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Quaternary Geological Ground Models for the Reduction of Engineering Risk

Dr David Giles, School of Earth & Environmental Sciences, University of Portsmouth & Chair of the Engineering Group

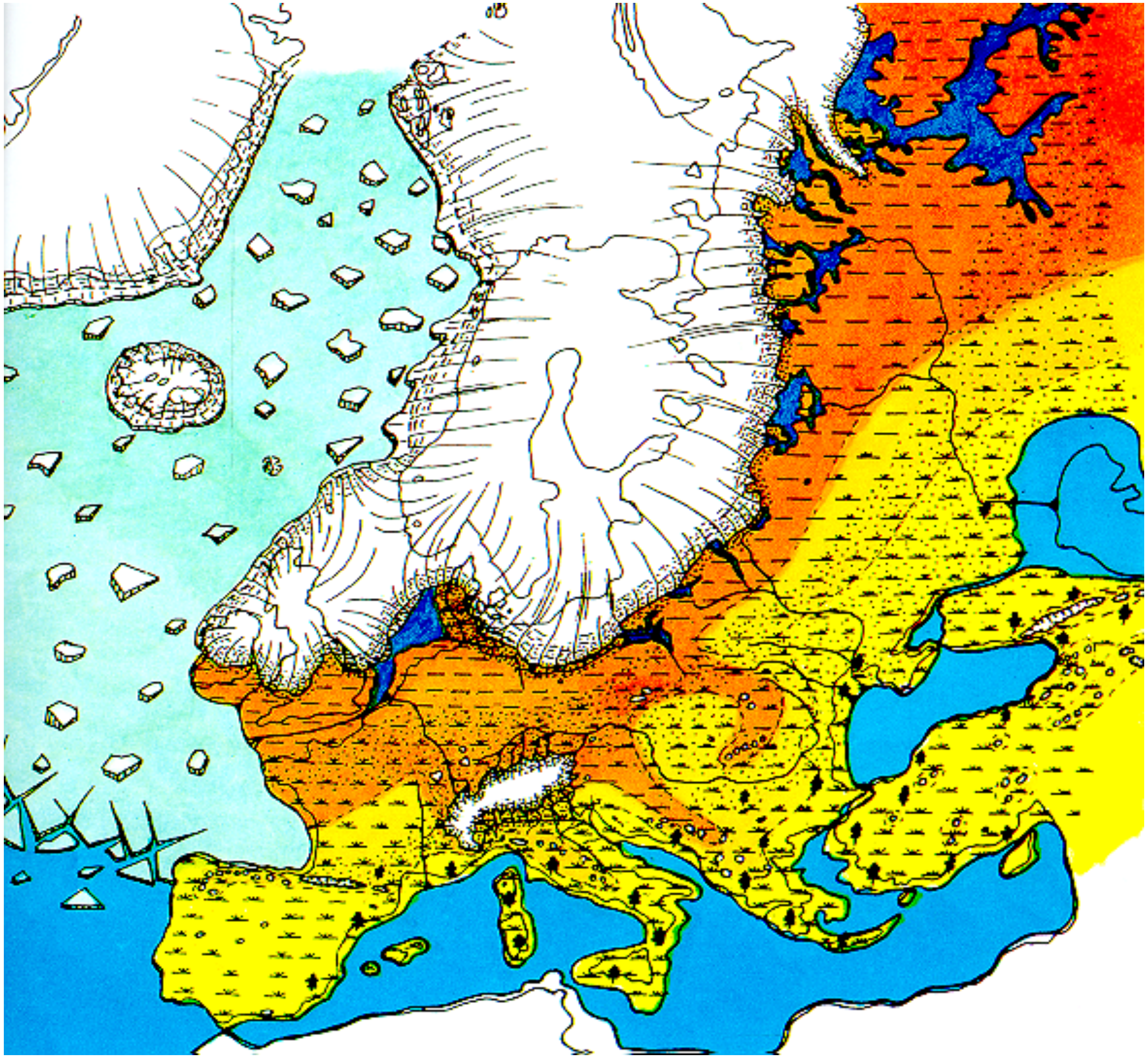
Bryan Lovell Meeting 2016: Water, hazards and risk: Managing uncertainty in a changing world

Themes – Ground Risk

- **Quaternary Geological Ground Models for the Reduction of Engineering Risk**
  - **Quaternary Period & Engineering Legacy**
  - ***Lateral & vertical variability***
  - **Diversity of materials**
    - **Strength**
    - **Permeability**
    - **Engineering behaviour**
  - **Diversity of landforms**
    - **Geohazards**
    - **Reactivation**
  - **Case studies**
- **How to reduce the risk?**
  - **Education & Field Experience**
  - **The EGGS Working Party Report**

Quaternary

- Glacial
- Non-Glacial
- Stadials
- Interstadials
- Sea-level rise & fall
- Cold, Very Cold, Warm & Very Warm



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UK Geology

Where are
The Quaternary
Deposits
&
Landsystems?

UK Geology

The Quaternary Legacy

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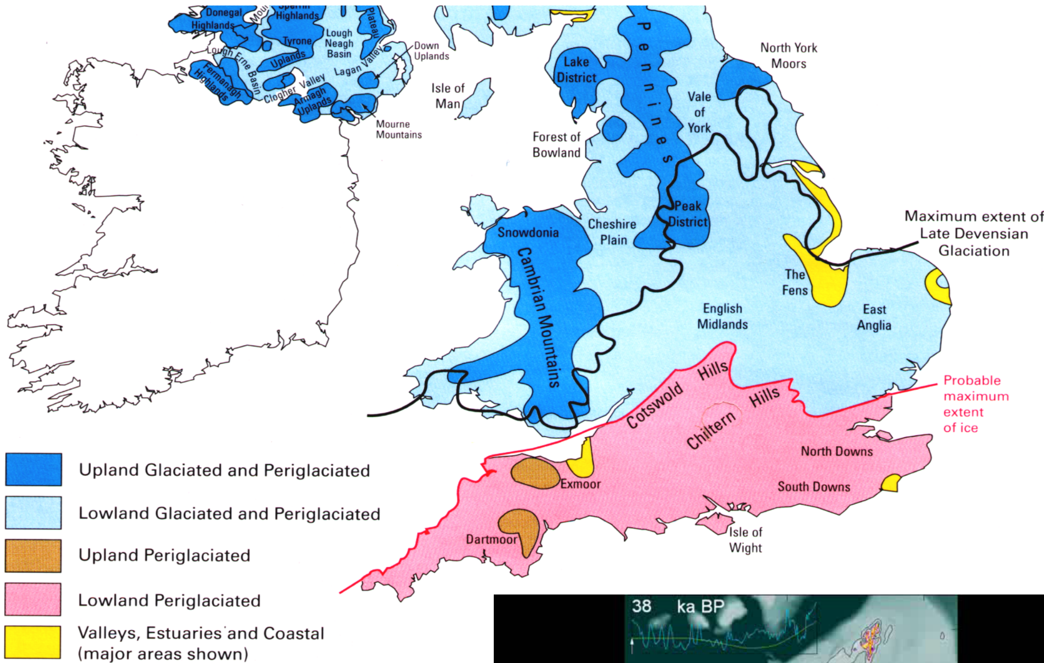
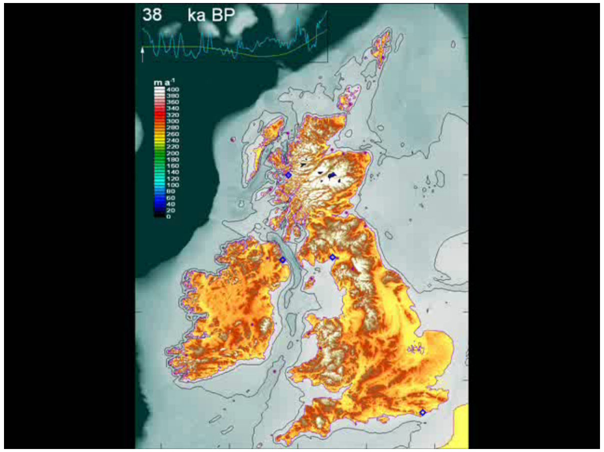
HS2



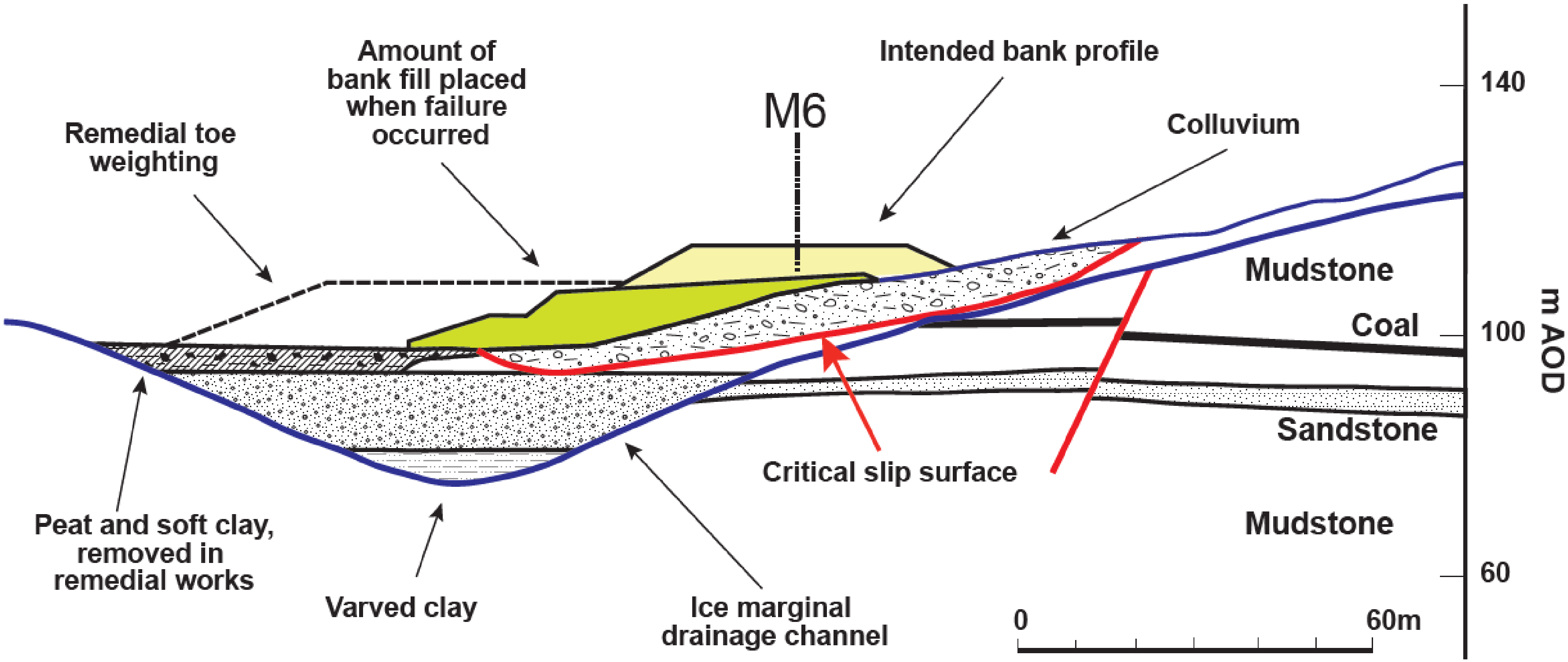


- **Periglacial**
- **Ice Marginal**
- **Glacial**

www.ies.aber.ac.uk/en/glaciology/britice-model

Quaternary Legacy

- How to deal with the engineering risk posed by the Quaternary Legacy Hazard?

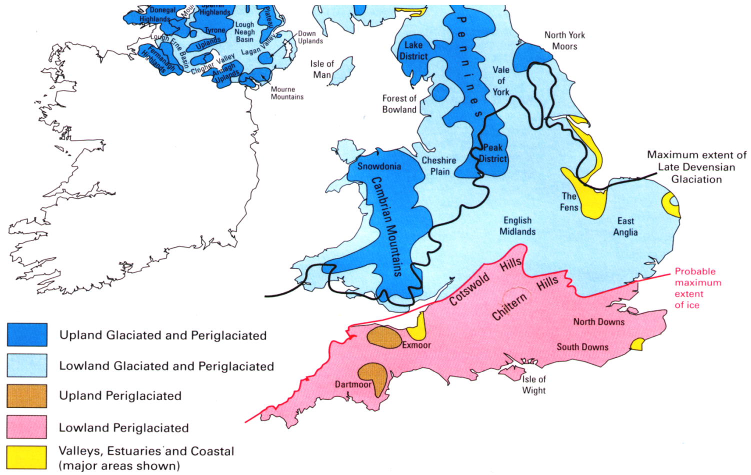


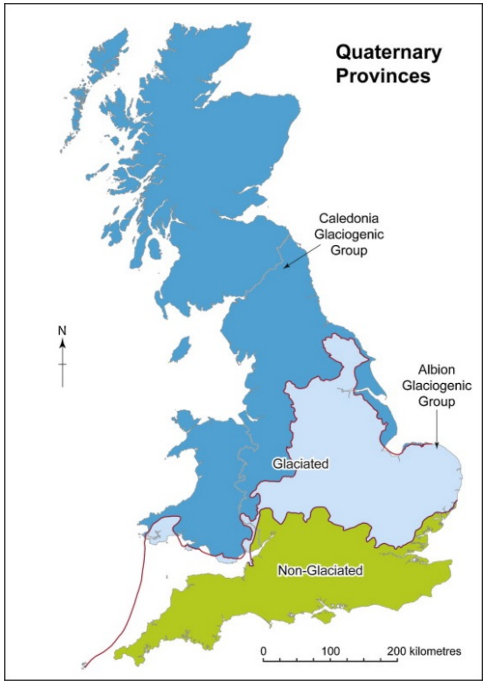
Waltons's Wood, M6, Staffordshire

Terrain Classification

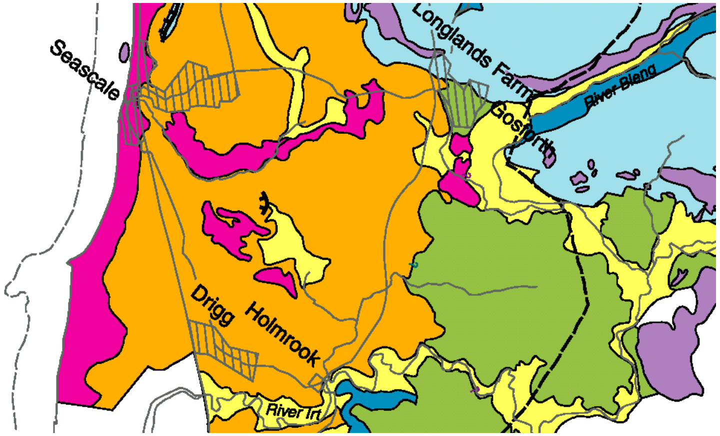
- Provinces
- Domains
- Landsystems
- Ground Models

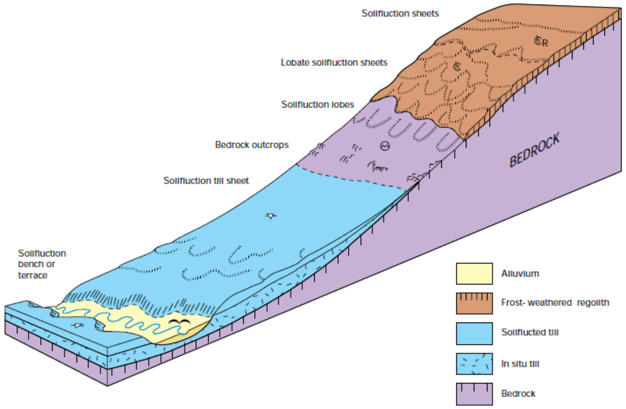
Foster et al (1999) Quaternary geology – towards meeting user requirements. BGS.





McMillan, A.A. et al (2000)
Hydrogeological characterisation of the onshore Quaternary sediments at Sellafield using the concept of domains





Booth, S., Merritt, J., & Rose, J. (2015). Quaternary Provinces and Domains–a quantitative and qualitative description of British landscape types. Proceedings of the Geologists' Association, 126(2), 163-187.

