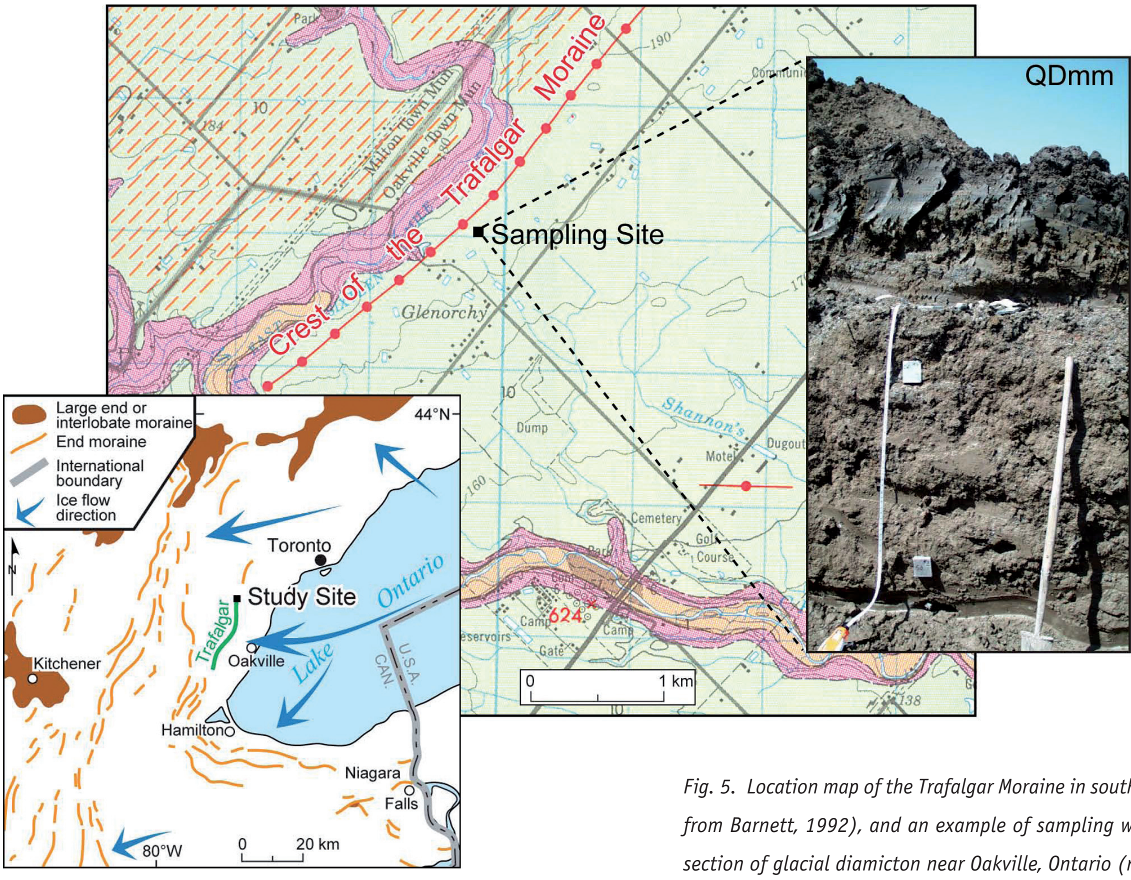


Fig. 5. Location map of the Trafalgar Moraine in southern Ontario (modified from Barnett, 1992), and an example of sampling with Kubiëna cans in a section of glacial diamicton near Oakville, Ontario (note shovel for scale).

exposures with orientation marked on them and later transported to the lab for thin-sectioning. The Quaternary diamicton samples (QDmm) from the Trafalgar Moraine were obtained from several borrow pits dug across the moraine surface and were obtained using Kubiëna cans inserted into the pit face (Fig. 5). The samples were wrapped in plastic, marked with an orientation and transported to the lab for standard soft sediment impregnation and thin-sectioning (Kemp, 1985; Boës & Fagel, 2005). In both cases a sampling strategy was adopted that took into account both the general nature of the diamicts and visible structural features and facies contacts.

In all 35 thin-sections (5 × 7 cm) were obtained from the Jurassic KBB and HBB diamictites, 17 from KBB, and 18 from HBB. Since many diamictite samples were friable, several samples had to be impregnated with epoxy resin prior to thin-sectioning (Camuti & McGuire, 1999). The Pleistocene diamicton samples (QDmm) resulted in 28 thin-sections being produced.

Microstructures within the diamicts

Examination of the diamicts from KBB, HBB and QDmm, in thin-section, reveal many remarkably similar features, especially the characteristics of the matrix, clast sizes, clast shapes and packing densities, and the types, variety and geometry of microstructures. Thin-sections were analysed with the aid of a low-magnification petrological microscope with a field of view of approximately 400 mm^2. Each thin-section, approximately 5 × 7.5 cm in size, was subdivided for examination into 4 to 6 frames (each frame being approximately 200 mm^2) (Fig. 6a) depending on how much of the thin section was *filled* with sediment. In order to assess all the attributes, in a frame by frame examination, results from 2 horizontally adjacent frames (double-frame (approx. 400 mm^2)) were summed. The results yielded 41 double-frame summations from each of KBB and HBB, and 40 double-frames from QDmm. Such numbers permit quantitative statistical assessments to be made and statistically significant results obtained (Table 1 and Graph 1).

Table 1 is a non-summative compilation of results established by counting the presence of specific structures and attributes for each thin-section double-frame. The tabulations comprise the following specific microstructures and characteristics: *viz.* short distance lineations (sdl), single lineations (ls), multiple directional lineations (lmd), rotational structures (rt), edge-to-edge grain crushing (ee), subangular clast fragments (<15 mm) (sa), subrounded clast fragment (<15 mm) (sr), well sorted, evenly distributed clast fragments within matrix (wsx), necking structures (ne), imbricate structures (im), grain-dominated matrix (gmx), clay dominated matrix (cmx), and grain line stacking

Table 1. Presence of microstructures and other sedimentary microtextural attributes within examined diamictite/diamicton thin-section frames from near Helmsdale, Scotland and near Milton, Ontario, Canada.

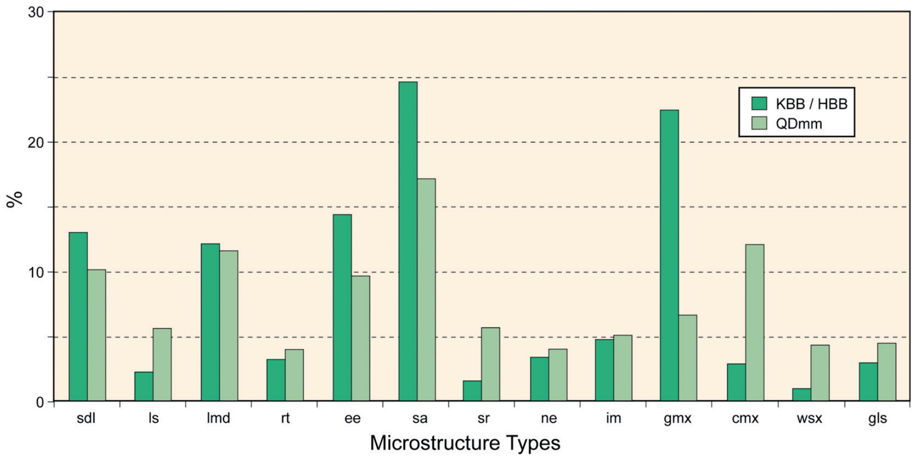
Microstructure Type	KBB	HBB	QDmm
single lineations (ls)	19	22	20
multiple directional lineations (lmd)	3	4	11
short distance lineations (sdl)	17	21	23
rotational structures (rt)	5	5	8
edge to edge grain contacts (ee)	20	27	19
subangular clasts (sa)	38	39	34
subrounded clasts (sr)	3	2	11
necking structures (ne)	5	6	8
imbricate structures (im)	8	7	10
grain-dominated matrix (gmx)	35	36	13
clay dominated matrix (cmx)	4	5	24
well-sorted clasts in matrix (wsx)	-	3	8
grain line stacks (gls)	5	4	9

(gls) (cf. Menzies, 2000a; Van der Meer et al., 2003). Graph 1 shows the percentage of each microstructure type identified in an averaged value for KBB and HBB from a total of 316 individual microstructures, and for QDmm for 198 individual microstructures.

