Macro-structural analysis: unravelling polyphase glacitectonic histories.

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Many Pleistocene glacial profiles look extremely simple, comprising till, or glacitectonite, overlying older sediments or bedrock (Figure 4.1). In more complex sequences the till may itself be overlain by younger sediments laid down as the ice retreated or during a completely separate, later phase of advance. Macroscopically, subglacial traction tills (Evans *et al*., 2007) are typically massive, unstructured deposits suggesting that it should be relatively straightforward to unravel the glacitectonic deformation history recorded by the sequence. Many reconstructions do indeed look very simple, slabs of sediment have been tilted and stacked and then overridden by the glacier to cap the structure with till. Added to this is the use of vertical exaggeration which makes the whole structure look like alpine tectonics (for an example see fig. 5 in van Gijssel, 1987). Dropping the exaggeration led to the recognition that actually we were looking at much more horizontal structures, i.e. overriding nappes and not imbricated slabs (van der Wateren, 1987).

Traditionally (van der Meer, 1987) glaciotectonics was thought to relate to large structures like big push moraines and not to smaller structures like drag structures underneath tills (Figure 4.2), let alone to the tills themselves. With the notion that deforming bed tills are tectonically and not sedimentologically structured and could be regarded as tectomicts (Menzies *et al*., 2006), comes the realisation that glacitectonics happens across a wide range of scales, from the microscopic to tens of kilometres. Only by realising the full range of glaciotectonic scales can we hope to understand the processes.

But it is not just scale. Analyzing tectonic structures must go hand-in-hand with the analysis of the sedimentology of the sequence. Failure of recognizing sedimentary structures and environments automatically leads to a failed understanding of tectonic structures. For instance, within a water-

Figure 4.1. Till cutting-off and covering glaciofluvial sediments, Kemijärvi, Finland

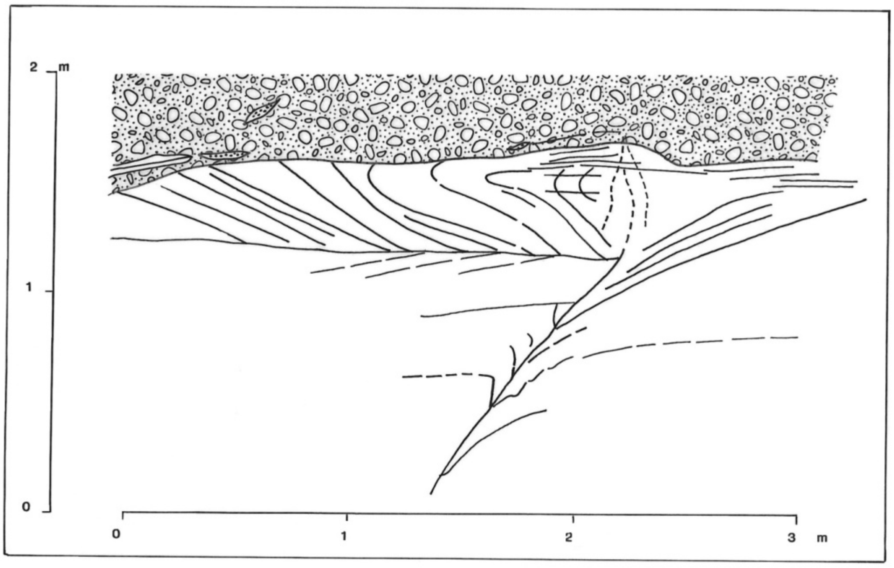

Figure 4.2. Drag structure underneath till, affecting the top of a frost crack. Ice movement left to right. Pit 'de Boer', Emmerschans, the Netherlands

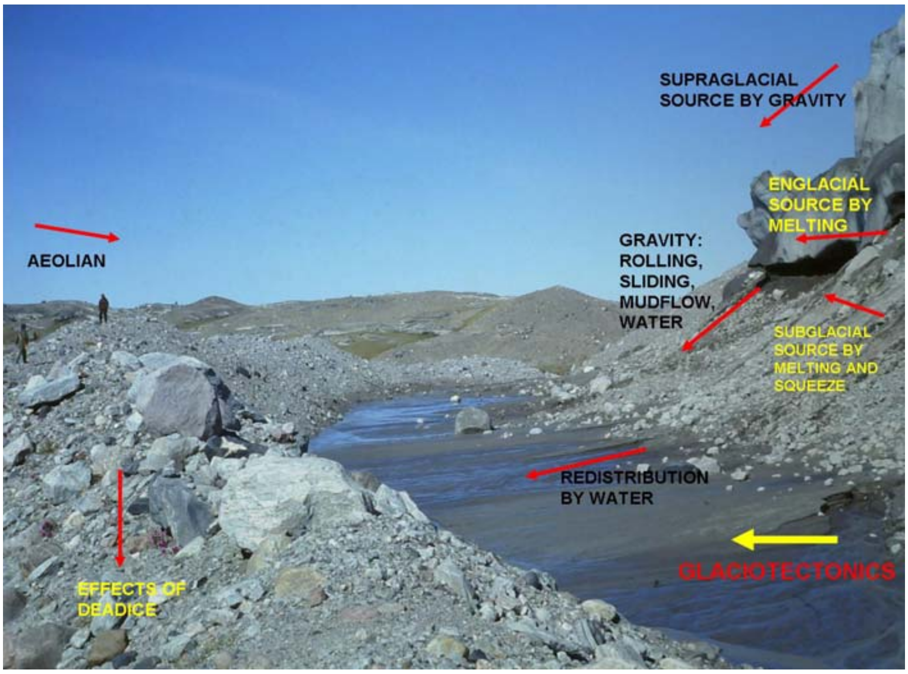

Figure 4.3. Example of the complexity of depositional systems along an ice margin. Leverett Glacier, W Greenland