Ground Models

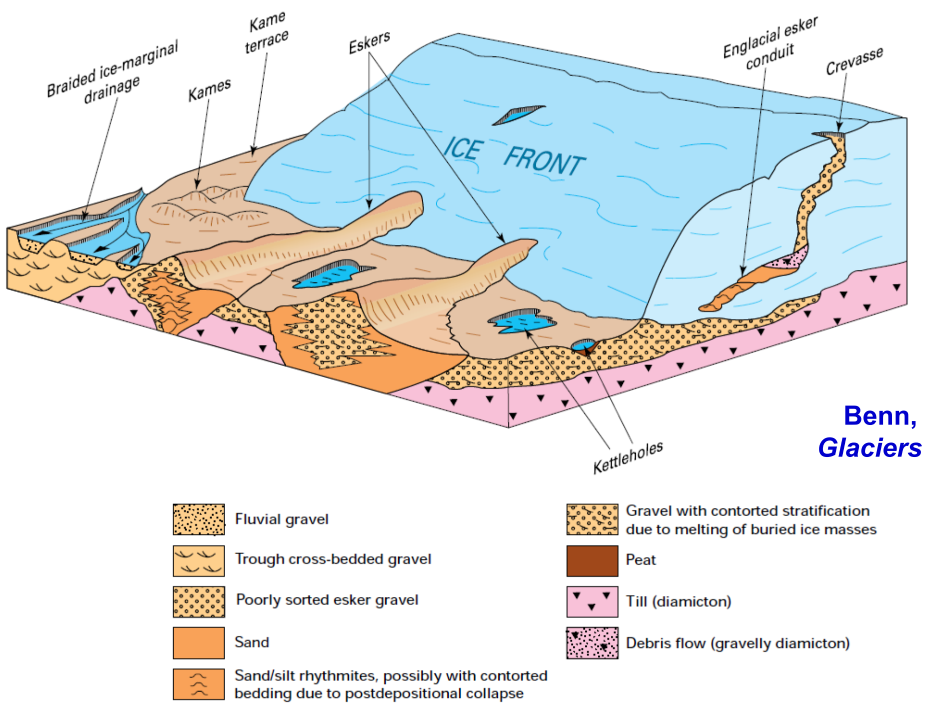
- **Landsystem v Process Form Models**

Landsystem

Area of common terrain attributes, different from those of adjacent areas, in which recurring patterns of topography, soils & vegetation reflect the underlying geology, past erosional & depositional processes, & climate

Process-Form Model

Conceptual model that emphasizes the genetic interrelationships of specific landform–sediment associations at both local & regional scales in terms of known process & form linkages

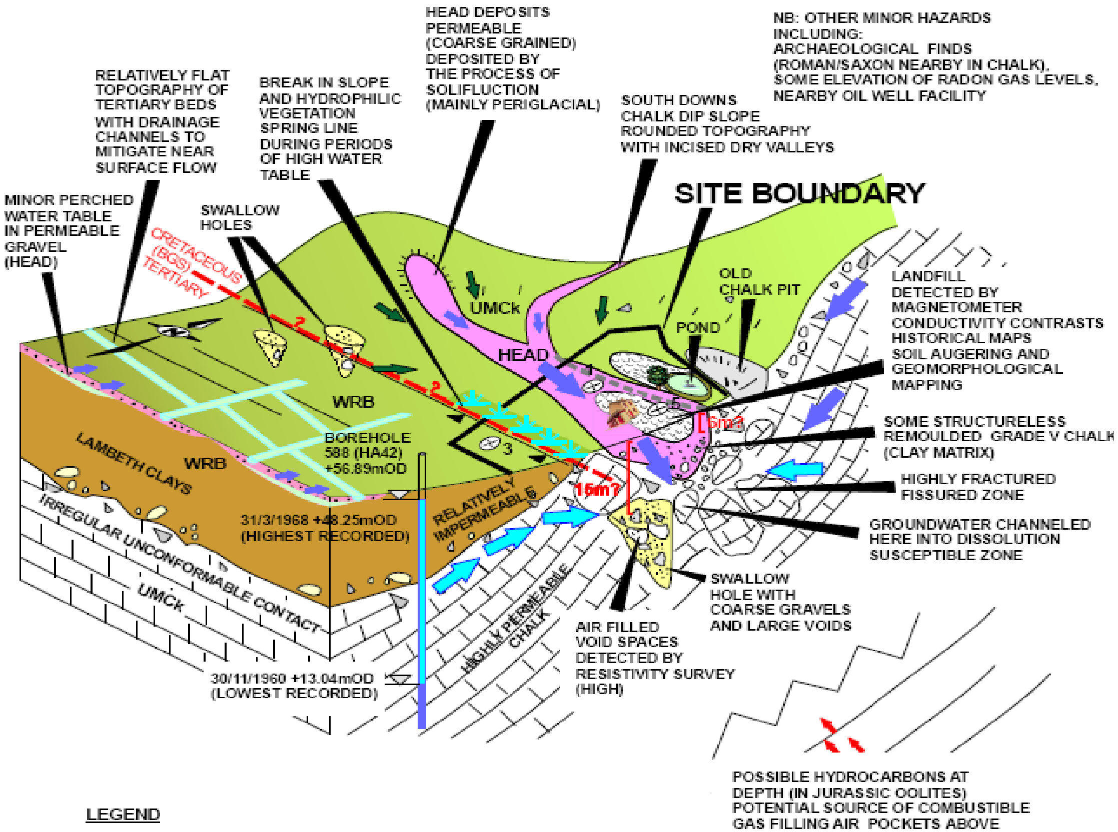


Benn, D., & Evans, D. J. (2014). *Glaciers and glaciation*. Routledge.

Types of Ground Model

- **Conceptual**
  - Essentially qualitative in nature & illustrate the key features of a geological situation & the processes active in that environment
- **Observational.**
  - Scaled down versions of actual ground conditions at specific sites
- **Analytical**
  - Representations of reality using mathematical formulae, different media or schematics

Engineering Geological Models - an introduction: IAEG Commission 25
S. Parry, F. J. Baynes, M. G. Culshaw, M. Eggers, J. F. Keaton, K. Lentfer, J. Novotny & D. Paul.



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Informing the Ground Model

Quaternary History

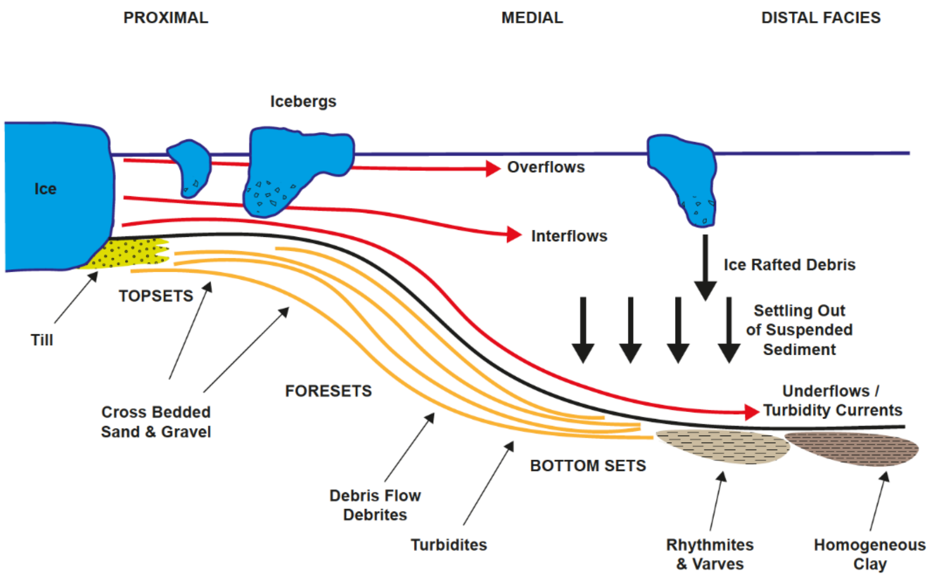
Glacial & Periglacial Genesis

Engineering & Geohazard Significance

"the present is the key to the past"
Charles Lyell
Principles of Geology (1830)

Engineering & Geohazard Significance

- **Sediment genesis & composition**
  - Glaciogenic, glaciofluvial, glaciolacustrine, glaciomarine
  - Periglacial
- **Material strength**
  - Anisotropic
- **Material permeability**
  - Anisotropic
- **Presence of geohazards**
  - Shear surfaces, high permeability layers, Reactivation
- **Appreciation of the significant lateral & vertical variability**
  - Scale



Reduction of Uncertainty

Reduction of Risk

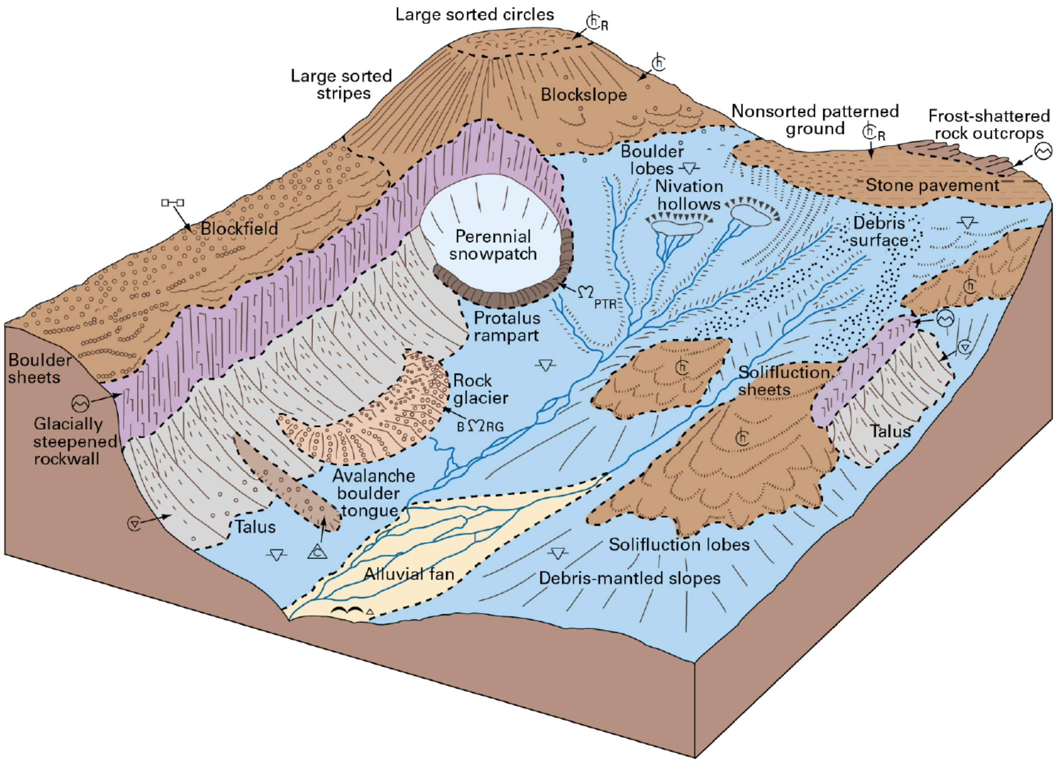
Informing the Ground Model

- **Building blocks required to develop ground models for glaciated & periglaciated terrains**

- **Catalogue of**
  - **Sediments**
  - **Structures**
    - **Macro**
    - **Micro**
  - **Landforms**

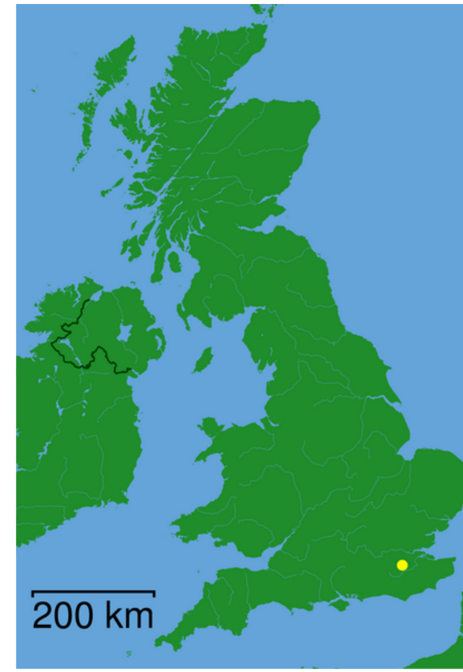
- **Field experience & recognition**

Schematic representation of the Late Devensian periglacial features of the Scottish Highlands that were probably active during the Loch Lomond Stadial (Ballantyne, 1984)