In many thin-sections, short distance lineations (discontinuities) (sdl) can be detected that stretch within the matrix for no more than 15mm (Figs 6b, d, e; 7a, b). These lineations typically are internal to any area of matrix never touching adjacent larger clasts and appear to be the result of short distance local readjustments of sediment either during stress application or due to localized stress relief. Lineations, both single (ls) and multiple directional (lmd), occur within larger matrix units than short distance lineations (sdl) (Figs 6b, d, e; 7a). Most of these longer lineations cross the matrix area between large clasts and can be traced for several millimetres often across small clasts into adjacent matrix areas. These longer lineations, in many thin-sections, were at approximately 22 - 25° or 75 - 85° to the horizontal. In the case of multiple lineations (lmd), individual lineations were found to cross-cut each other between approximately 10° and 30° or at 80° to 60° (Figs 6b; 11b, c, e). In both cases theses much longer lineations (discontinuities) appear to be indicative of stress application and often give a sense of shear within a larger area of sediment, in some instances these microstructures are symptomatic of localised faulting. Multiple lineations also appear indicative of sediment rotation and stress application from several directions indicating that the sediment has been *turned over* or in some way re-oriented before subsequent stress adjustments have occurred.

Within coarser matrix, clast fragments were observed touching at their edges creating edge to edge grain and breakage contacts (ee) are visible. In some cases the broken fragments remain only a short distance from the original clast contact point (Figs 6c; 7a; 8b; 9). These edge to edge contacts, where breakage and grinding has occurred, have been detected in many other sediments where high stress levels have resulted in significant grain to grain contacts along edge asperities (Van der Meer, 1993, 1996; Van der Meer at al., 2003; Hart, 2006; Larsen et al., 2006; Menzies et al., 2006; Phillips, 2006; Lee & Phillips, 2008).

In places rotational structures (rt) were detectable but only in large matrix areas (>225 mm^2) (Figs 6e; 11a-d). It is possible that there is a minimal matrix area below which there is insufficient space for rotational structures to develop (Hiemstra & Van der Meer, 1997; Hiemstra & Rijsdjik, 2003; Hart, 2006; Larsen et al., 2006). These rotational microstructures are indicative of ductile deformation occurring within the sediment during progressive non-pervasive motion in which different components of the sediments revolve around *sticky points* indicative of fluctuating porewater content and effective stress levels within the deforming sediment. It is a common characteristic of deforming multi-phase component sediments that in *motion* rotation occurs resulting in microstructure development.



Graph 1. Percentage of each microstructure type identified in and averaged summation of KBB and HBB, and for QDmm (abbreviations are as shown in Table 1).

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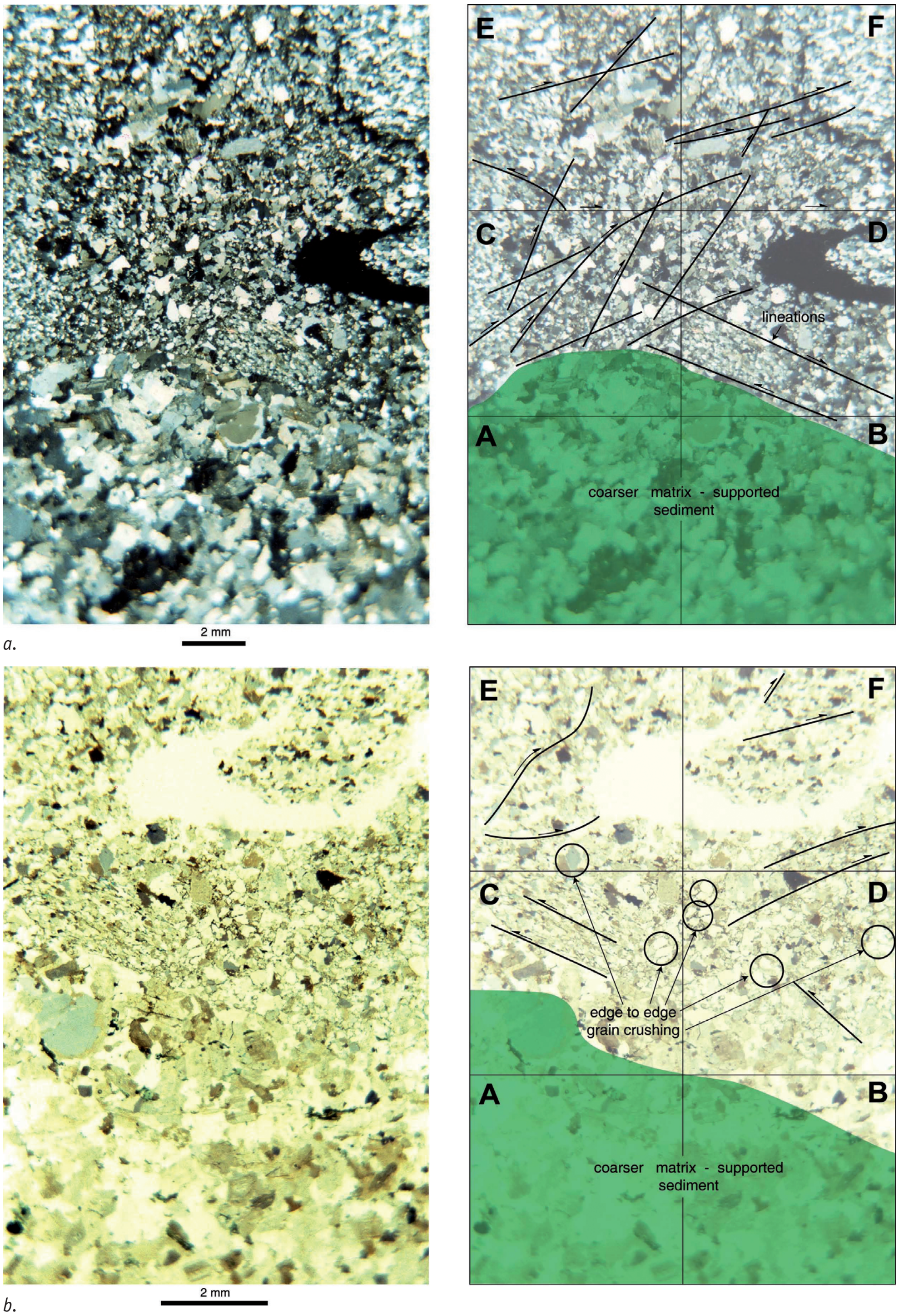

Fig. 6. Photomicrographs of KBB2-A. a. General photograph of thin-section, note schematic diagram overlying right hand thin-section showing Frames (A-F); b. Note large number of short distance lineations (sdl), many of which are cross-cutting; c. Edge to edge grain (ee) breakage shown in central zone; d. Note grain line stacking (gls), bending of grain line stacks (gls) and short distance lineations (sdl); e. Note necking structures (ne), grain line stacks (gls) and short distance lineations (sdl). Bar scale is shown on all photo-micrographs.

For the purposes of this paper, clast fragments are defined as particles >15 mm in diameter embedded within the matrix. Both subangular (sa) and subrounded (sr) clast fragments occur in the thin-sections (Pettijohn, 1975, p. 177) (Figs 7a; 8a, b; 9). In two instances, (Figs. 7a; 8), the matrix exhibits a remarkably well sorted and even distribution of clast fragments within matrix (wsx).