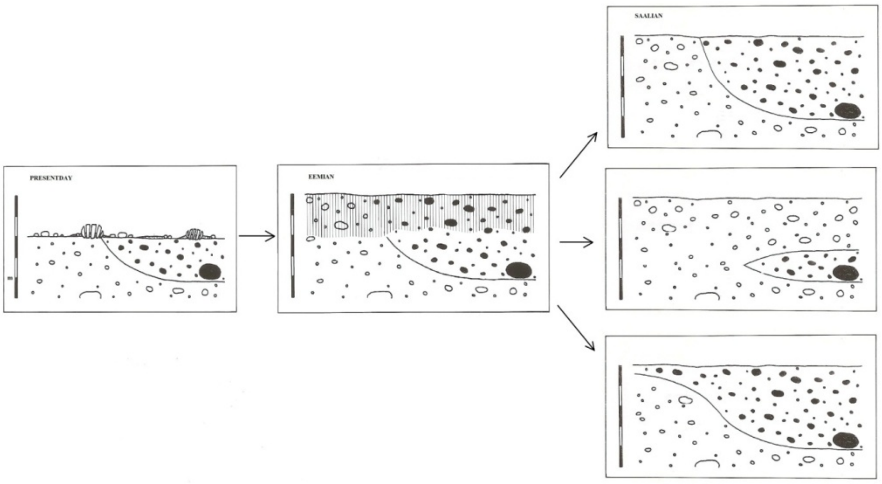

Figure 4.4 (previous page - bottom). Problems of reconstruction, based on real situation in the Netherlands (van der Meer and Lagerlund, 1987). The left-hand panel shows the current situation: a last glacial periglacial surface cuts off a penultimate glacial till consisting of two beds of different composition and provenance, the dark toned one occurring as floes in the top of the other. The middle panel shows the Eemian soil that must have developed in the till which was subaerial at that time, in analogy with Holocene soils it may have been up to 2 metres thick. This soil has been removed by periglacial activity during the last glacial. The right hand panels show at least three different ways of reconstructing the original configuration of the different tills. There is, however, no way of telling which reconstruction is right until we find a fully preserved sequence

saturated environment load-casting is quite common, even in front of a glacier. If the resulting ball-and-pillow structures are tectonised and sheared by a glacier advance we have two active structures on top of each other, but one is a (sedimentary) density-driven deformation structure, the other glaciotectonic. Temporally, the two deformation events do not need to be close related at all.

One of the problems with unravelling glaciotectonic structures is that, contrary to Pleistocene sequences, the active glacier margin is often very complex. Figure 4.3 shows an example of an active ice margin in West Greenland. At this locality, sediment is being released from the glacier which is riding up to the margin, itself a major obstruction. The sediment source is supraglacial as well as englacial and subglacial and movement of the material is by sliding and or rolling over the steep wet surface, by mudflow or washing depending on the amount of water. But these processes do not always happen at the same place, or with the same intensity throughout the day or the season. Add subglacial compression and we already end up with a complex mixture of material, most likely diamictic in nature and with different (supraglacial and subglacial) signatures. Depending on the availability of water, this diamictic material can then be liquefied and transported by running water, forming fans. However, if the water is ponded sediments will acquire lacustrine characteristics. In the example shown sedimentation is actually occurring on an ice cored moraine, the ice slowly and irregularly melting, which results in different ways of redistributing the sediments, including mixing which partly leads to the formation of diamicts again. For good measure we have to add an aeolian input into this as well. This part of Greenland is covered by loess and deposition and deflation of silts is an ongoing process. This aeolian component is often ignored, although its importance has been recognised for a long time (Hobbs, 1935; Ashley, 1985; Oerlemans, 2010). Finally, with the glacier advancing the whole sediment pile, including the ice core, can get tectonised, which makes part of the structure unstable itself leading to remobilization of sediments, while other parts may become folded or faulted. Figure 4.3 only shows one example of an infinite range of combinations of sediments and processes, both terrestrial, tidewater and subaqueous.

Finally, when studying Pleistocene sequences, it must be realised that more often than not, part of the sequence will be eroded and we are only looking at part of the puzzle, with some pieces missing forever. Trying to understand how much may be missing at least gives an idea about the limitations to our reconstruction. Figure 4.4 shows an example of the problems of reconstruction when dealing with an incomplete sequence. The occurrence of till floes of completely different composition has in the past led to theories about two glaciations, about one glacier riding on top of another, of till rafting....etc. It should be realised that the older the glaciation we are dealing with, the larger the chance that essential parts of the sequence have been eroded.

In the following chapter, Chapter 4, two case studies examine macro-scale structural sequences relative to the behaviour of the Irish Sea Ice Stream. The first, by Thomas and Chiverrell detail a spectacular range of structures bordering the British and Irish sides of the Irish Sea basin. The second case study, by van der Meer and colleagues discusses the glacitectonised deposits in eastern Ireland.