Classic Geology Geosites: Siccar Point

Classic Engineering Geology Geosites: Sevenoaks



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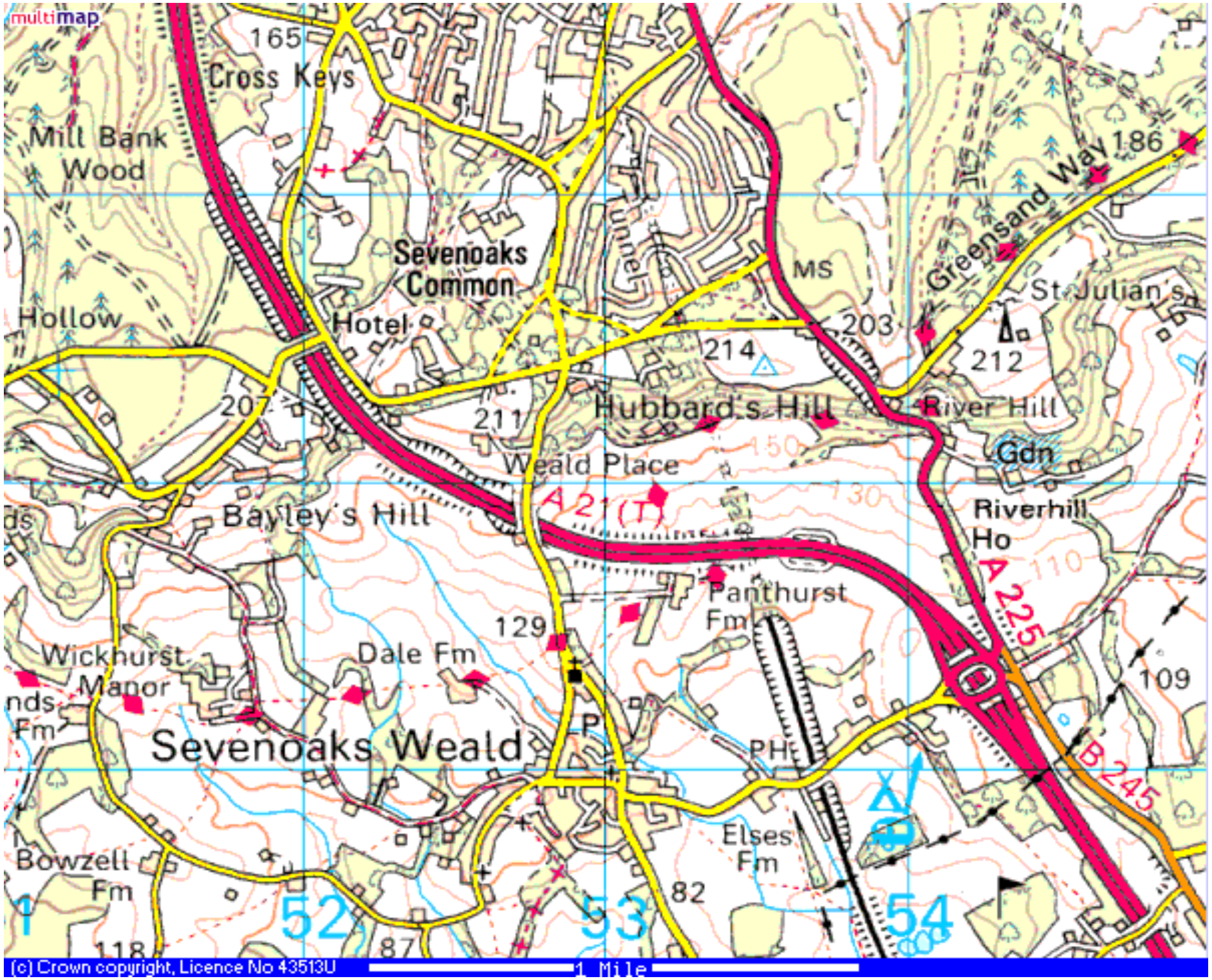
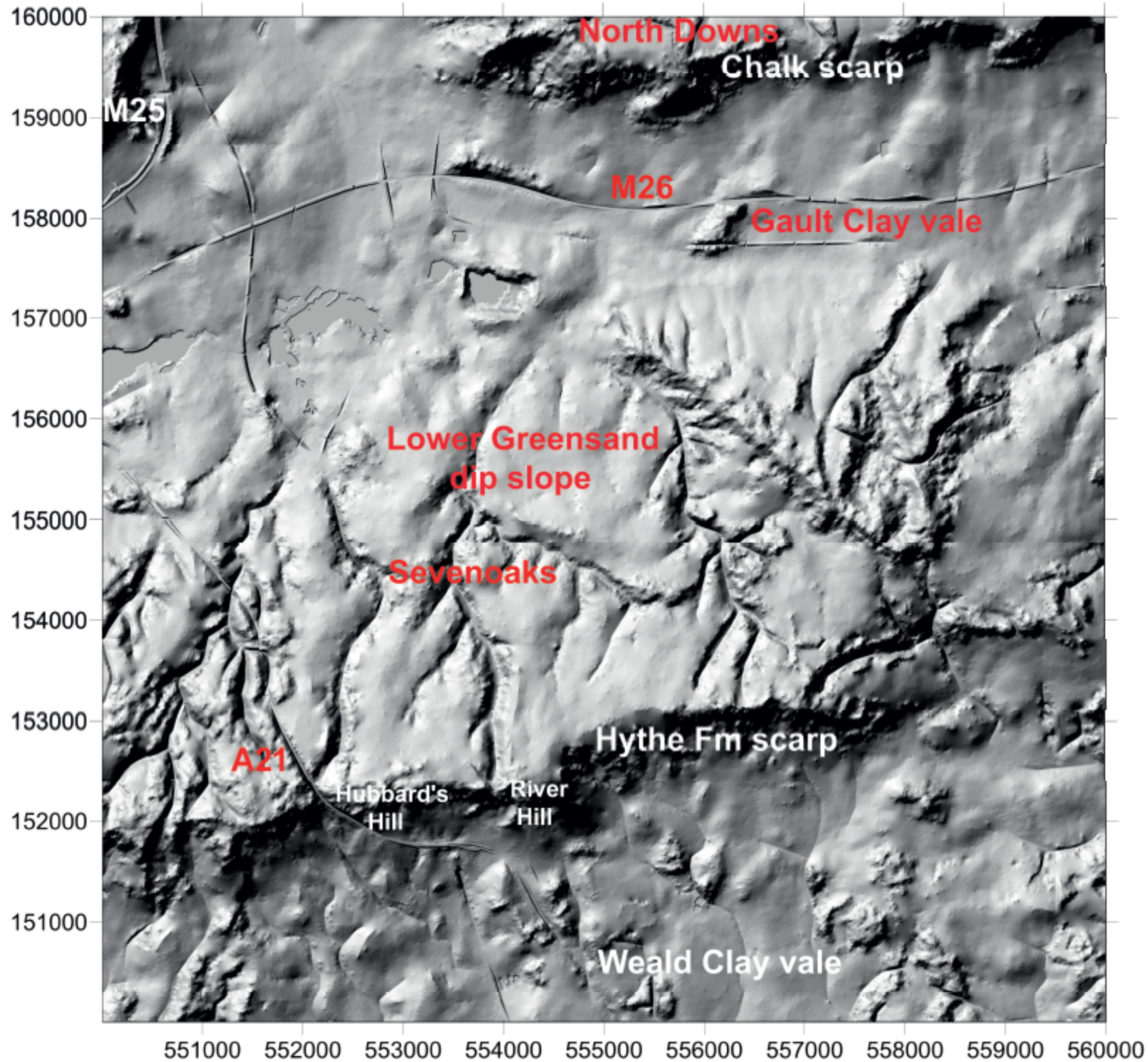
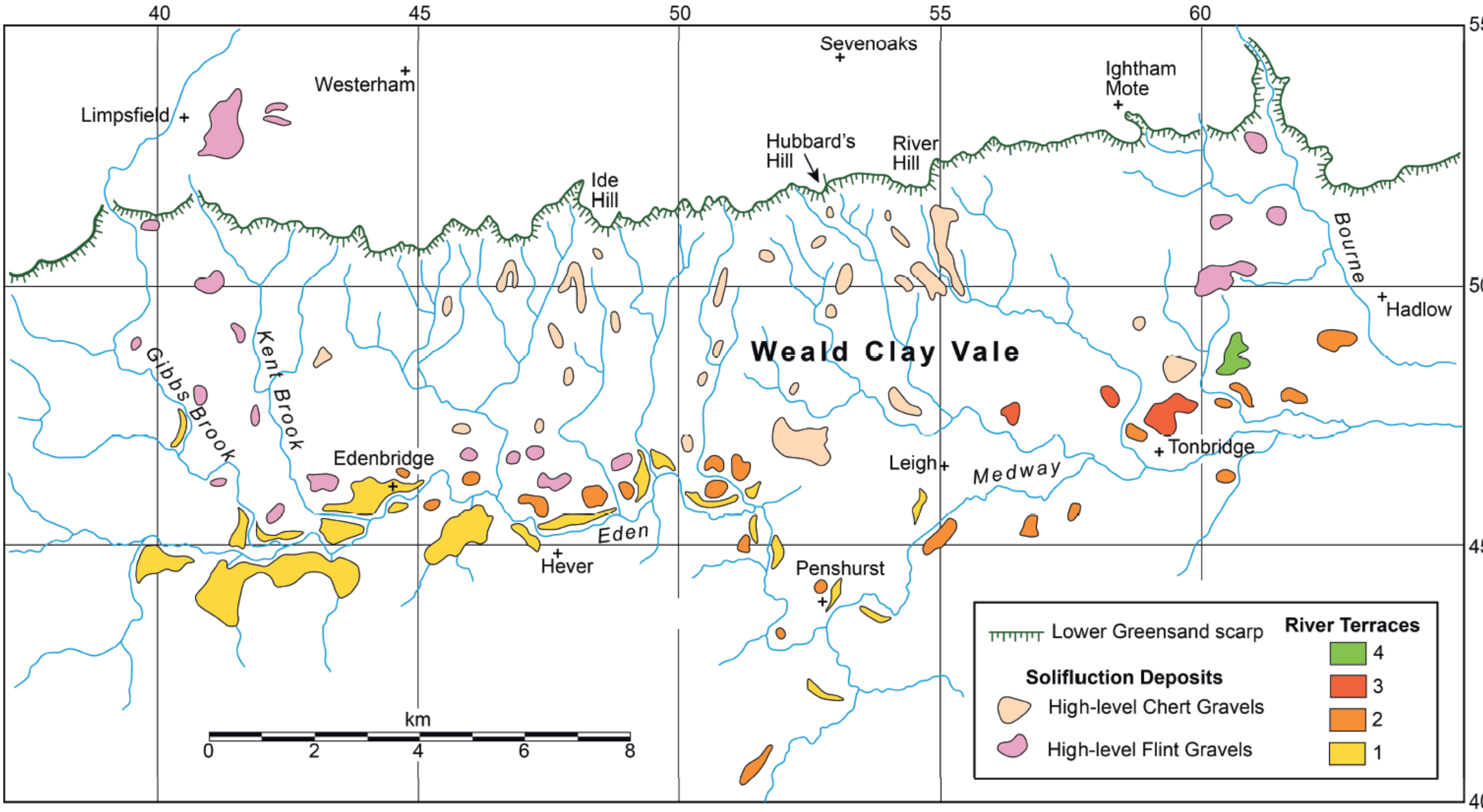
Case Study: A21 Sevenoaks Bypass



Case Study: A21 Sevenoaks Bypass

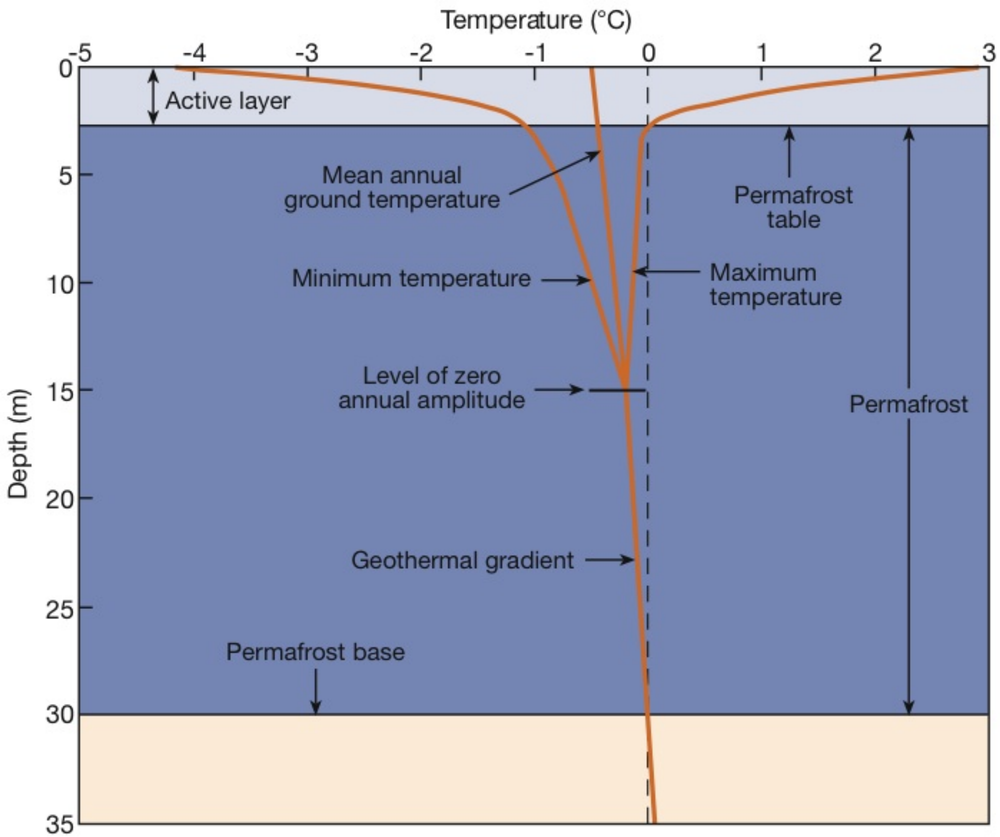
Hill-shaded NEXTmap Digital Terrain Model of Sevenoaks region.

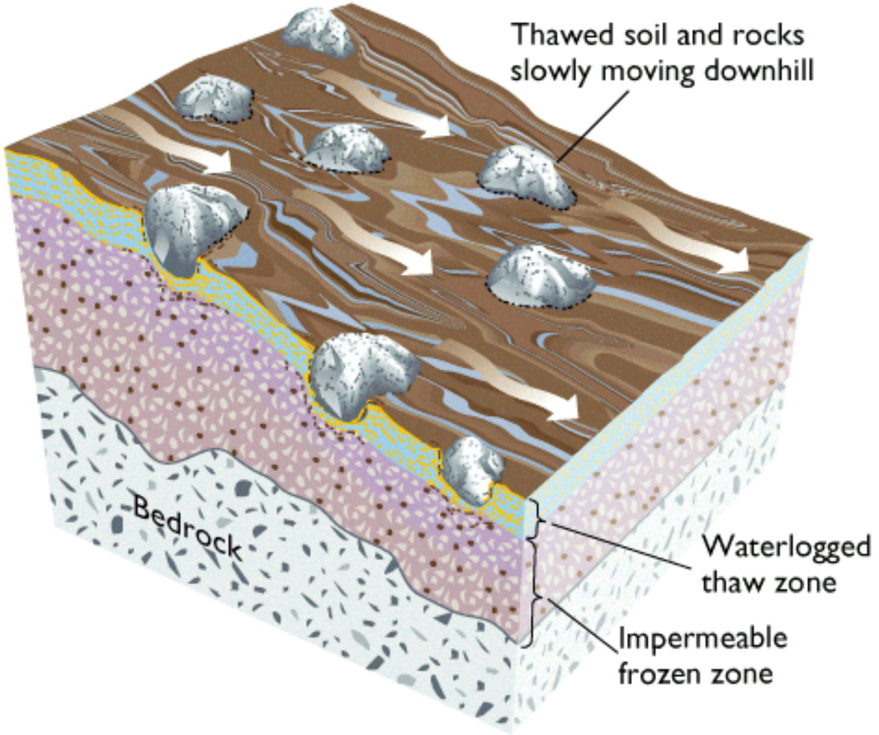




Map of solifluction deposits and river terraces in the Weald Clay Vale and Eden-Medway catchment (modified from Skempton and Weeks 1976).

Periglacial Solifluction

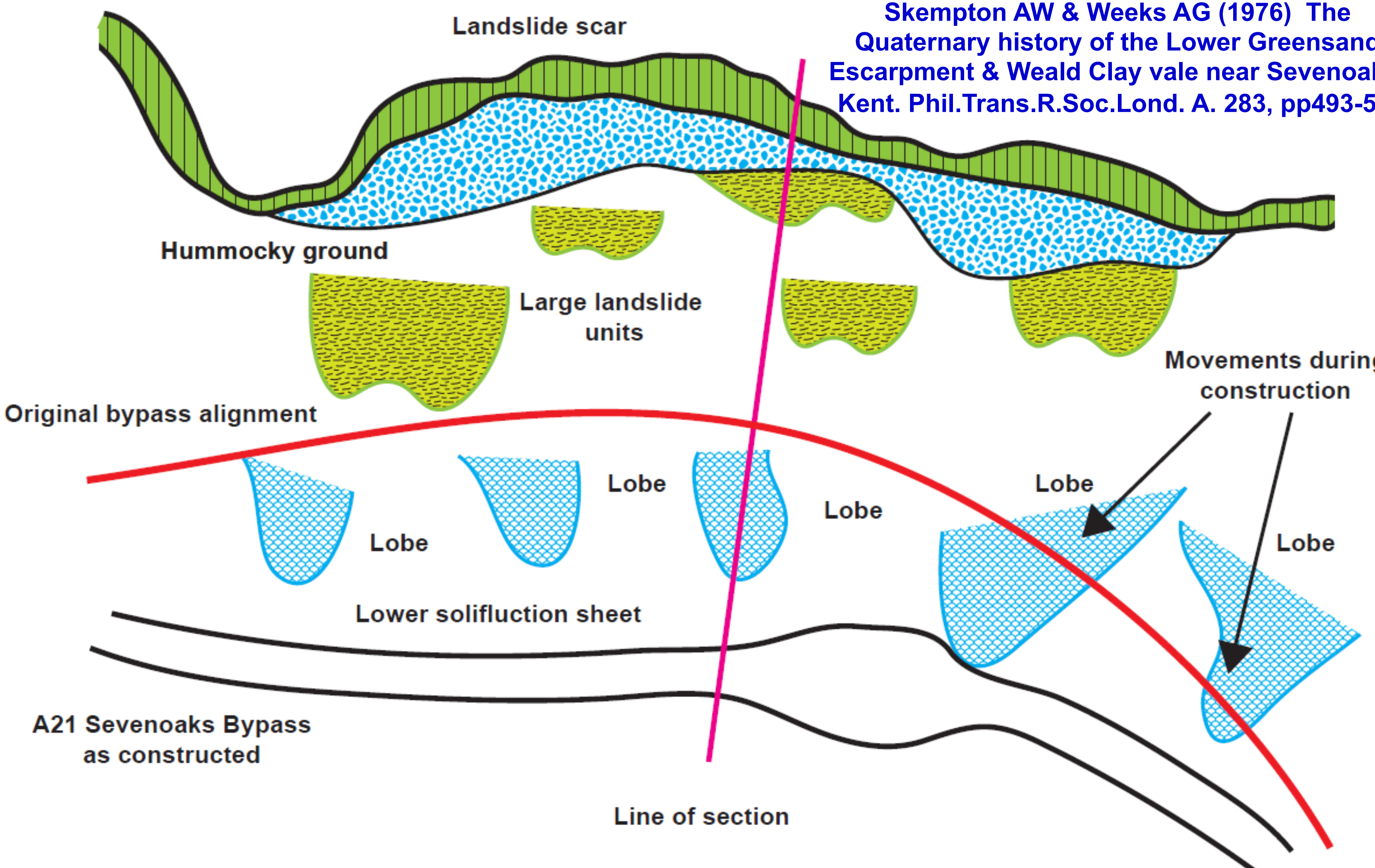




Slurry Flow
Or
Land slide

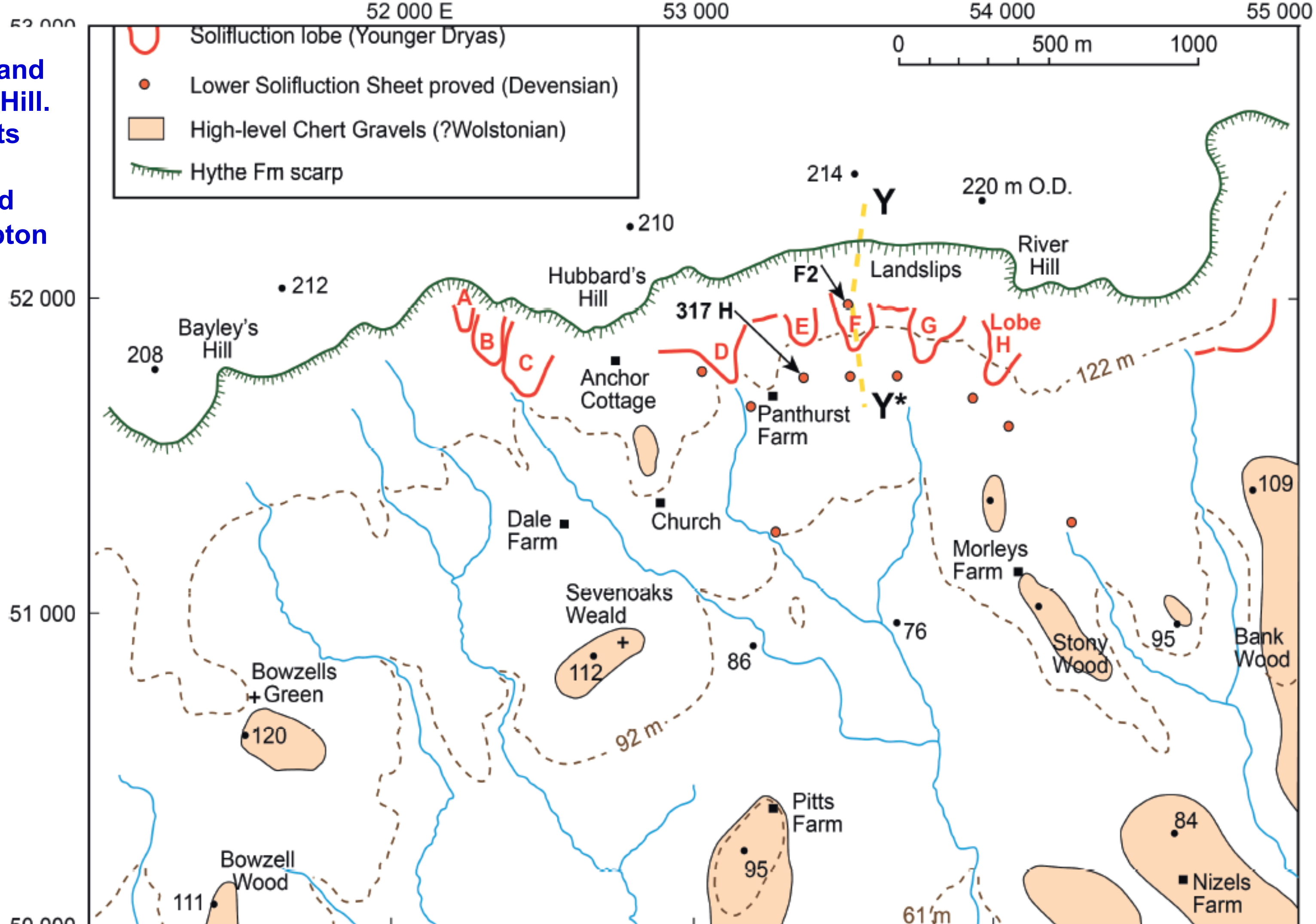

Detachment slide/mudflow in Longyeardalen, Svalbard 14th Oct.
Department of Arctic Geology @UNISvalbard