In a few cases necking structures (ne) were detected within matrix where small clast fragments had apparently been *squeezed* between large clasts indicative of ductile sediment plastic deformation (Menzies, 2000a; Lachniet et al., 2001) (Figs 6e; 7b). A common occurrence, within many of the samples, is the close packing of medium to larger sized clast of an imbricate nature within the coarse matrix (im) (Figs 8a, b; 9). These structures appear symptomatic of close packing of grains following on from plastic deformation. Likewise, some samples exhibit a grain-dominated matrix (gmx) with little or no clays present. A common attribute of many samples was the presence

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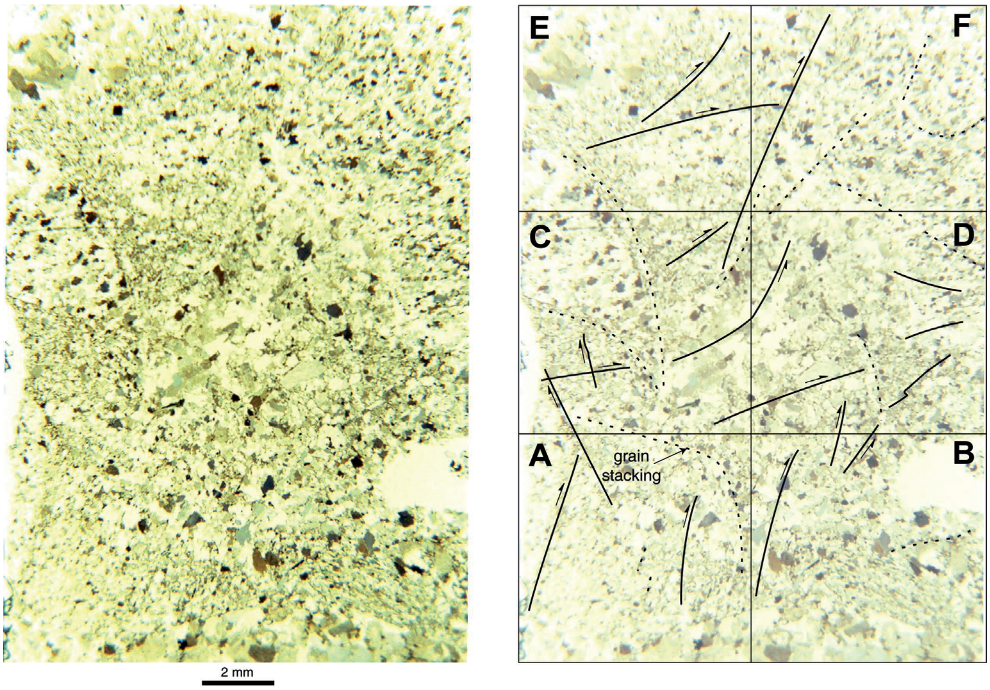

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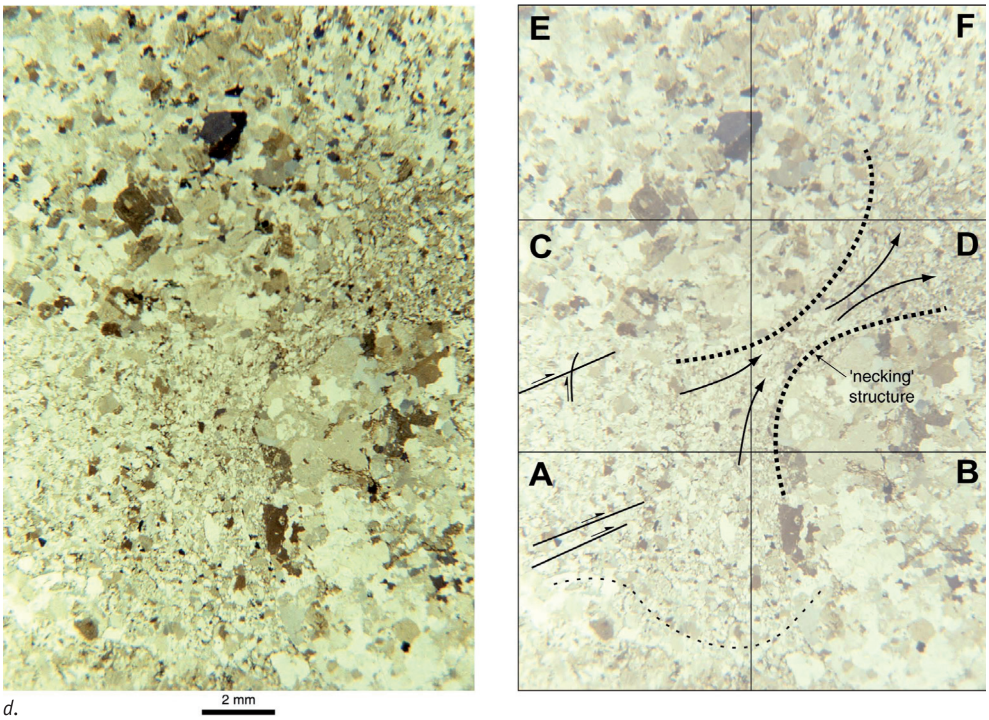
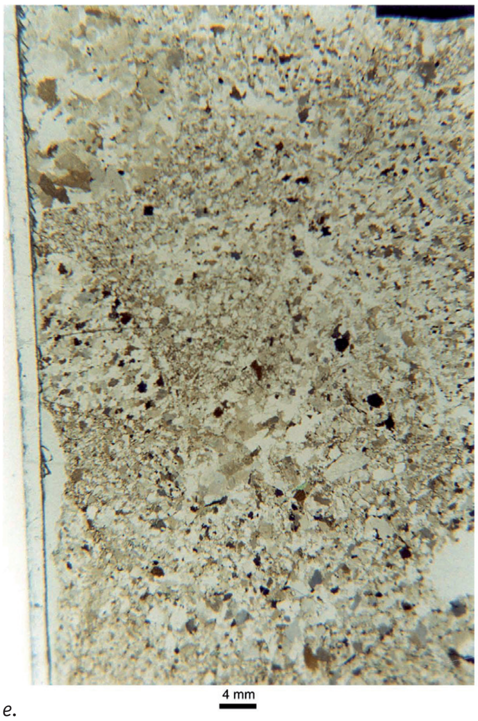
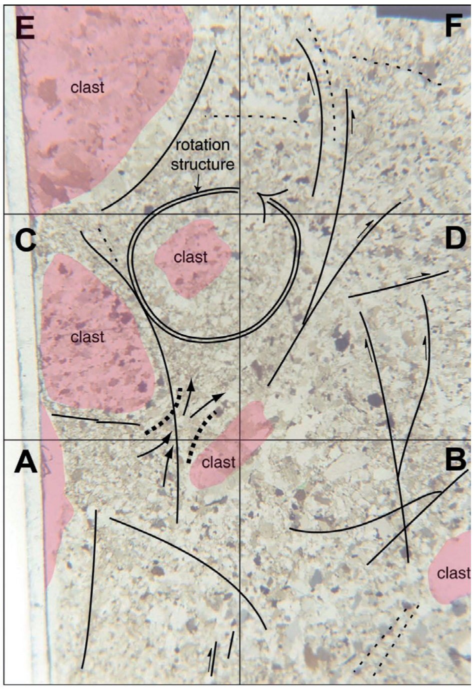


d.

of grain line stacking (gls) where lines of small clast fragments can be detected touching in vertical or horizontal lines (Figs 6d, e; 11a, d, e). In a few instances the stacked lines curve but remain in contact (Fig. 6d). The presence of grain stacking is clearly indicative of either localized discontinuities forming and grains adjusting along those lines of sediment failure or, as deformation occurs, a *streaming-out* of smaller grains occurs within the deforming sediment matrix.

In general, no single microstructure found in these diamicts can be used as a diagnostic differentiating attribute. Only in combination, as an assemblage, do these constituent elements indicate or give strong clues as to the processes involved in the deposition or emplacement of these diamicts. To determine diagnostic criteria on which an interpretation can be achieved, a statistical assessment was made of microstructures present in all sampled thin-sections (Carr, 2000; Menzies, 2000a; Menzies et al., 2006; Phillips, 2006).

e.

Examples of Thin-Sections from KBB, HBB and QDmm

Examples from KBB (Figs 6a-e; 7a, b; 10a), HBB (Figs 8a, b; 9; 10b) and Qdmm (Fig. 11a-e) are presented here as representative of diamicts. In each case, a diagrammatic cartoon, subdivided into frames, is presented adjacent to photomicrographs of each sample to permit clarification of the structures present in each thin-section.

Thin-Section KBB-2A (Fig. 6) contains several large subrounded clasts and a relatively coarse matrix composed dominantly of small subangular clasts. Figure 6a illustrates the dense nature of this particular sedimentary rock with multiple cross-cutting lineations (lmd). Many of the clasts exhibit evidence of edge to edge crushing events (ee) (Fig. 6b) with either contact crushing being observed in the thin-section, or very small clast fragments of the crushing event seen adjacent to the contact. In Figure 6c grain stacks can be observed (gls), and, in a few locations, stacked grains show slight bending as in the top left corner of the thin-section (Frames C + E). Within Figure 6d in Frame D intrusion of the matrix into a large crack within a large clast can be observed displaying a *necking* structure (see Glossary at end of paper). In Figure 6e a rotation structures (rt) within the matrix can be noted between lineations (the lineations being near-vertical).