Skempton AW & Weeks AG (1976) The Quaternary history of the Lower Greensand Escarpment & Weald Clay vale near Sevenoaks, Kent. Phil.Trans.R.Soc.Lond. A. 283, pp493-526

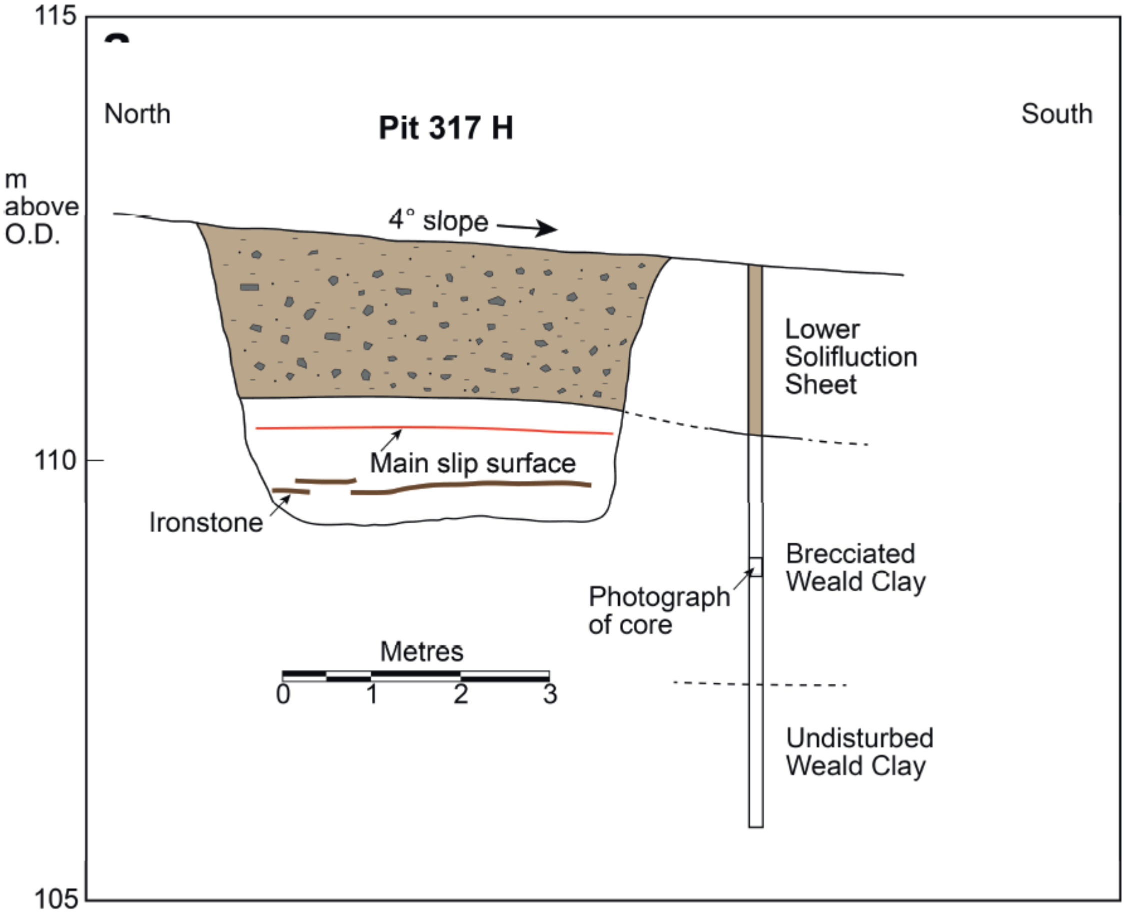


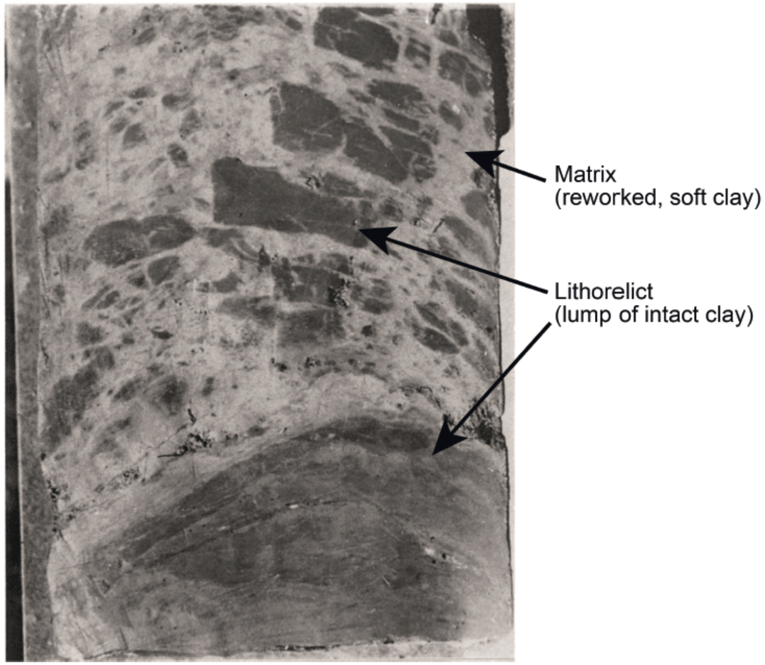
Murton & Giles, 2016

Solifluction deposits and lobes near Hubbard's Hill. Locations of trial pits 317H and F2 are indicated (modified from Skempton and Weeks 1976).



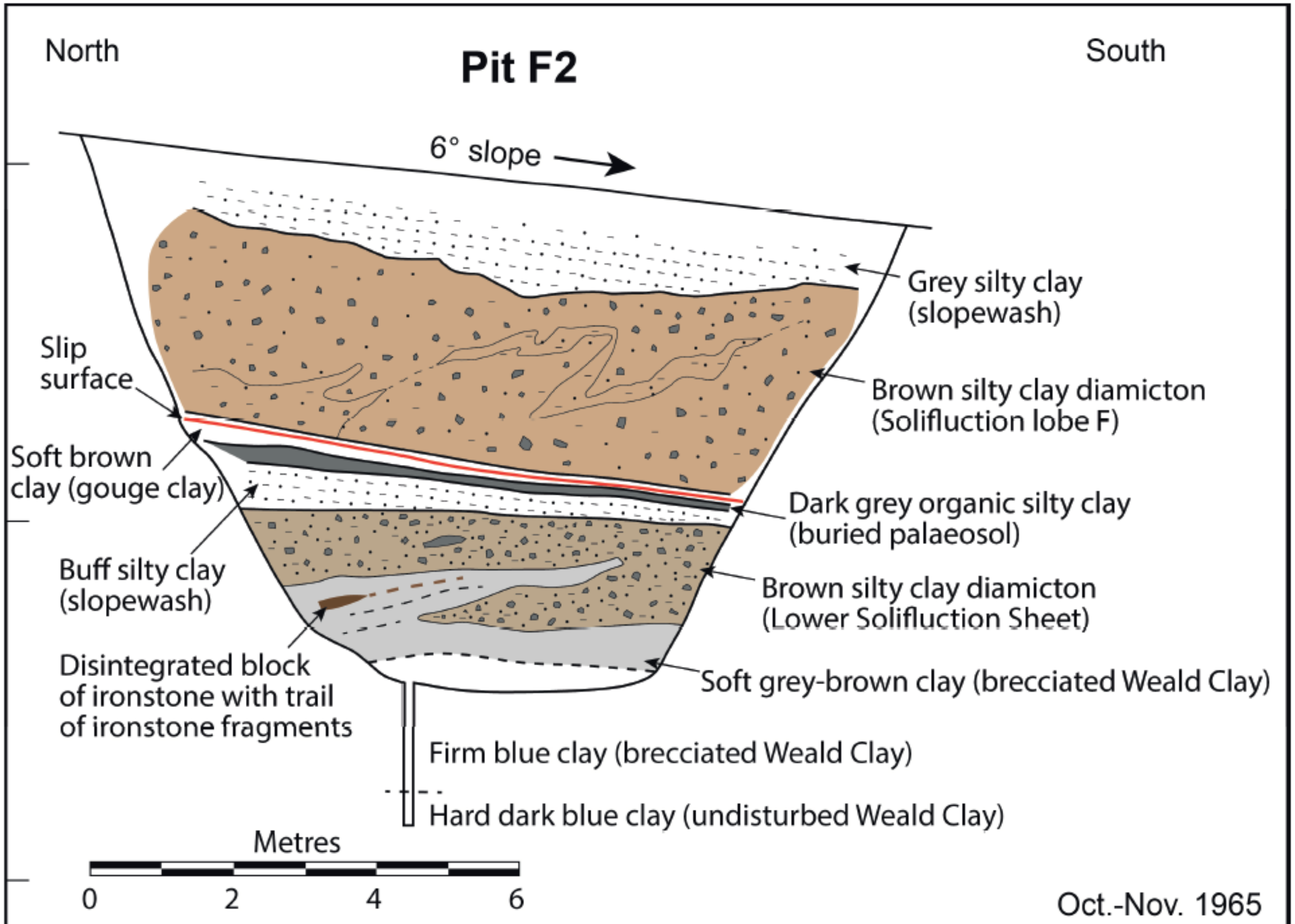
Sevenoaks Trial Pits





Vertical cross section through trial pit 317 H and adjacent borehole, 100 m south of solifluction lobe E. Brecciated Weald Clay, 3.5 m depth in borehole 317H. Angular to subangular lithorelicts of clay are set within a matrix of soft, reworked clay. Core diameter is 10 cm (modified from Skempton and Weeks 1976).

Trial Pits



Vertical cross section through trial pit F2 in solifluction lobe F, showing two clayrich head deposits separated by a prominent slip surface (modified from Skempton and Weeks 1976).

Failing Slope at Lobe G (or C ?)

AG Weeks (1969)

Excavating Lobe G (or C ?)

AG Weeks (1969)

Toe of Embankment Failure, Lobe B

AG Weeks (1969)

Lobe F

AG Weeks (1969)

TP F2 Failure Surface

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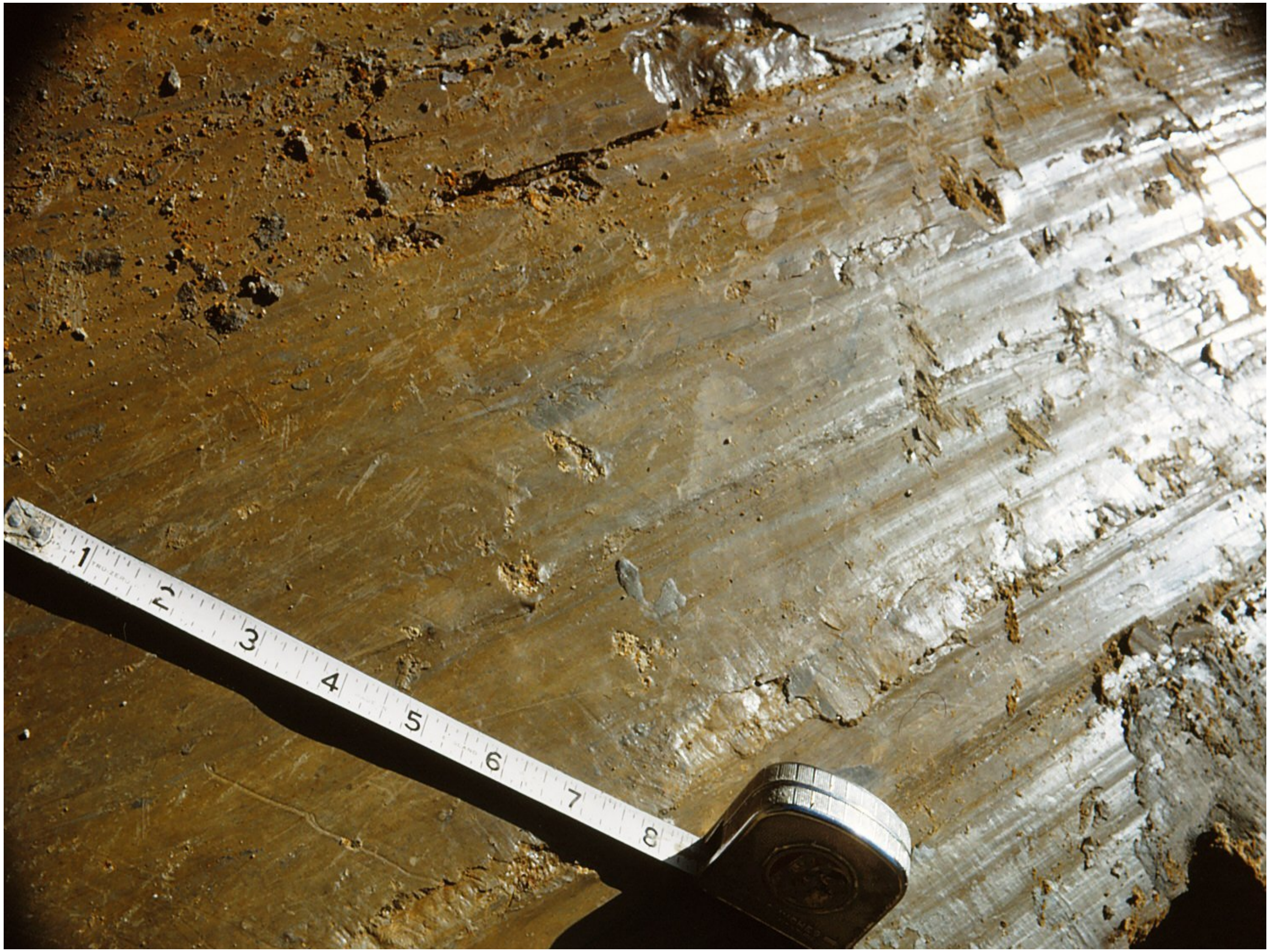
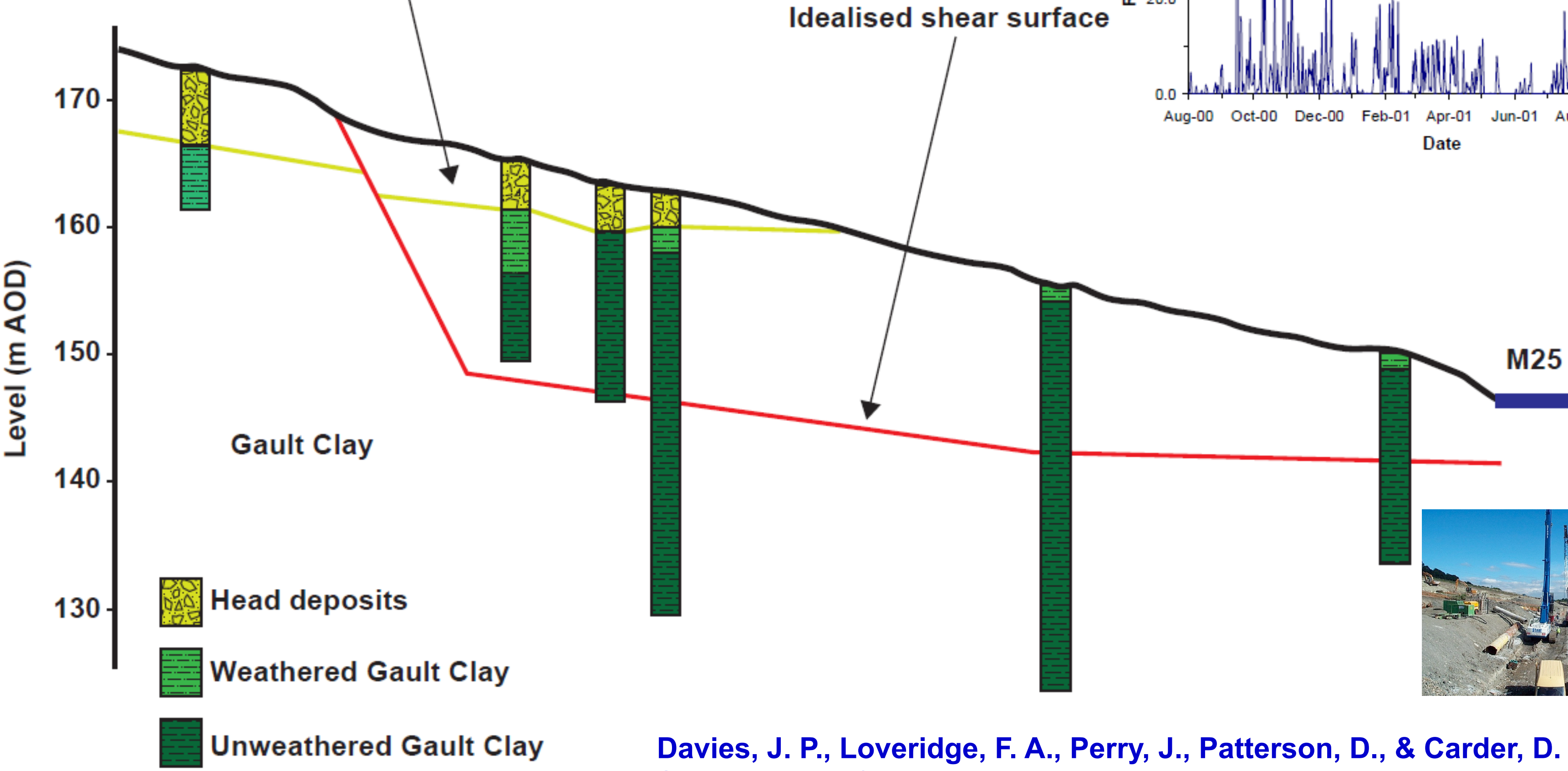
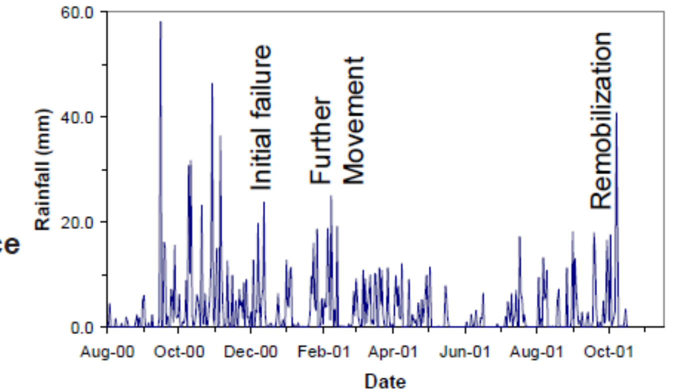
TP F2 Failure Surface