Thin-Section KBB-2B (Fig. 7), similar to KBB-2A, contains several large clasts but a much more angular matrix that exhibits a large number of edge to edge crushing events and occasional short distance lineations (sdl) (Fig. 7a). In Figure 7a there are several minor lineations that appear close to medium sized clasts near-which necking (ne) microstructures can be observed (Fig. 7b).

Thin-Section HBB2/2A (Fig. 8) contains a large number of typical structures for the Helmsdale diamictites. Unlike the previous thin-sections, the matrix is variable with both coarse (gmx) and finer (cmx) zones (domains) within the matrix. Many subrounded small clasts occur within the matrix. In Figure 8a a series of larger clasts are relatively adjacent and small short distance lineations (sdl) can be observed. Where larger clasts dominate, edge to edge crushing (ee) events can be observed (Fig. 8b).

Thin-Section HBB2/2B (Fig. 9) contains a series of closely adjacent larger subrounded clasts with a coarse matrix dominated by small subangular clasts. Evidence of edge to edge crushing (ee) and crude lineation can be seen in many frames. In Frame A, evidence of clast imbrication (im) can be observed. A domain of finer matrix (cmx) surrounds some of the large clasts and between the larger clasts necking structures (ne) can be observed in Frames C and F.

Thin-Sections KBB-2B/1 (Fig. 10a) and HBB1/2 (Fig. 10b) are examples of bioclastic facies units that are found interfingering many of the diamictic KBB and HBB units. The thin-section shown in Figure 10b contains a large number of crudely aligned near-horizontal angular shell fragments.

Thin-Section QDmm HT/1d4 (Fig. 11) illustrates a subset of thin-sections where a brown coarser banded matrix predominates

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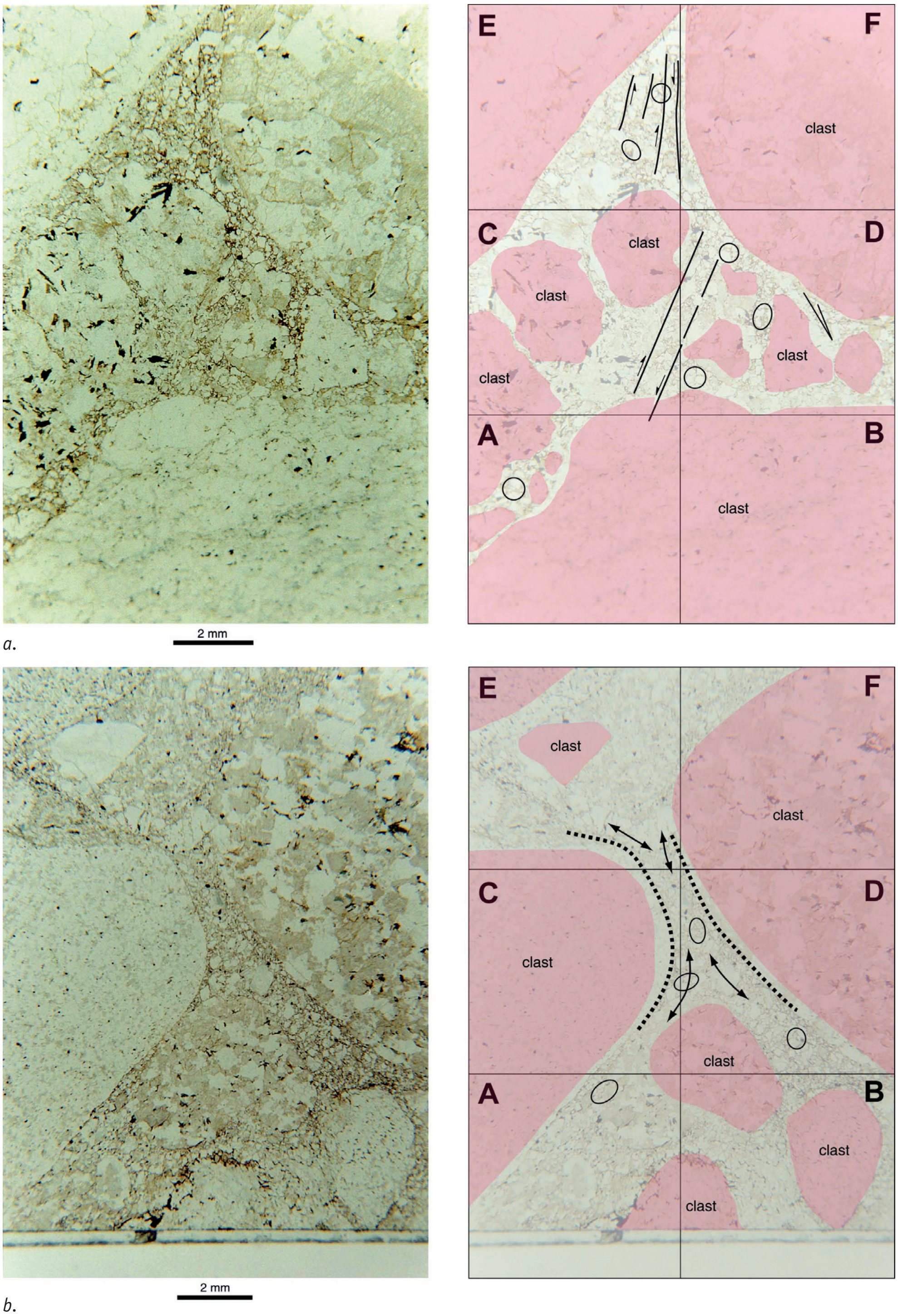

Fig. 7. Photomicrographs of KBB2-B. a. Note edge to edge grain contacts (ee) and short distance lineations (sdl) structures; b. Note necking (ne) and edge to edge grain contact (ee) structures.

with well rounded clasts, many of grey Palaeozoic dolostone origin. In Figure 11a a series of crudely aligned short distance lineations (sdl) can be observed along with a several large rotation structures (rt). Within Figure 11b, in Frame A, some fine matrix material (cmx), rotational structures (rt), multiple lineations (lmd) occur while slight banding at the top of the frame, can be observed in Frames B, C and D. In Frame B, similar to Frame A, much stronger lineations with three directions are evident at 45° to the vertical in the northeast quadrant, 45° to the vertical in the northwest quadrant and a third lineation, perhaps Riedel shears, at 67° to the vertical in the northwest quadrant. In Figure 11c several small clasts exhibit alignment in Frames A and B and appear linked to bracketing lineations. Other cross-cutting lineations (lmd) can be observed in Frames C and B. In Figure 11d there are two *till pellets* or *clots* to the left of the centre of the thin section. Likewise this thin section contains numerous short distance lineations (sdl), grain stacks (gls) and evidence of edge to edge grain crushing events (ee).