AG Weeks (1969)

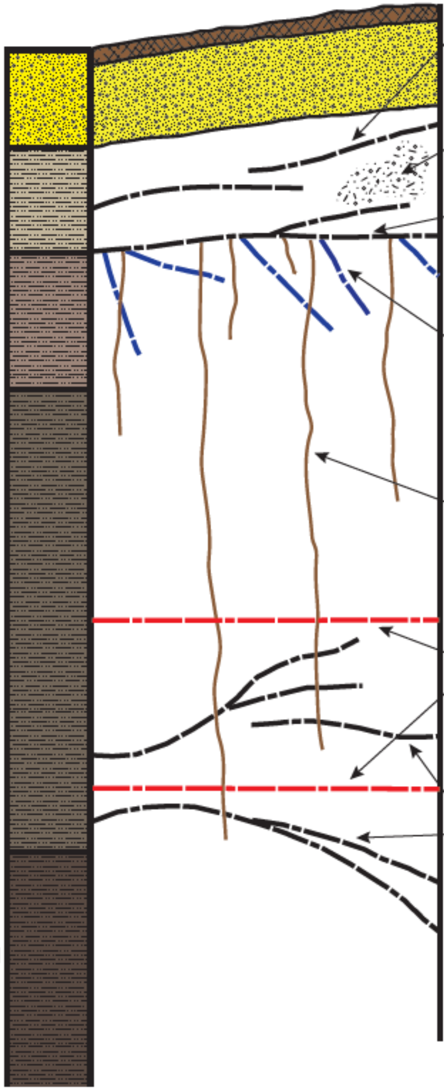
M25 Periglacial Shears





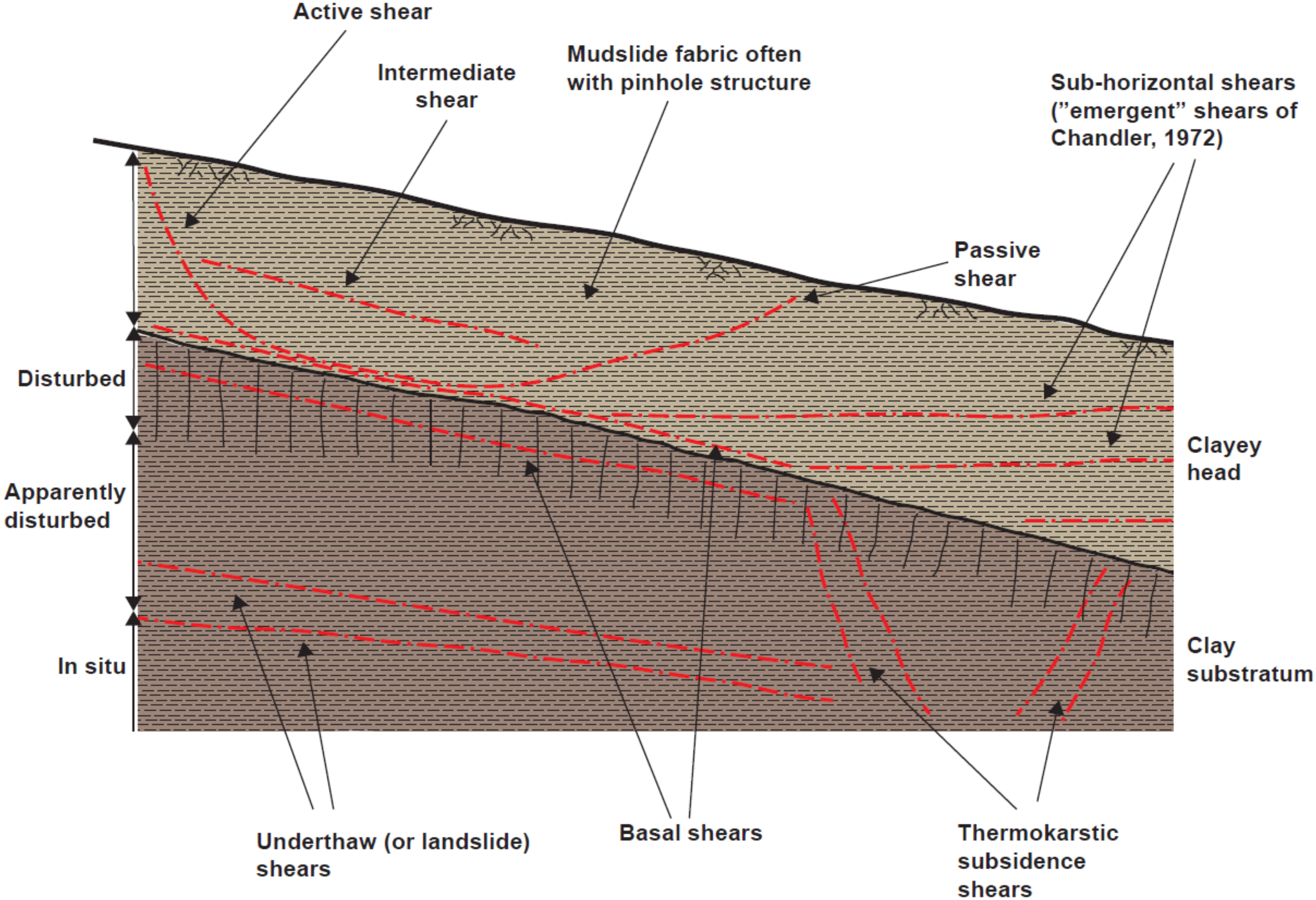
Davies, J. P., Loveridge, F. A., Perry, J., Patterson, D., & Carder, D. (2003). Stabilisation of a landslide on the M25 highway London's main artery.

Periglacial Shears



After Spink (1991)

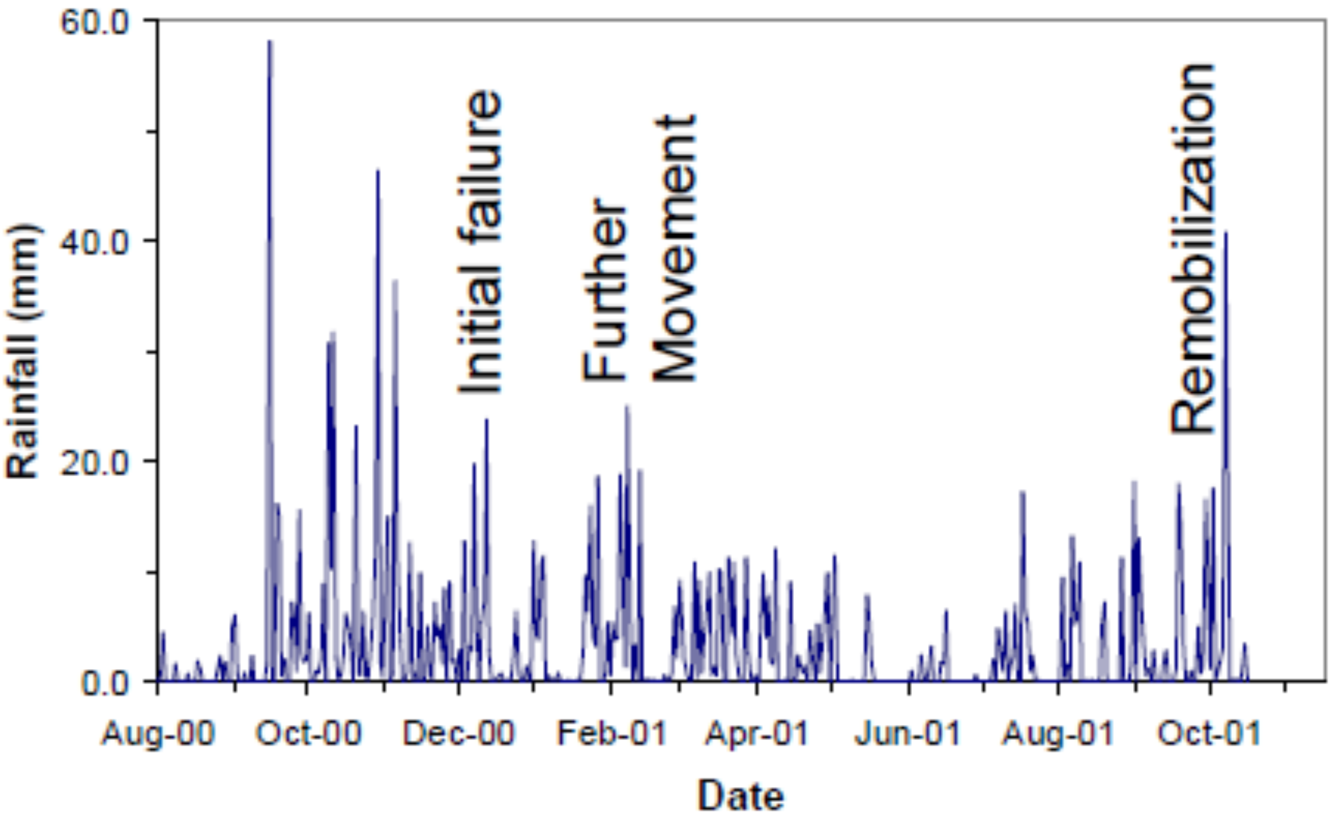
Periglacial Shears



After Hutchinson (1991)

M25 Periglacial Shears

The Geological Society
serving science & profession
2016 YEAR OF WATER



Davies, J. P., Loveridge, F. A., Perry, J., Patterson, D., & Carder, D. (2003). Stabilisation of a landslide on the M25 highway London's main artery.

A21 Sevenoaks Bypass

Reduction of Risk

- **Education**
  - **Quaternary as critical as the solid part!**
- **Field experience**
  - **With a reducing undergraduate field programme**
- **Case study write-up**
  - **With pressure on REF publications**

- ***'Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains – Engineering Group Working Party Report'***

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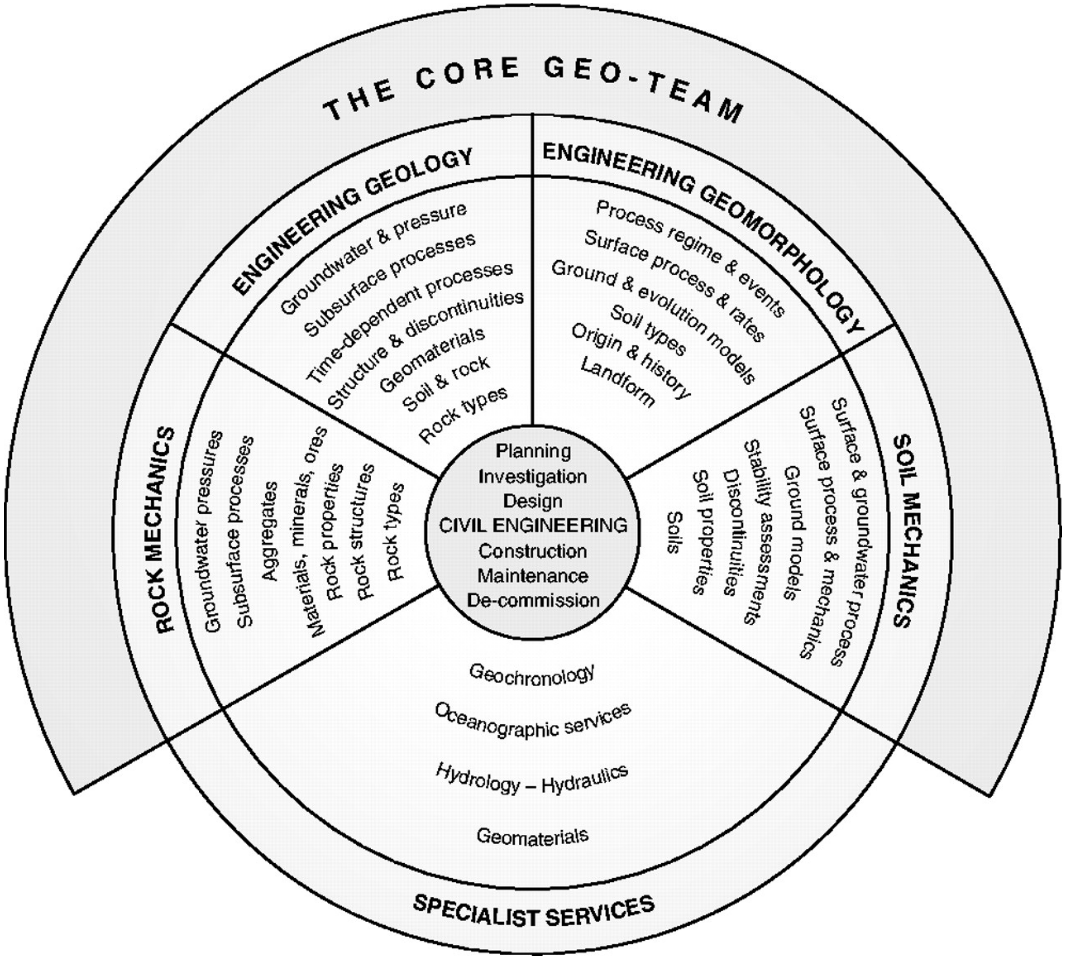
Reduction of Risk