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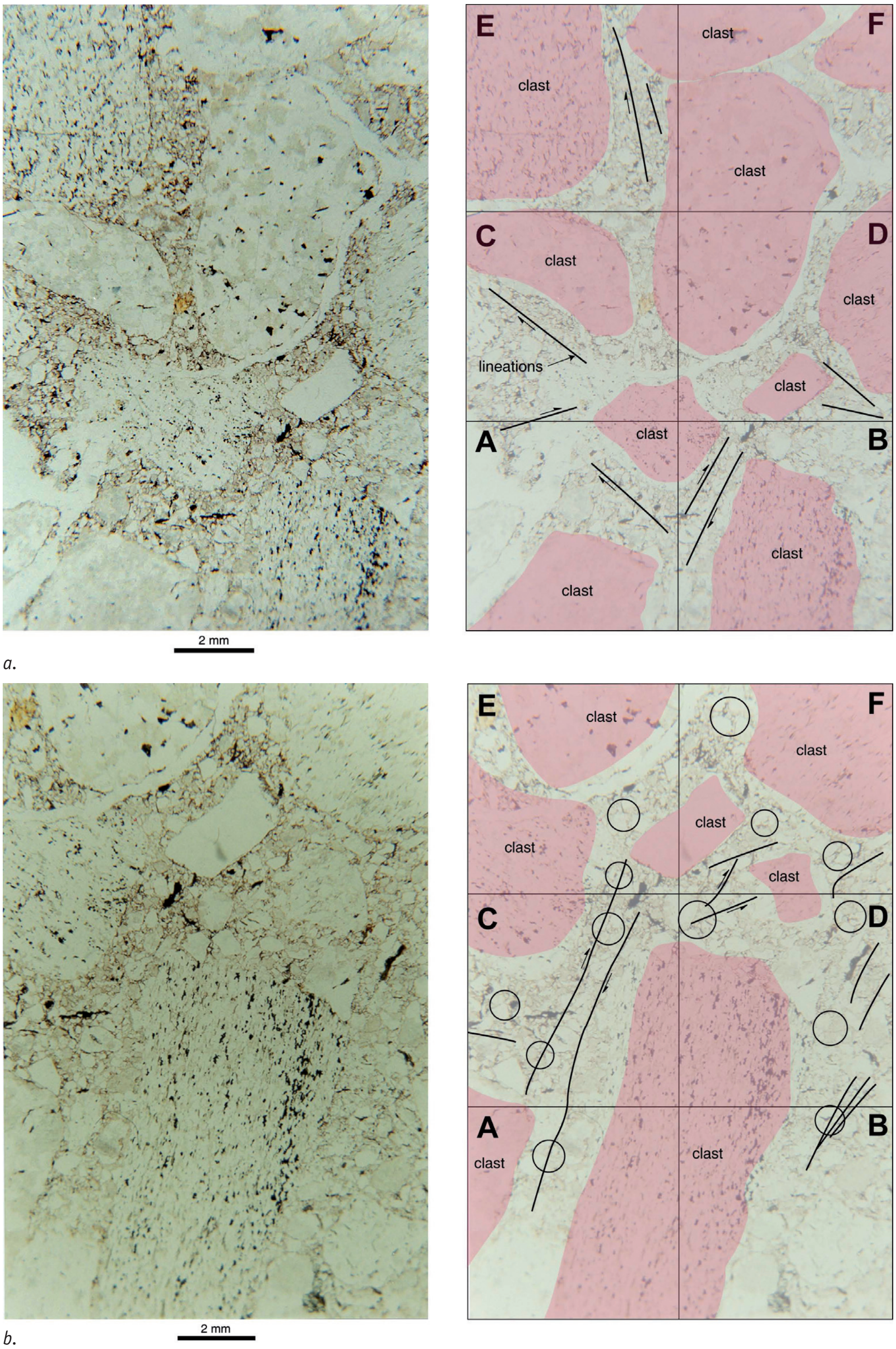

Fig. 8. Photomicrographs of HBB2/2A. a. General photograph of thin-section showing the coarse angular fragments within the finer matrix, note imbrication; b. Note large number of edge to edge grain contact structures (ee) and short distance lineations (sdl) microstructures.

Figure 11e shows a dense matrix dominated sediment with many crudely aligned short distance lineations (sdl), with paralleling grain stacks (gls). This thin section exhibits a strong directional orientation of grains and lineations. There are two dominant lineation directions at approximately 80° to each other.

The microstructures, within the KBB and HBB and QDmm reveal extensive evidence symptomatic of varying levels of deformation from localised intense deformation (as exemplified by necking structures, and rotation structures) resulting from ductile deformation, to other locations where rapid local changes in stress levels resulted in brittle fracturing (as exemplified by lineations, faulting and angular fragmentation of subunits within thin-sections). In all cases, the diamict matrix shows evidence of either fluctuating porewater content or thermal variations from melted to frozen states and/or vice versa (the shifts from ductile to brittle deformation and vice versa) most

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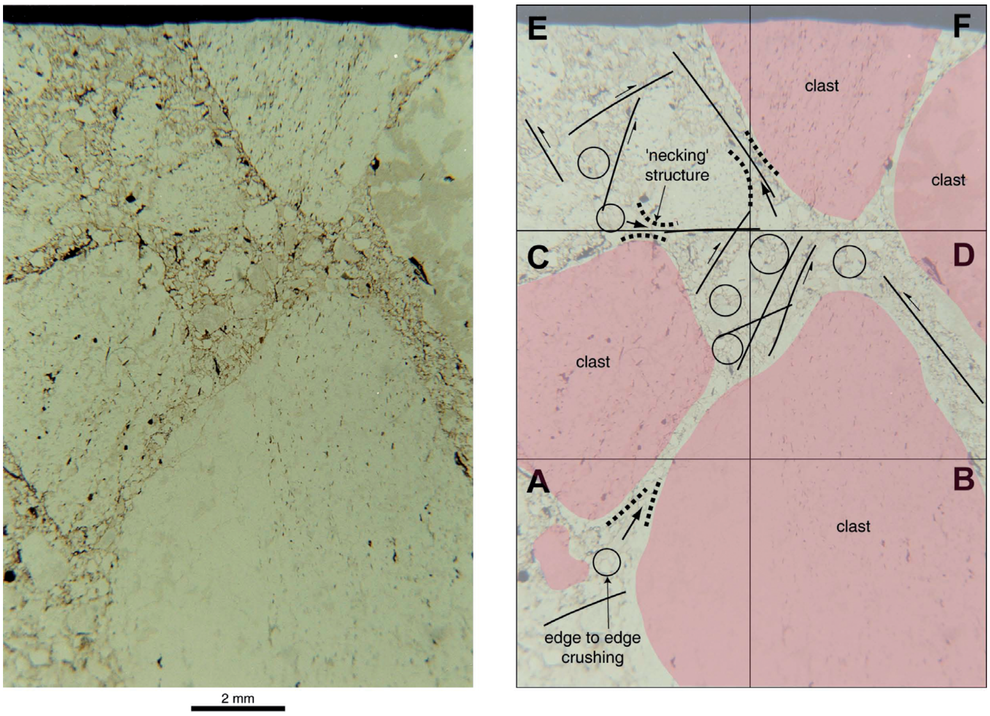
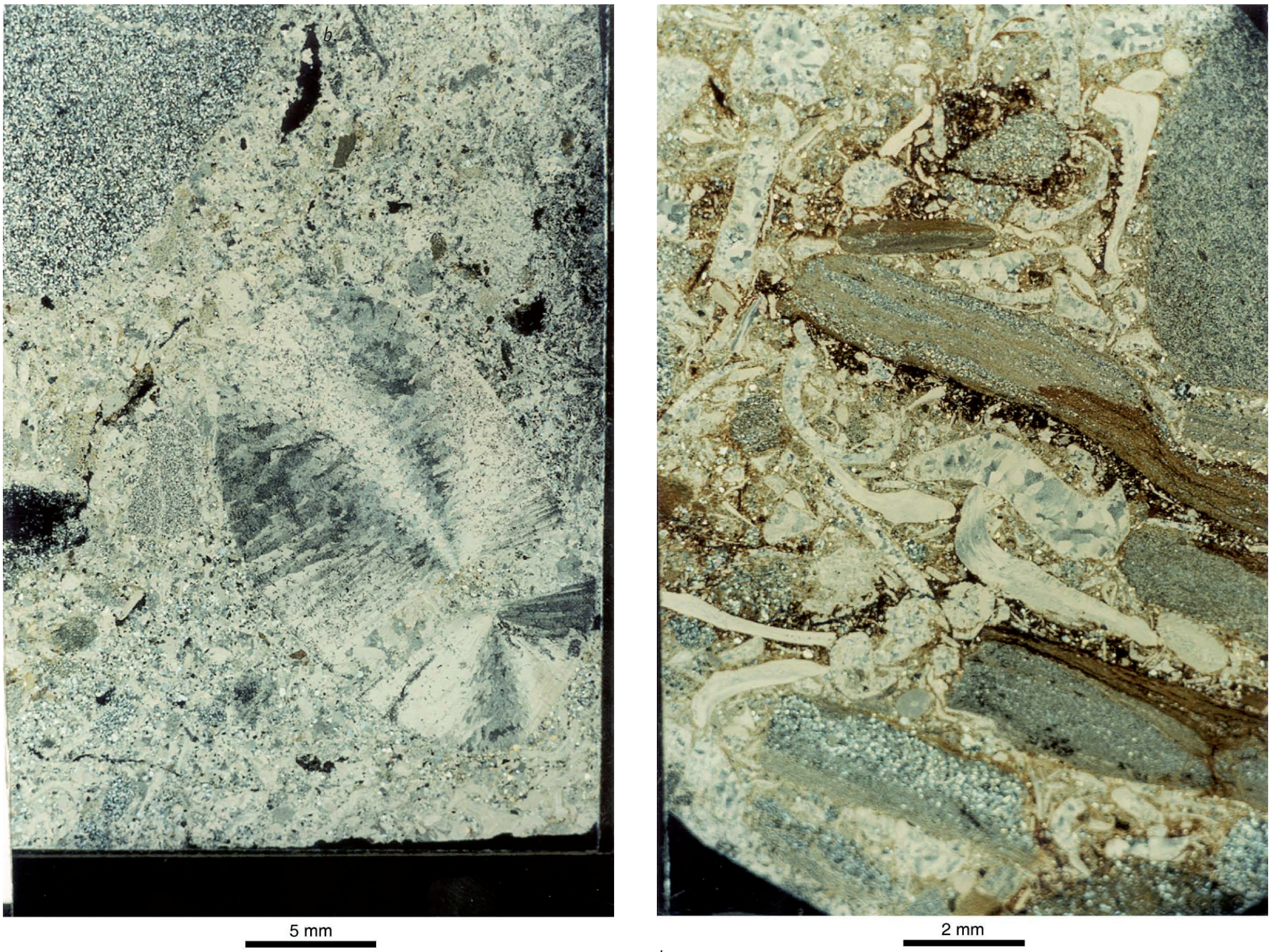


Fig. 9. Photomicrograph of HBB2/ 2B a general photomicrograph of thin-section.



a. *b.*

Fig. 10. Photomicrographs of bioclastic material within the black shales within: a. the Kintradwell Boulder Beds; b. the Helmsdale Boulder Beds.

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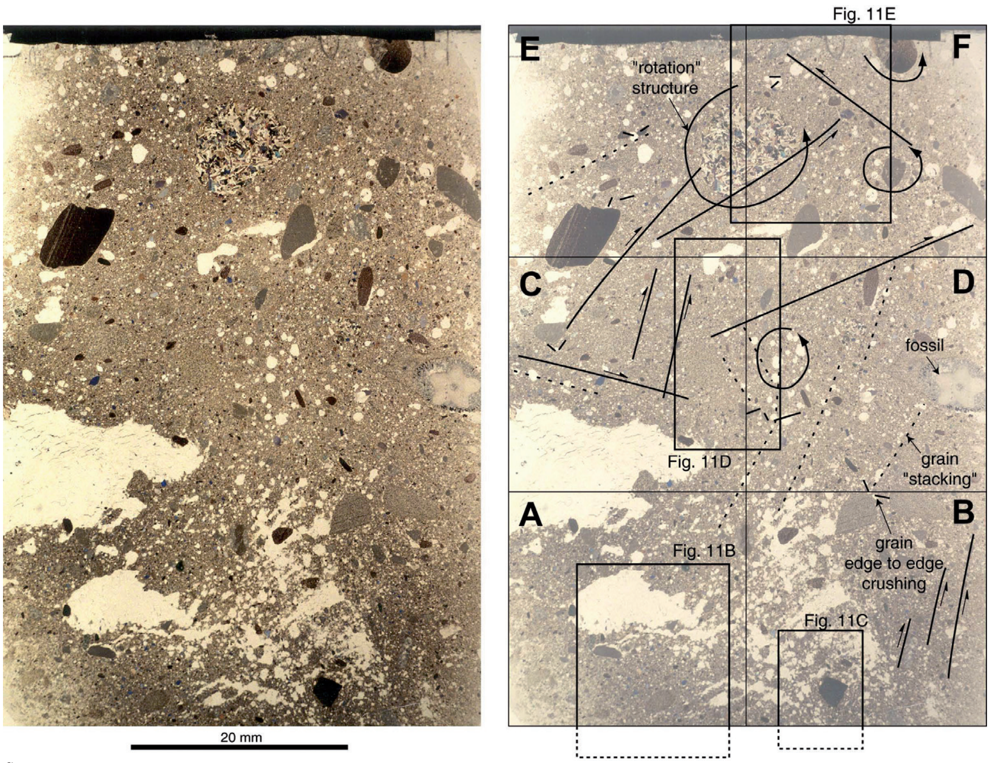
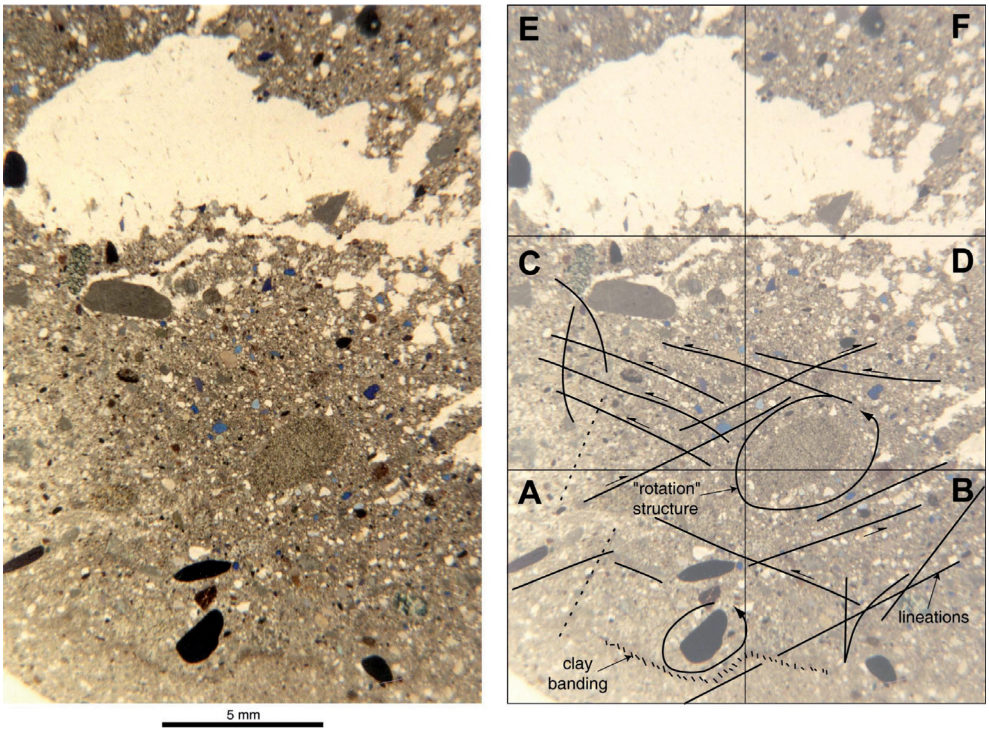


a.



b.

Fig. 11. Photomicrographs of Qdmm. a. General photograph of thin-section note the rotational (rt) and grain line stack (gls) microstructures; b. Note rotational (rt), clay banding and short distance lineation (sdl) microstructures; c. Note large number of multiple directional lineations (mdl); d. Note large till >pellets=, short distance lineations (sdl), grain line stacks (gls) and rotational (rt) microstructures; e. Note large number of short distance lineation (sdl), grain line stacking (gls) and multiple directional lineation (lmd) structures.

likely indicative of changing effective stress levels that altered sediment mobility during and following deposition (Van der Meer, 1996; Menzies 2000; Van der Meer et al., 2003; Menzies et al., 2006; Boulton & Zatsepin, 2006; Larsen et al., 2007; Phillips and Auton, 2007; Lee & Phillips, 2008). The diamicts reveal evidence, from the microstructures, of movement associated with lateral translational stress typical of various styles of mass movement, and subglacial deformation (cf. Bertran & Texier, 1999; Lachniet et al., 2001; Menzies & Zaniewski, 2003; Larsen et al., 2006; Phillps, 2006; Thomason & Iverson, 2006; Bardou et al., 2007; Phillips & Auton, 2007). There appears to be no evidence of endogenic stress application as a result of seismic or tectonic stress fluctuations (cf. Scott and Price, 1988; Stewart et al., 2000; Matsuda, 2000; Menzies & Taylor, 2003).