- Quaternary Knowledge & Field Experience



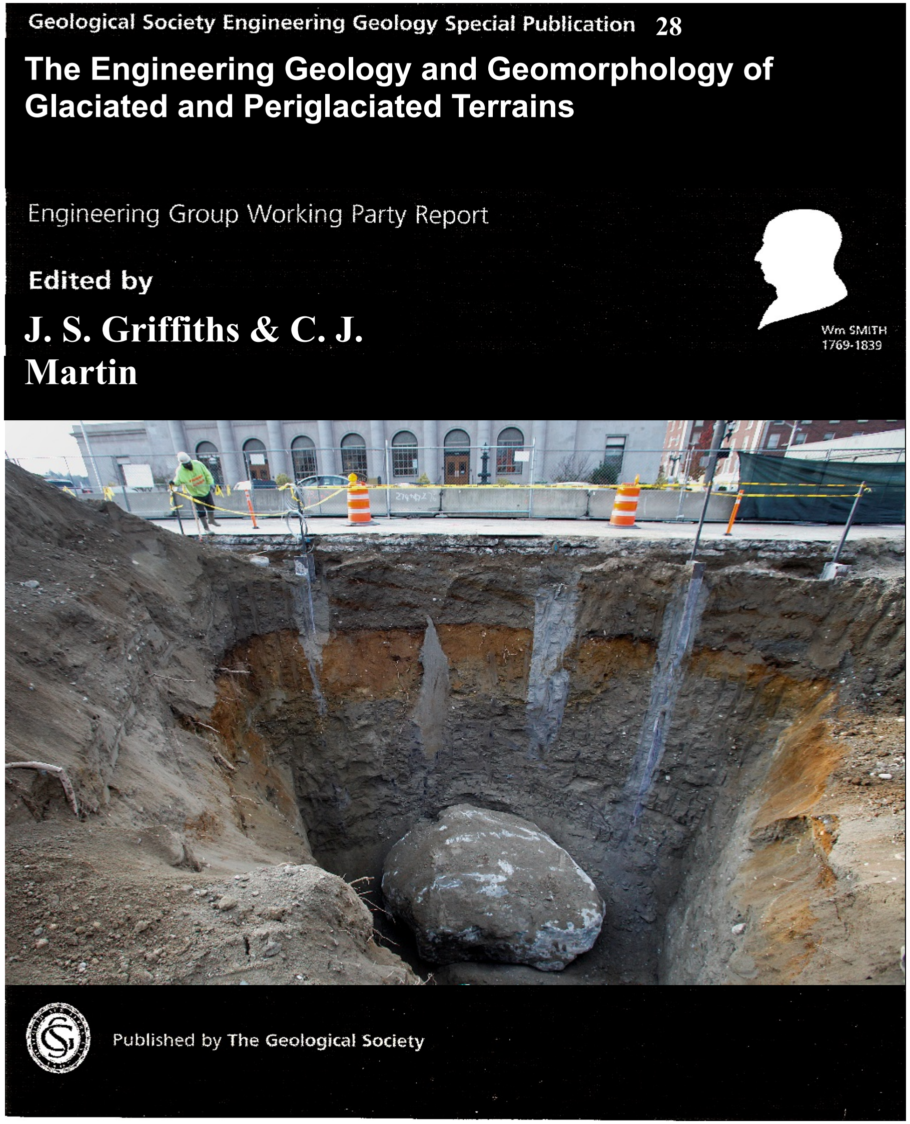
Prof Denys Brunsden (2002) Glossop Lecture

Geomorphological roulette for engineers and planners: some insights into an old game

Quarterly Journal of Engineering Geology and Hydrogeology, v. 35:101-142

Scope of the Report

- British Isles focus, but global application & examples
- Relict materials & landforms, but cognisant of formative processes
- Cold ‘stadials’, not warm ‘interstadials’. Quaternary only
- Link between modern geomorphological terminologies & long-standing engineering geological nomenclature (Eurocode 7 & BS 5930)
- Extensive visual glossary
- Landsystems approach with ground models advocated



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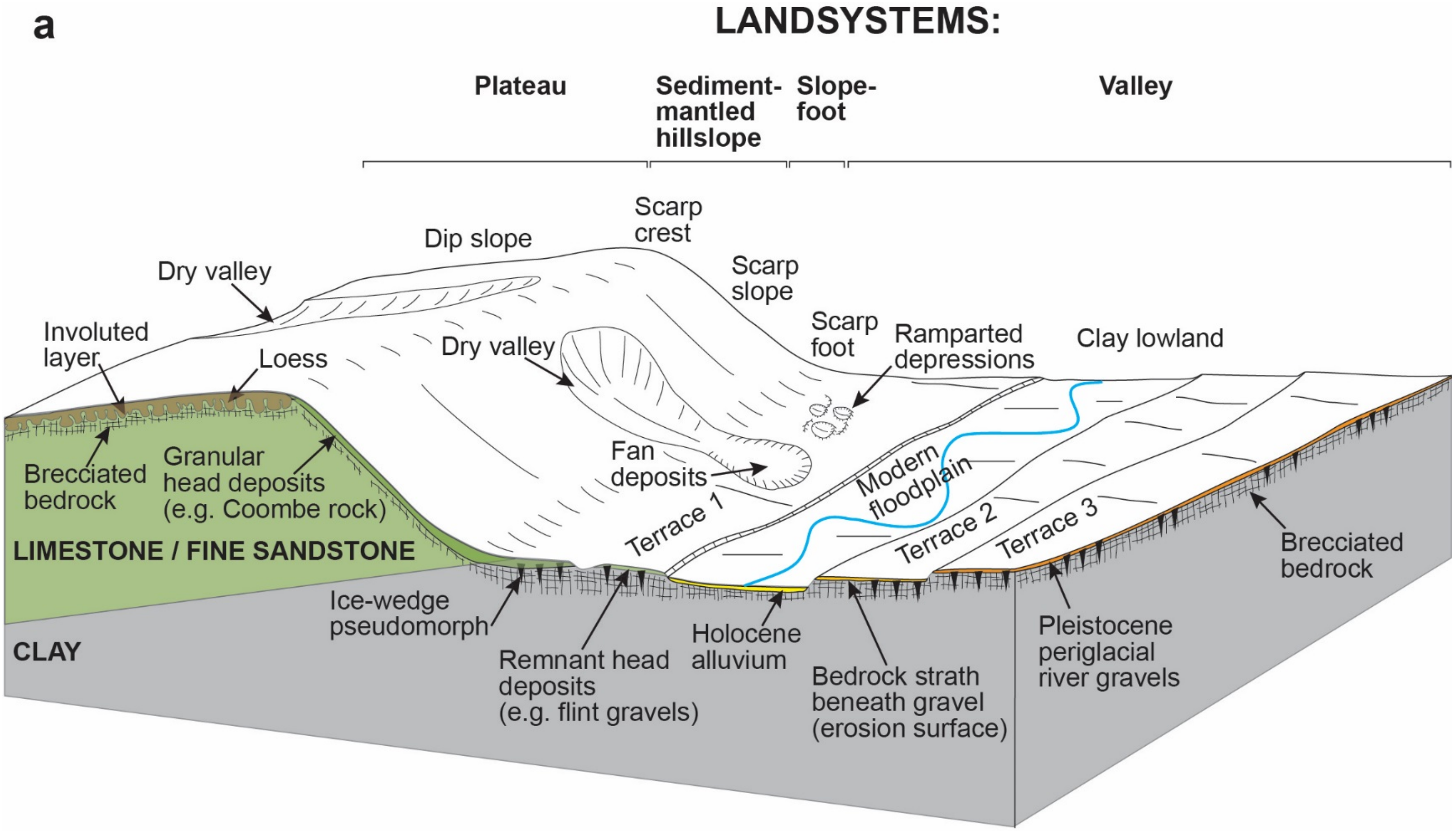
Key Themes

- Inherent complexity in glaciated and periglaciated terrains
  - Superposition of processes
  - Lateral & vertical variability of ground and groundwater conditions
- Lends itself to landsystems approach
  - Ground model & risk register updated as project understanding develops
- Multi-disciplinary approach advocated
  - Quaternary science, geography, geomorphology, geology, hydrogeology, geophysics, archaeology, geotechnical engineering
  - Breadth of available information and resources
  - Caution when interpreting differing references and case studies
- Latest scientific approaches incorporated into engineering practice
  - Eurocode 7 / BS5930 description of materials combined with new classification for materials and landforms
  - Reclassification of 'Glacial Till'
  - Importance of segregated ice during periglacial conditions

Lowland Ground Models

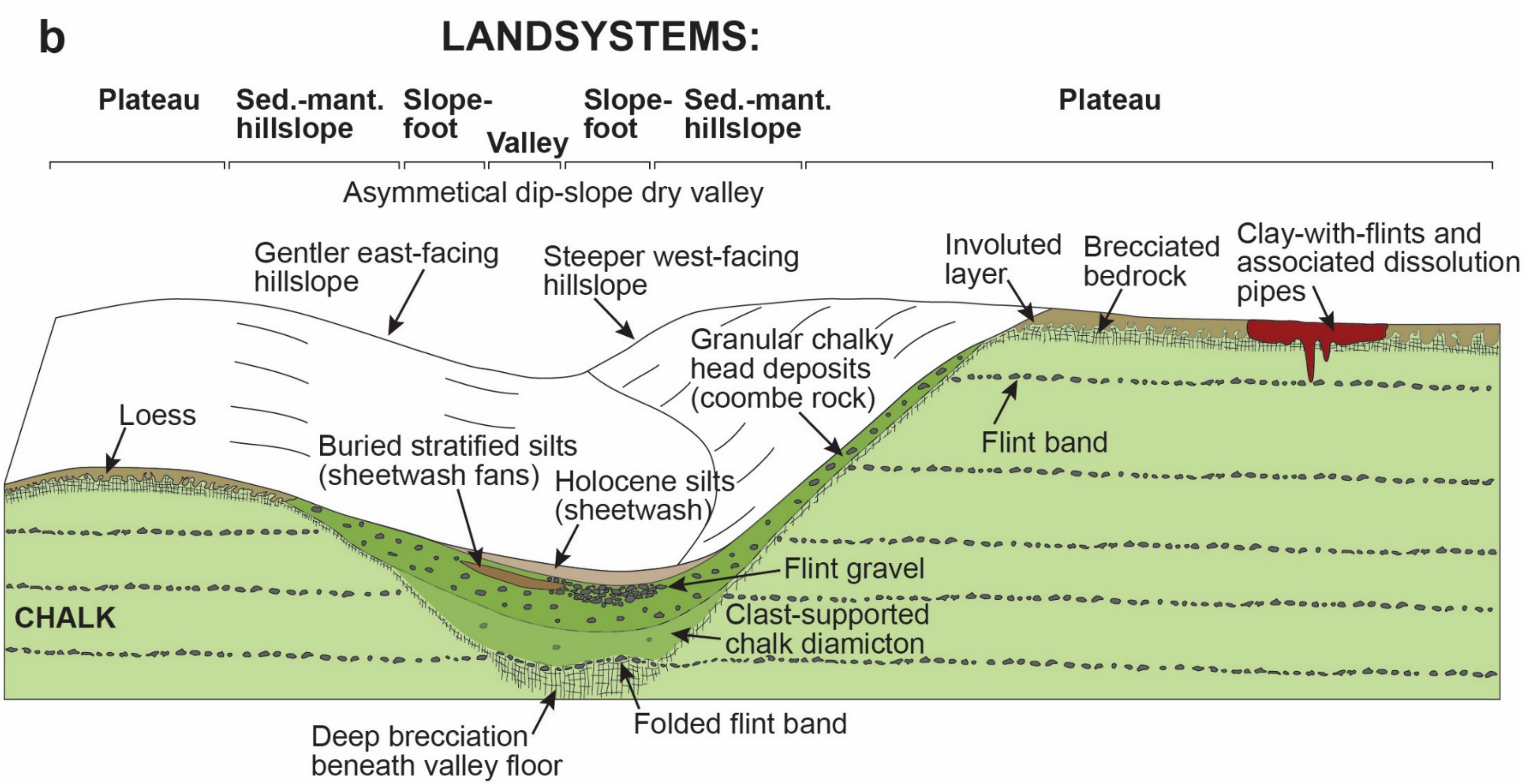
- **Limestone plateau-clay vale ground model**



Murton & Ballantyne 2016

Lowland Ground Models

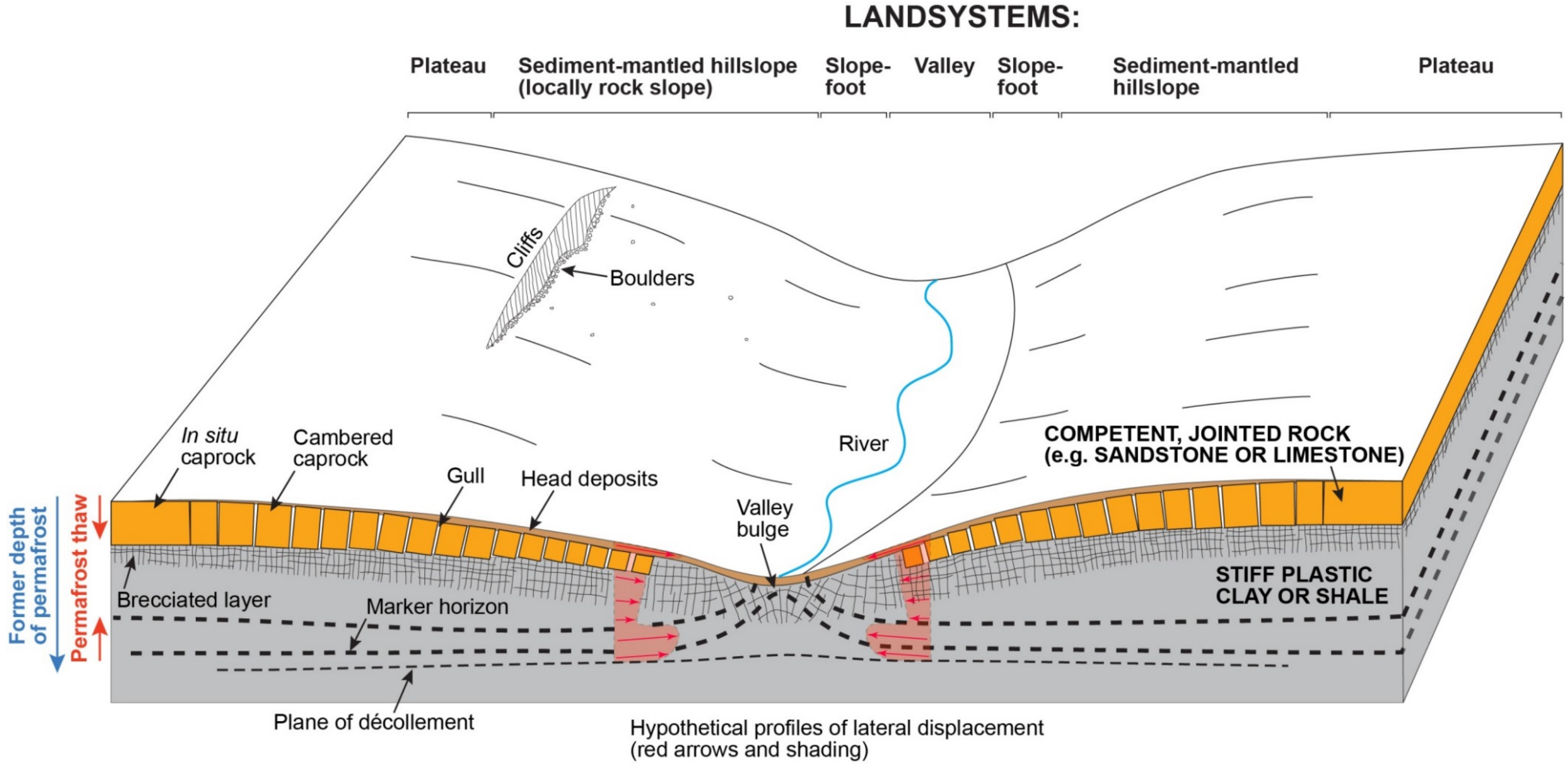
- **Limestone plateau-clay vale (Chalk dry valley) ground model**



Murton & Ballantyne 2016

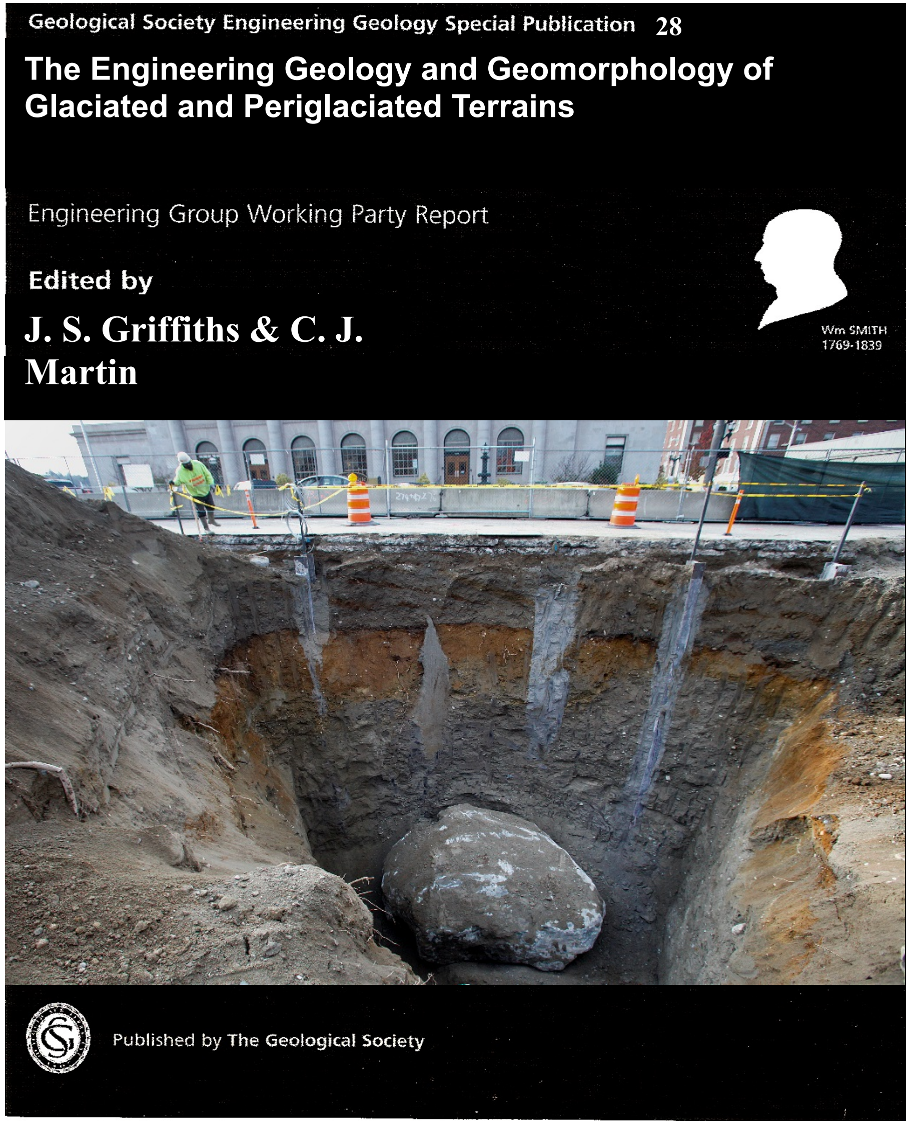
Lowland Ground Models

- Caprock plateau-mudstone valley ground model



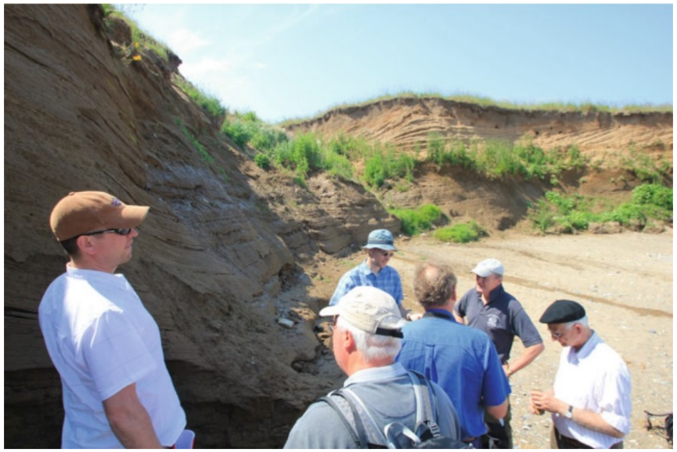
Murton & Ballantyne 2016

Thank You


Geological Society Engineering Geology Special Publication 28
The Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains
Engineering Group Working Party Report
Edited by
J. S. Griffiths & C. J. Martin
Wm SMITH 1769-1839
Published by The Geological Society

EGGS Working Party

- Prof. James Griffiths (Editor)
- Mr Christopher Martin (Chair)
- Mrs Anna Morley (Secretary)
- Prof. Martin Culshaw
- Dr Michael de Freitas
- Prof. David Evans
- Dr David Giles
- Dr Sven Lukas
- Prof. Julian Murton
- Prof. David Norbury
- Prof. Mike Winter



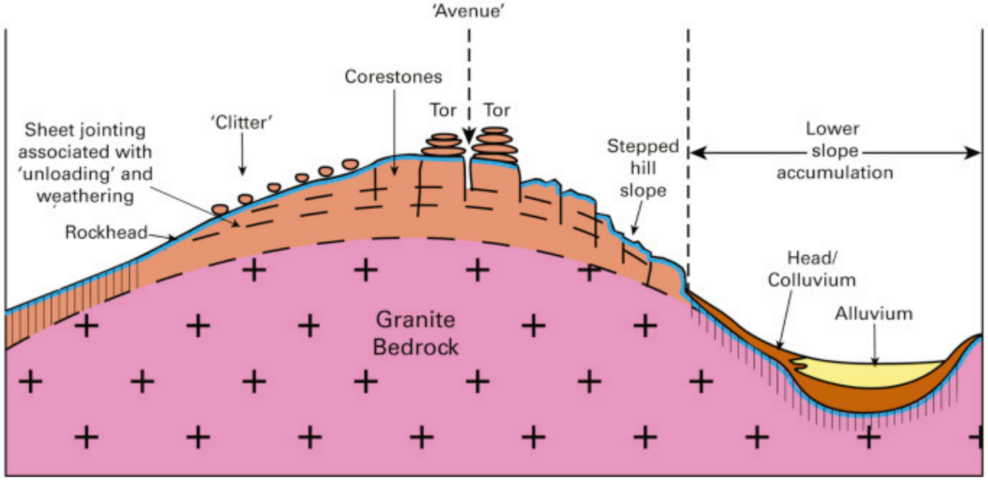
Structure of the Book

- Introduction to Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains (Martin et al.)
- The Quaternary (Lukas et al.)
- Geomorphological Framework - Glacial and Periglacial Sediments, Structures and Landforms (Giles et al.)
- Conceptual Glacial Ground Models: British and Irish Case Studies (Evans)
- Periglacial and Permafrost Ground Models for Great Britain (Murton & Ballantyne)
- Material Properties and Geohazards (Culshaw et al.)
- Engineering Investigation and Assessment (De Freitas et al.)
- Design and Construction Considerations (Winter et al.)
- Conclusions and Illustrative Case Studies (Griffiths & Giles)

The Periglacial Landsystem

- **Lowland Periglacial Terrain Landsystems**
  - Plateau
  - Sediment-mantled hillslope
  - Rock slope
  - Slope-foot
  - Valley
  - Buried
  - Submerged
- **Upland Periglacial Terrain Landsystems**
  - Plateau
  - Sediment-mantled hillslope
  - Rock slope
  - Slope-foot

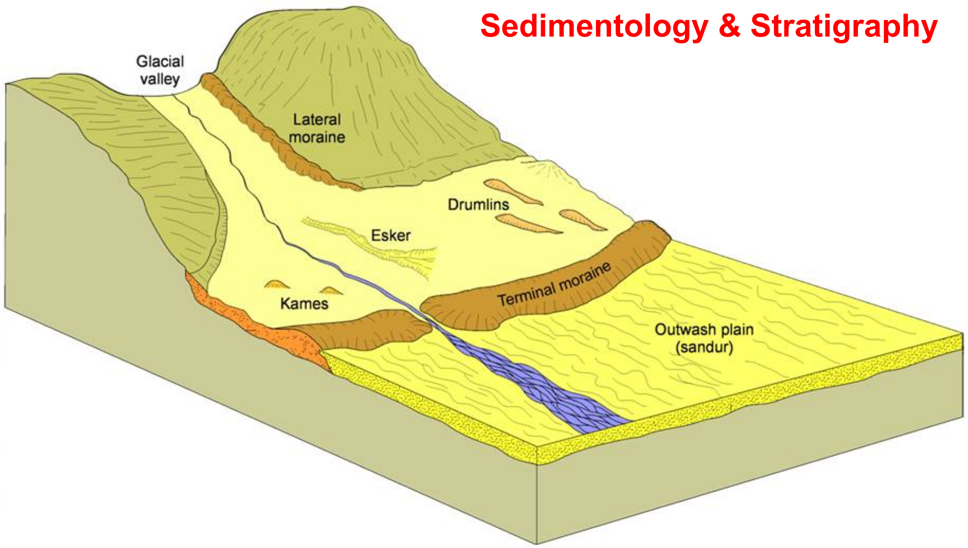
Booth, S., Merritt, J., & Rose, J. (2015). Quaternary Provinces and Domains–a quantitative and qualitative description of British landscape types. Proceedings of the Geologists' Association, 126(2), 163-187.



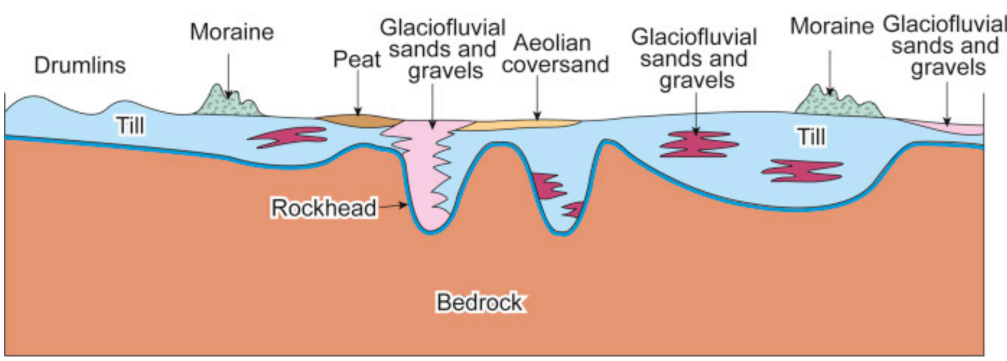
The Glacial Landsystem

- **Ice sheet related landsystems**
  - Subglacial footprint
  - Ice-marginal complexes
  - Supraglacial debris complexes
- **Upland glacial landsystems**
  - Subglacial footprint
  - Ice-marginal complexes
  - Supraglacial debris complexes
- **Glaciofluvial landsystems**
  - Ice-contact settings
  - Proglacial settings
- **Subaqueous glacial landsystem**
  - Ice-proximal depo-centres
  - Distal sediment piles

Nichols 1991
Sedimentology & Stratigraphy

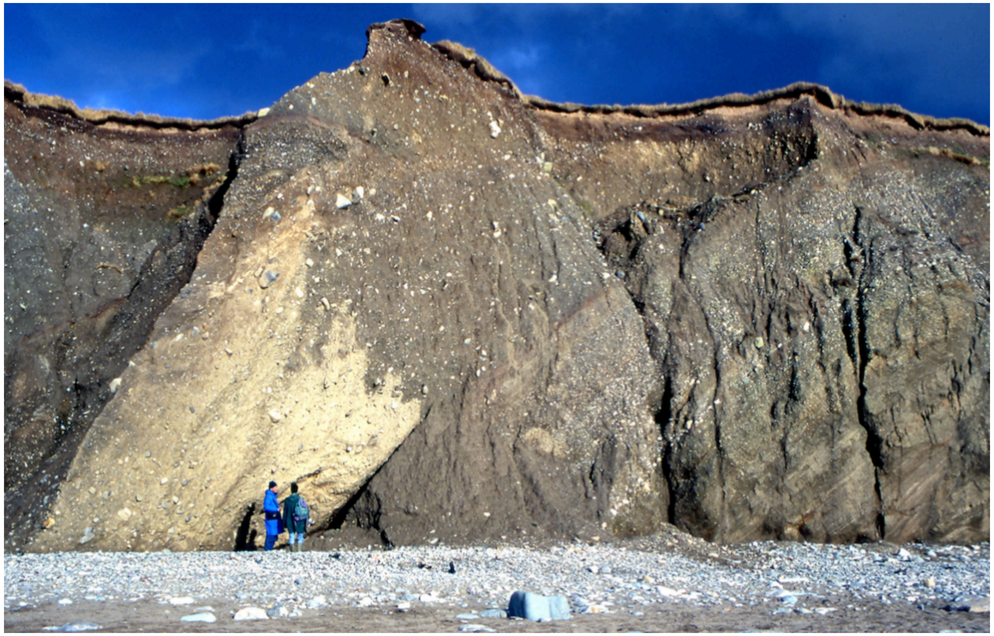


Booth, S., Merritt, J., & Rose, J. (2015)



Deposits, Structures & Landforms

- Building blocks for the Conceptual Ground Model
- Sediments
- Glacial Environment
  - Glacial Depositional Processes
  - Glaciolacustrine & Glaciomarine Processes
  - Glaciofluvial Processes
- Periglacial Environment
  - Periglacial Slope Processes
  - Periglacial Fluvial Processes
  - Fluvio−Aeolian Processes
  - Cold−Climate Periglacial Aeolian Processes
  - Periglacial Weathering Processes



Dinas Dinlle thrust block moraine North Wales (P. Brabham)

Deposits, Structures & Landforms

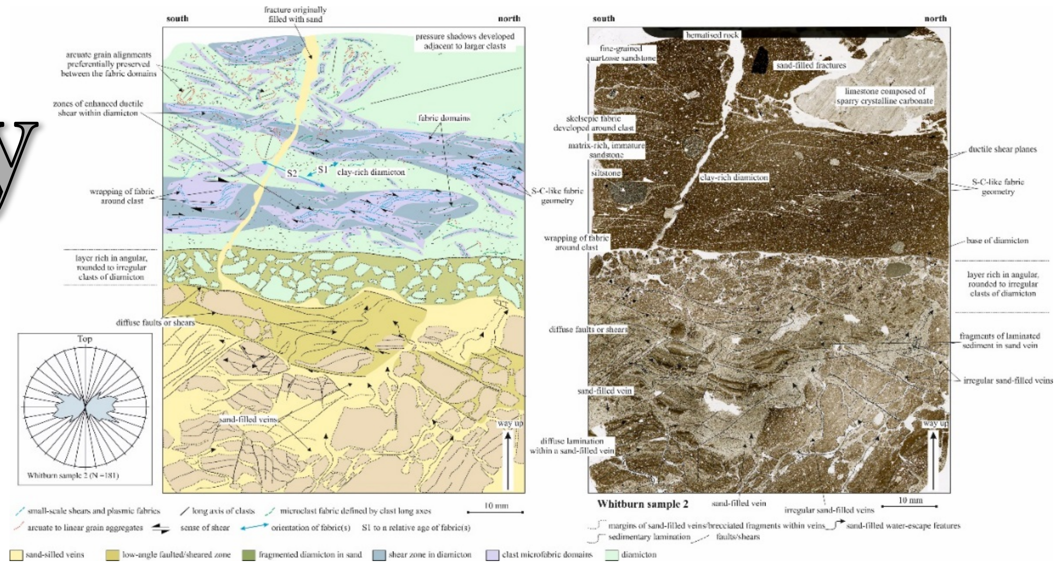
- Building blocks for the Conceptual Ground Model
- Macro Structural, Erosional & Sediment Architectural Elements
  - Glaciogenic Sediment Macrostructures
  - Glaciotectonic Macrostructures
  - Macroscale Erosional Forms
  - Glaciofluvial Macrostructures & Architectural Elements
  - Glaciofluvial Macrostructures & Architectural Elements
  - Periglacial Macrostructures

Ice-wedge pseudomorph within periglacial fluvial sand & gravel, Whisby quarry, Lincoln, England. (J.B. Murton).