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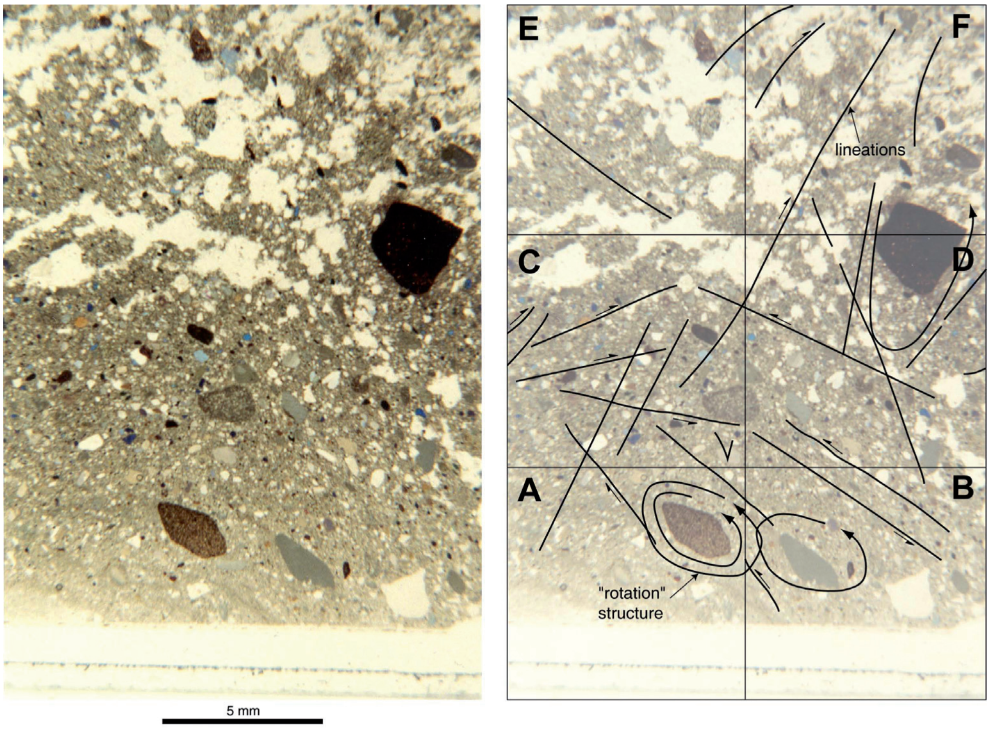
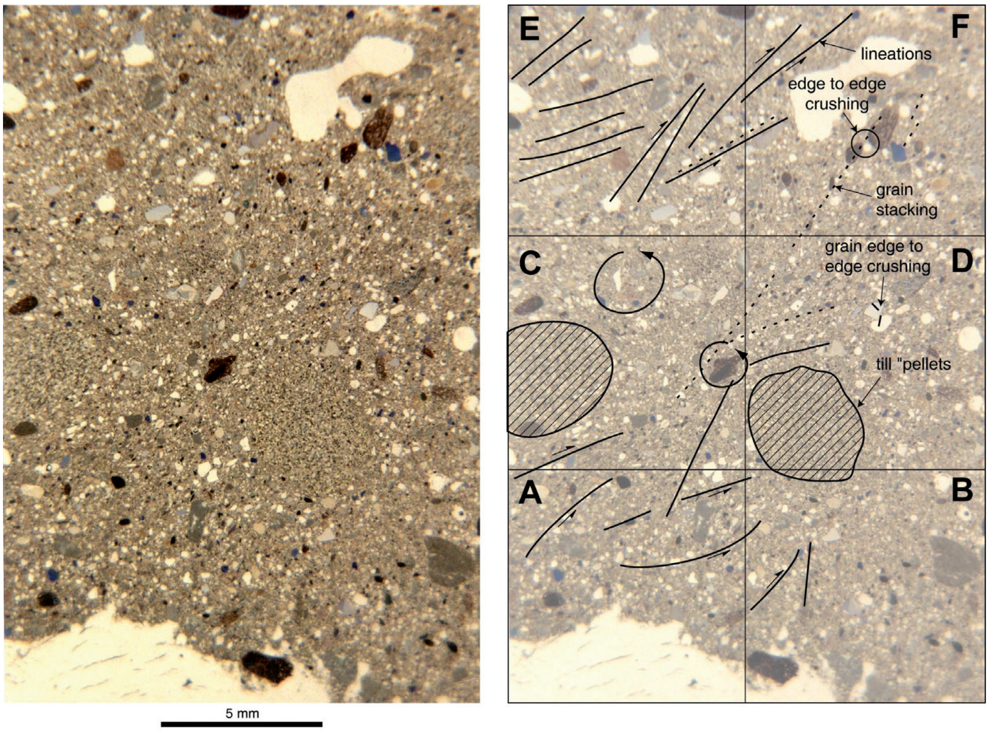


c.



d.

Statistical Analyses of Microstructures within the Diamictites

Statistical analyses of the data from Table 1 were done in which null hypotheses were posed such that “there was no statistical difference between any two of the sample data sets”. A simple Chi-square test (df = 12) was performed on all data sets resulting in a $\chi^2 = 4.39$ for KBB on HBB samples, $\chi^2 = 42.64$ for KBB on QDmm samples, and $\chi^2 = 36.67$ for HBB on QDmm samples. These results establish that the null hypothesis can be accepted with a 99% confidence limit for the KBB on HBB samples alone. The hypothesis for the KBB and HBB samples independently tested on QDmm samples was not accepted even at the 0.01% confidence limit. In statistical terms, therefore, it can be stated that

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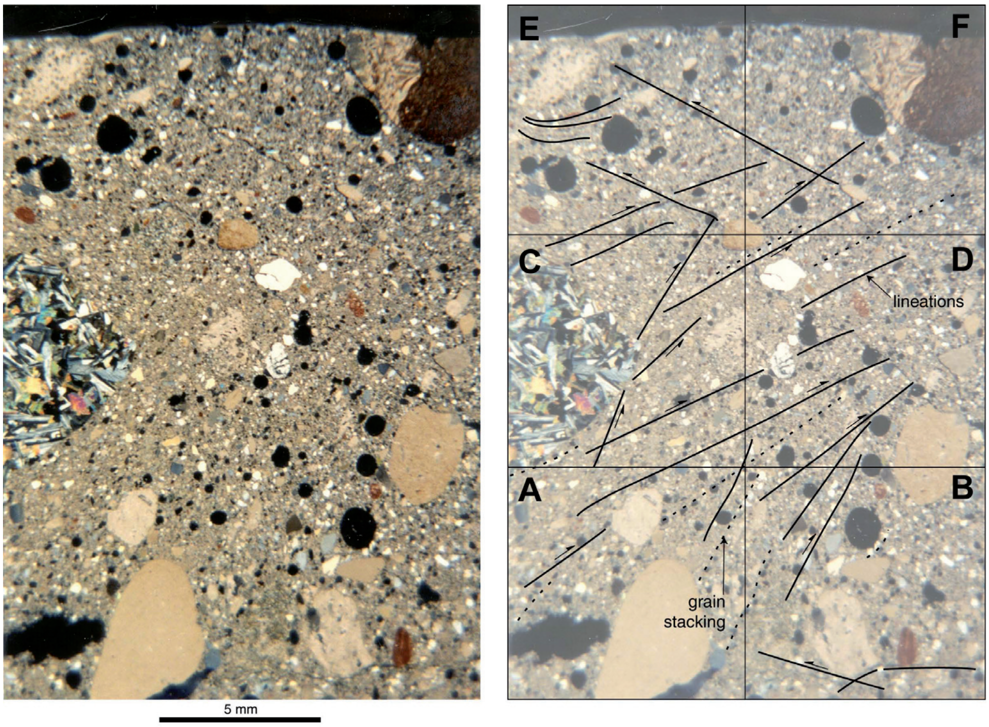

e.

the KBB and HBB samples would appear to be sub-populations of the same larger population whereas the samples of QDmm are from a different population set. These statistical results are, therefore, in agreement with the known fact that the QDmm samples are a glacial diamicton and both the HBB and KBB samples, from a Jurassic marine diamictite; a fact that has been qualitatively argued but can now be shown to be statistically valid.

From Table 1 and Graph 1, the Pleistocene diamicton (QDmm) has, in comparison to the Jurassic diamictite (KBB and HBB) samples, many more multiple directional lineations (lmd) (5.6% to 2.2%), subrounded clasts (sr) (5.6% to 1.6%), clay matrix rich (12.1% to 2.9%), a well sorted matrix (wsx) (4.4% to 1.0%) and grain line stacks (gls) (4.5% to 2.9%). In contrast, KBB and HBB samples (averaged) have more edge to edge crushing events (ee) 14.4% to 9.6%), subangular clasts (sa) (24.6% to 17.2%), considerably more common grain-dominated matrix (gmx) (22.5% to 6.6%), and a much fewer number of domains of clay-dominated matrix (cmx) (2.9% to 12.1%). Finally, the percent number of rotational structures (rt), short distance lineations (sdl), single lineations (ls), necking structures (ne) and imbricate structures (im) are remarkably similar for both groups of sediment.

Interpretation of Microstructures within the Diamicts

The differences between the two sets of diamictites and the diamicton are, in thin-section, subtle but statistically significant. Both KBB and HBB diamictites contain microstructures indicative of syngenetic deformation during deposition. Deformation appears to have been both ductile (microstructures: 'rt', 'ne', 'gls') and brittle (microstructures: 'ls', 'lmd', 'sdl', 'ee', 'im') indicative of variations in porewater content and pressure fluctuations, and/or increased dilatancy, or considerable thermal changes of state, or rapid changes in applied external stress levels (Menzies, 2000a; Phillips & Auton, 2000, 2007; Lachniet et al., 2001; Phillips, 2006; Larsen et al., 2006; Thomason & Iverson, 2006; Larsen et al., 2007; Menzies & Brand, 2007). Compaction during deposition is exemplified by edge-to-edge ('ee') compression and grain grinding. Compaction and lateral adjustments can be seen in linear discontinuities ('ls', 'lmd', 'sdl'). Some are internal and localised thus producing short, within matrix, forms ('sdl'), whilst others are related to larger lateral movements that transgress larger areas of matrix ('ls'). The lineations may exhibit evidence of either multiple directions of stress induced strains or sediment rotation and repeated stress application. In some locations the sediments have undergone rotational deformation ('rt'), evidence of high strain within localised areas of the diamict. As previously noted, rotational structures only appear to occur in those areas where matrix *patches* >15 mm in approximate diameter. It is possible that in smaller areas rotation either does not develop or that stress levels, when bridging such small areas, do not result in rotational deformation (cf. Hiemstra & Van der Meer 1997; Hiemstra & Rijsdijk, 2003). Rotational structures may also be indicative of sediment being stressed from various directions possibly indicating sediment *tumbling* during the depositional process (cf. Hiemstra & Van der Meer, 1997). The KBB and HBB samples have rotational structures, multiple directional lineations, and little other evidence of strong ductile deformation. However, ductile deformation did occur, though of limited extent, in small areas of the sediment; while strong evidence of brittle structures in the form of edge to edge grain crushing and short distance lineations (possibly the result of limited grain to grain readjustments) are widespread (Phillips & Auton, 2000, 2007; Larsen et al., 2006). There is little evidence in KBB and HBB samples of porewater-induced microstructures such as water escape structures or strong cutanization within voids. In general, limited deformation appears to have occurred of a relatively low intensity and non-pervasive nature. The KBB and HBB samples reveal deposition or emplacement within an environment in which porewater induced motion was limited, yet ductile and strong brittle deformation processes were active.

Diamictites formed as a result of mass movement, whether as dry debris flows or saturated mudslides, exhibit an assemblage of structures indicative of translational movement across either the earth's surface or across a lake or sea bed (cf. Jenner et al., 2007). It is apparent that the velocity of motion, particle size composition and especially porewater content greatly influences the nature of the mass movement of sediment; such that high numbers of edge to edge grain crushing events can be expected to occur with few, if any, ductile deformation structures likely present. In contrast, those mass movements, in which high water contents are present, may exhibit more evidence of ductile deformation in the form of necking structures, rotation structures and curved grain stacks (Maltman, 1988; Bertran, 1993; Bertran & Texier, 1999; Lachniet et al., 2001; Menzies & Zaniewski, 2003). In mass movement sediments, since there is a relatively low overburden pressure (or in the case of subaqueous mass movement, high effective pressures alleviate the impact of pressure from the water column on individual grains) other than overlying sediment, rotational structures, and multiple lineations can be expected to be fewer in number than in diamicts formed beneath an active ice sheet. Due to the nature of the mass movement sediment flows generally include coherent rafts of local and exotic sediments, forming separate domains, that are entrained on top of, within, and at the base of sediment flows (Menzies & Zaniewski, 2003). Where mass movement occurs subaqueously, porewater content is high and, therefore, porewater motion and structures associated with porewater dissipation (from higher to lower pore pressure areas within a saturated sediment) are likely to be few in number, and of limited extent (cf. Mulder & Alexander, 2001; Jenner et al., 2007).

The Pleistocene diamicton, in contrast, is a typical subglacial sediment (cf. Van der Meer, 1996; Hiemstra & Van der Meer, 1997; Lachniet et al., 2001; Menzies & Shilts, 2002; Van der Meer et al., 2003; Evans et al., 2006; Menzies et al., 2006; Larsen et al., 2006; Phillips and Auton, 2007; Lee & Phillips, 2008). It is interesting to note that the Pleistocene diamicton (QDmm) in comparison to the Jurassic diamictites (KDD and HBB) has commonly more multiple lineation structures (lmd) and subrounded clasts (sr), and slightly more rotation structures (rt) and grain stacks (gls) (Graph 1).

In sharp contrast to mass movement sediments, subglacial sediments exhibit a wide range of structures (Van der Meer, 1993, 1996; Menzies, 2000a,b; Van der Meer et al., 2003; Larsen et al., 2006; Menzies et al., 2006; Larsen et al., 2006) that indicate intense ductile deformation, typically, of non-pervasive deformational conditions. Characteristically, rotational structures, multiple lineations, multiple domains, and porewater escape structures are only a few of the set of structures indicative of subglacial processes, where large overburden tangential stresses due to active ice motion have been applied.

Summary

Micromorphological examination of a large number of thin-sections, including a novel approach in diamict *typing* or *fingerprinting* using statistical analyses, has permitted the palaeoenvironmental reconstruction of the sedimentological conditions under which these various diamicts were deposited. The diamictites, at Kintradwell and Helmsdale, appear to come from the same source, and to have been emplaced under similar, possibly, identical conditions. The microstructural evidence points to subaqueous mass movement, in which relatively short run-outs of gravity-induced sediment movement had occurred within a marine environment. No evidence can be found that can attribute the cause of the mass movement events other than gravitational instability. Whether these mass movements were triggered by seismic events could not be verified in either macro- or microscale examination but the microstructures present would appear to negate such an origin. In contrast, similar macroscopic diamicts from southern Ontario reveal, on the basis on micromorphology, to be of subglacial origin formed beneath an active deforming sediment layer under an ice lobe of the Laurentide Ice Sheet.

This work has permitted a broader examination of diamictic sediments using micromorphology, accompanied by statistical analyses, as another diagnostic tool in palaeoenvironmental reconstruction and sediment type differentiation. Statistical analysis to compare *types* of sediments based upon composite arrays of identifiable microstructures has demonstrated the ability to identify the likely origin and formative depositional and/or emplacement processes of various sediments in terms of summative *type characteristics*. The longer term goals of this *sediment typing* or *micromorphological fingerprinting* will be to allow discriminant comparisons of small sets of sampled sediments against a data bank of already *typed* micro-characteristics from *known* identified sediments.

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Glossary

Cutanization
The development of cutans (argillans) within a sediment. As porewater 'flushes' clay through pores, voids and channels, clay adheres to the walls of these spaces and slowly builds up laminae coatings (termed cutans or argillans).

Plasma
Particles of colloidal size (<2 µm); may consist of clay minerals, oxides and hydroxides of Fe, Al and Mn, soluble salts, etc.

Plasmic fabric
Birefringence models of the plasma, based on the optical properties of the particles as well as the optical properties caused by the orientation of particles relative to each other.

Skelsepic
Plasma particles are oriented around a skeleton grain.

Turbate (rotation)
Areas or zones of microscale deformation composed of both admixtures of plasma and skeleton grains.

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