Deposits, Structures & Landforms

- **Building blocks for the Conceptual Ground Model**
- **Microstructures**
  - **Periglacial Microstructures in Engineering Soils**
  - **Periglacial Microstructures Superimposed on Glaciogenic Sediments**
  - **Glaciogenic Sediment Microstructures**

Stress History



Base of subglacial mass flow diamicton into meltwater canal, Whitburn, County Durham. Shows localized shearing in diamicton, and disruption and fragmentation due to liquefaction of underlying stratified sediments. (E. Phillips)

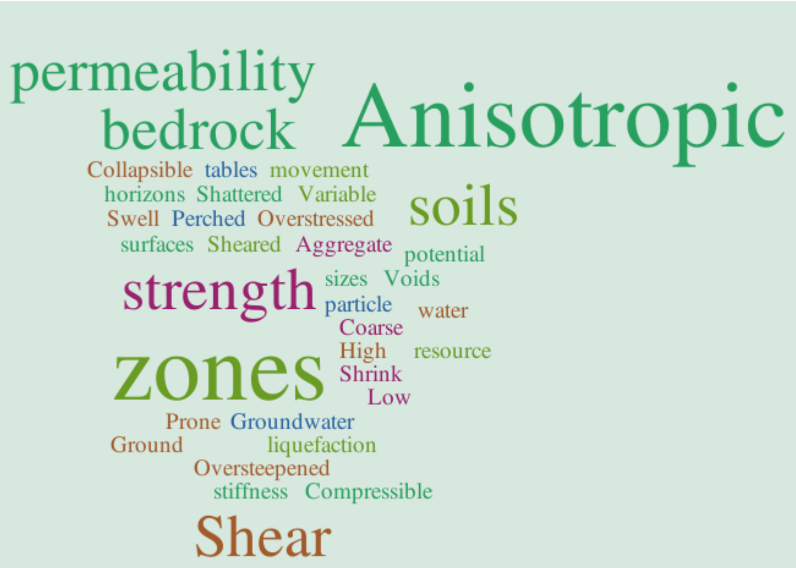
Deposits, Structures & Landforms

- Building blocks for the Conceptual Ground Model
- Landforms
  - Glacial Landforms
  - Glaciotectonic Landforms
  - Glaciofluvial Landforms
  - Subaqueous Landforms
  - Plateau Landsystem
  - Sediment Mantled Hillslope Landforms
  - Rock Slope Landforms
  - Valley Landforms
  - Buried Landforms

Ice rafted chalk megablocks, Overstrand, Norfolk, England. (D. Giles)

Engineering Significance

- **Principal Engineering Significance of Glacial & Periglacial Landsystems – Deposits, Structures & Landforms**
  - Aggregate resource
  - Variable particle sizes, Coarse horizons
  - Anisotropic permeability, Anisotropic strength, stiffness
  - Compressible soils, Swell / Shrink potential
  - Ground movement, Low shear strength
  - Groundwater, High permeability zones
  - Oversteepened zones
  - Overstressed zones
  - Perched water tables
  - Prone to liquefaction
  - Shattered bedrock
  - Shear surfaces, Sheared bedrock
  - Voids, Collapsible soils



Developed Nomenclature

- Geological Origin Name and Qualifiers with Examples in accordance with BS5930
- For example:

- Glacial Depositional Processes
  - Subglacial Traction Till
  - Glaciotectonite
  - Supraglacial mass flow diamicton/ glaciogenic debris flow deposit

Table 3.5 Geological Origin Name and Qualifiers with Examples in accordance with BS5930 (Anon, 2015)

GEOLOGICAL ORIGIN	Geological Qualifier for Origin	Extended Terms Used in Text	Terminology Replaced	Geological Origin Example
GLACIAL DEPOSITS	Undifferentiated			(GLACIAL DEPOSITS Undifferentiated)
	Subglacial traction till		Boulder Clay Lodgement Till Deformation Till Subglacial Melt-Out Till Sublimation Till Comminution Till Lee-side cavity fills/ice-bed separation deposits Endiamict Glaciotectonite Tectomict Soft bed till Deforming bed till	(GLACIAL DEPOSITS Subglacial traction till)
	Glaciotectonite		Comminution Till Deformation Till Exodiamict Glaciotectonite Tectomict	(GLACIAL DEPOSITS Glaciotectonite)
	Mass flow debris	Supraglacial mass flow diamicton/ glaciogenic debris flow deposits	Supraglacial Melt-Out (Moraine) Till Flow till	(GLACIAL DEPOSITS Mass flow debris)

Developed Nomenclature

- Geological Origin Name and Qualifiers with Examples in accordance with BS5930
- For example:

- Periglacial Slope Processes
  - Granular head deposits
  - Clay–rich head deposits
  - Slopewash deposits
  - Fluvio–colluvial deposits
  - Talus deposits
  - Avalanche deposits
  - Blockslope deposits
  - Debris-flow deposits

Previous terms

Diagnostic characteristics

Environment of formation

Common Structures present

Principal Engineering significance

Typical images

Proposed sediment name

Sediment Name 3.5.1.3	**Supraglacial mass flow diamicton/glaciogenic debris flow deposit**
Previous Terms	Supraglacial morainic till, flow till, melt-out till, ablation till
Diagnostic Characteristics	Predominantly clast-supported, massive to crudely stratified or graded diamictons but the sedimentology of supraglacial depo-centres is complex due to multiple cycles of redeposition during formation. Typical facies associations comprise interbedded diamictons and discontinuous bodies of laminated lacustrine sediments, and glaciofluvial sands and gravels. Internal disturbance is common and characterized by normal faulting, flow folding and soft sediment deformation.
Environment of Formation	Glacier surfaces or on ice-cored moraines
Common Structures Present	Although they appear largely massive, individual debris flows can form tabular or lens-shaped units, often with erosional, channelized bases and flat tops. Successive flows can therefore be distinguished by their upper and/or lower boundaries, which are commonly marked by basal concentrations of clasts, upper washed horizons/ interbeds of silt, sand or gravel, or very subtle partings. Each of these characteristics, as well as any internal structures, reflect the nature of the mass flow type, specifically related to the moisture content and coherence of the matrix. Supraglacial mass flow deposits are most confidently identified when juxtaposed with typical supraglacial facies associations. At microscale, structures are particularly well developed at the basal boundaries of individual flows. Here the substrate can be characterized small folds, thrusts and shears, associated with rotated to slightly attenuated diamicton pebbles derived from the overlying debris flow. The debris flow-substrate interface can be marked by elongate 'flames' of the substrate material separating lobate or pendant structures of the debris flow diamicton, which are progressively tilted downflow. The base of the debris flow can contain detached 'flames' or ribbons of the substrate material as well as indicators of rotational deformation, such as circular, arcuate and galaxy-like grain arrangements. Importantly, none of these features is singularly diagnostic of debris flow deposits and can be found in subglacial tills also.
Principal Engineering Significance	Variable particle sizes, Anisotropic permeability, Anisotropic strength, Anisotropic stiffness, Perched water tables, Coarse horizons, Shear surfaces, Sheared bedrock
Typical Images	

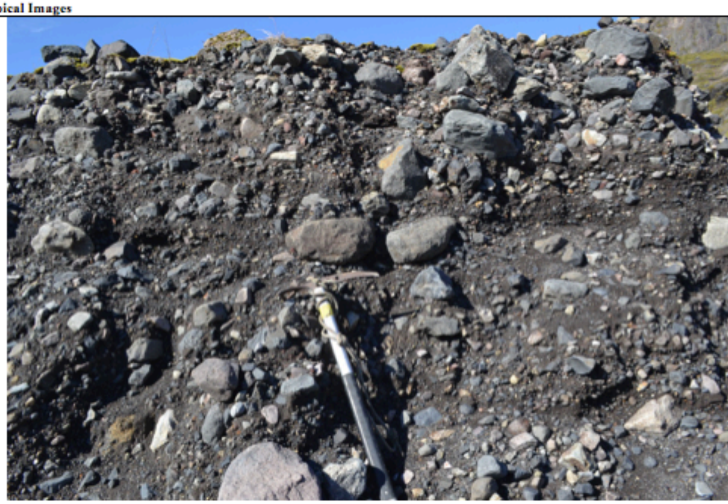


Fig 3.5.1.3a Crudely stratified gravelly mass flow deposits comprising a stacked sequence of discontinuous layers of predominantly clast-supported but locally matrix-supported diamictons separated in places by gravelly lags, Kvíárjökull, Iceland. (D.J.A. Evans)

Sediments

Sedimentological description

Engineering description

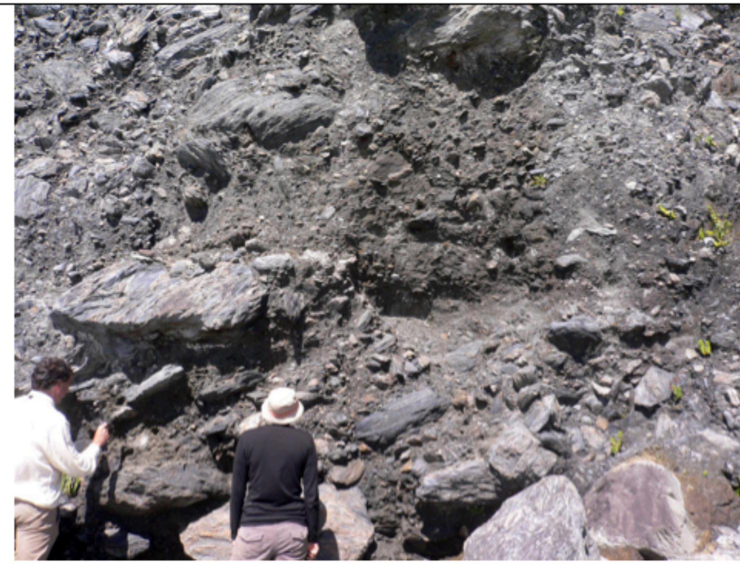


Fig 3.5.1.3c Very crudely stratified boulder-rich and predominantly clast-supported diamictons with contorted bedding structures and localized pockets of stratified sand and gravel. Gillespie's Beach, New Zealand. (D.J.A. Evans)

Sedimentological Description	Engineering Description
Crudely stratified diamictons with a range of clast contents and matrix properties. Often interbedded with or separated by discontinuous layers of silt, sand and gravel. Can display crude grading, often with basal concentrations of clasts. Flow structures or soft sediment deformation features are visible wherever the deposits possess any stratification.	Often indistinctly bedded gravelly sandy CLAYS with low to medium cobble and low boulder content. Occasionally fine upwards. Bedding affected by flow and soft structure deformation features.

Principal References

Lawson (1979), Eyles (1979), Johnson & Rodine (1984), Owen (1994), Johnson & Gillam (1995), Phillips (2006), Evans et al. (2010)

Engineering Geology Case Studies

Bell (2000), Culshaw et al. (1991), McMillan et al. (2000), Reeves et al. (2006a, 2006b)

Principal references

Engineering geology case studies

Macro Structures

Structure Name 3.7.14	Relict periglacial shears
Diagnostic Characteristics	Underlie gently sloping ground underlain by weathered clay bedrocks. Shear surfaces may be polished and striated. Shallow, low-angle basal shears are the most extensive form, at depths of *c.* 1.5–3.0m, at or near the base of the reworked clay or the top of destructured clay, and subparallel to the ground surface. Deeper, subhorizontal continuous shears occur near the base of weathered clay at depths of *c.* 4–8m. Smaller, discontinuous shears produced by internal deformation during mass movement are commonly associated with both the shallow and the deeper shears. High-angle shears sometimes present in reworked and destructured clay, and occur to depths of *c.* 3m beneath hillslopes of 5° or less. Shears are often difficult to see in freshly dug sections when the soil is at its natural water content, and time is needed for drying to cause shrinkage so that the clays pull apart along the shear surfaces.
Principal Engineering Significance	Ground movement, Shear surfaces, Low shear strength, Anisotropic permeability

Typical Image

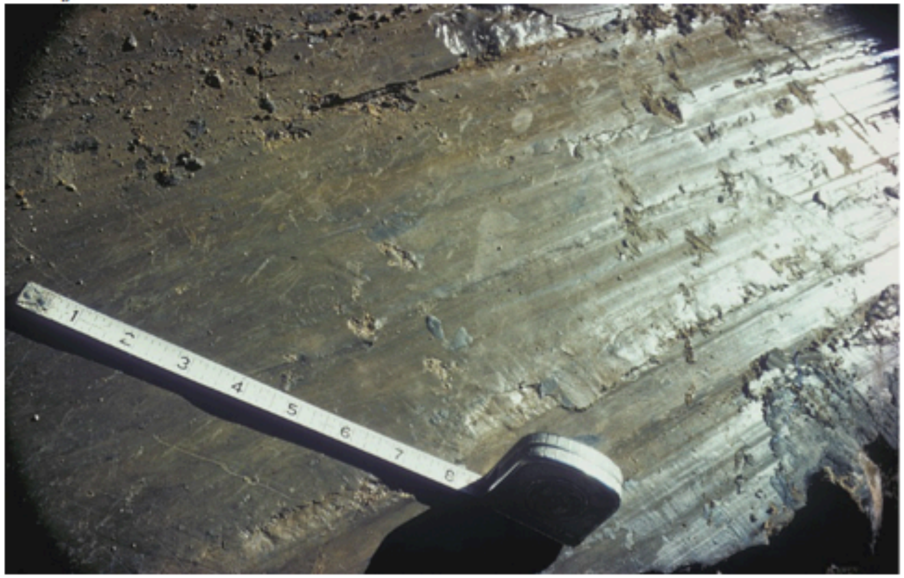


Fig 3.7.14 Basal shear surface with striations and polish in clay-rich head deposits, Sevenoaks, Kent, England. Scale in inches. (J.N. Hutchinson)

Principal References

Harris (2013);
Hutchinson (1991), Spink (1991), Skempton & Weeks (1976), Chandler (1970, 1972), Harris (1977), Skempton et al. (1991)

Diagnostic characteristics

Principal Engineering significance

Typical images

Principal references

Engineering geology case studies

Micro Structures

3.8.2.4 Calcitans Microstructures

Calcitans are discontinuous coatings of secondary calcium carbonate that form by precipitation beneath particles. In this example, they are not found on the same side of the aggregates but in different orientations, which indicates that the aggregates have rotated after the calcitans started to form. Rotation probably accompanied gelifluction.

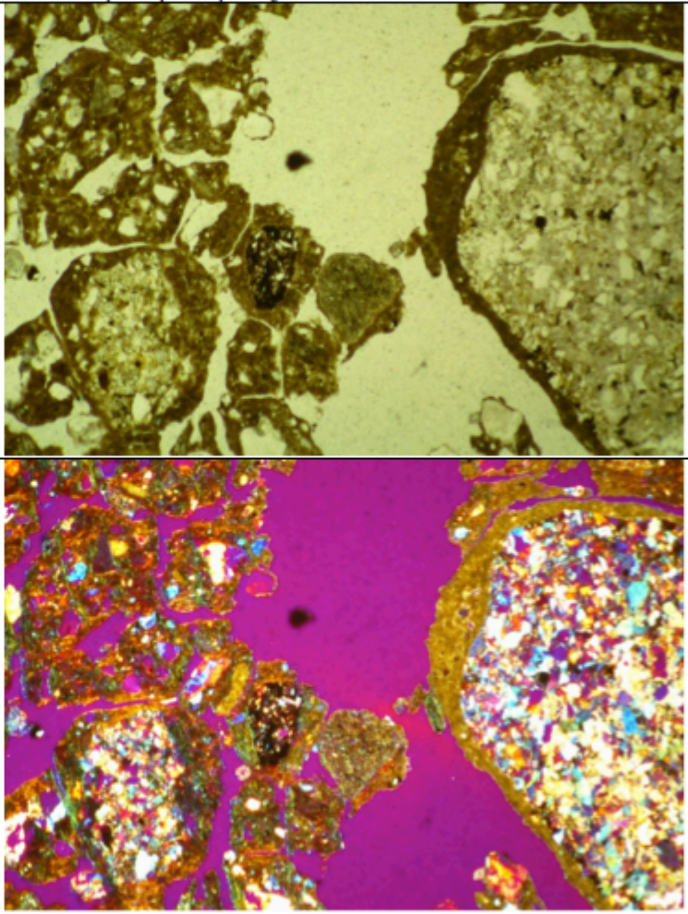


Fig 3.6.7.4a PPL Fig 3.6.7.4b XPL with gypsum wedge. Calcitans (dark brown in upper image) surrounding sediment aggregates ('pebble structure'; multi coloured in lower image) in silty-clay diamicton (till), Mount Provender, Shackleton Range, Antarctica. Field of view = 6.4 mm wide. (J. van der Meer)

Principal References

van der Meer et al. (1993)

Periglacial Landforms

Terrain Unit	3.11.2.1 Solifluction Sheets and Aprons
Image	 Fig 3.11.2.1a Relict solifluction sheets, Broadway, Cotswolds, Worcestershire, England. (D. Giles)
Form / Topography	Solifluction landforms are expanses of mobile or formerly mobile sediments on gentle to moderate slopes that have moved downslope by solifluction and which often terminate downslope at a step or riser. Solifluction sheets generally have little or no surface expression. Morphologically they are smooth convexo-concave slopes that can extend from several hundred metres to 3 or 4km downslope. Shear surfaces can be found typically at 2-3m deep in clay-rich deposits.
Landsystem	Lowland Periglacial Terrain: Upland Periglacial Terrain: Sediment-Mantled Hillslope Landsystem
Process of Formation	Predominant form of periglacial mass movement in active periglacial environments and solifluction deposits and landforms are widespread and are common in relict form. Result from the slow downslope movement of soil due to recurrent freezing and thawing of the ground. Solifluction is due to one or more of three related processes: needle-ice creep, frost creep and gelifluction. Emplaced on slopes with inclinations as low as 1-2° due to excessive pore water pressures generated in thaw.
Modern Analogue	 Fig 3.11.5.2.1b2 Active solifluction sheet Beinn Bheoil, N Highlands, Scotland. (C.K. Ballantyne)
Associated Features	Solifluction lobes, benches and terraces.
Principal Engineering Significance	Ground movement, Shear surfaces, Anisotropic strength, Low shear strength
Principal References	Ballantyne & Harris (1994), Harris (1987, 2013) Hutchinson (1991, 1992), Spink (1991), Skempton & Weeks (1976), Chandler (1970, 1972), Harris (1977), Skempton et al. (1991), Croot & Griffiths (2001), Whitworth et al. (2005)

Image of relict form

Form / Topography

Landsystem

Process of formation

Image of modern form

Associated features

Principal engineering significance

Principal references

Engineering geology case studies

Glacial Landforms

Terrain Unit	3.10.1.6 Whaleback
Image	 Fig 3.8.1.6a Whalebacks, Coire Lagan, Skye, Scotland (D.J.A Evans)
Form / Topography	A streamlined smoothed or scratched bedrock knoll with symmetrical longitudinal profiles, several metres to a few hundred metres high, resembling a whale in profile.
Landsystem	Upland glacial landsystem (hard rock terrain): Subglacial footprint
Process of Formation	Formed by abrasion of both stoss and lee sidesof a rock knoll. Small whalebacks can form under only a few hundred metres of ice, larger ones under deep ice streams.
Modern Analogue	 Fig 3.8.1.6b Striated whaleback, Konowbreen, Svalbard (D.J.A Evans)
Associated Features	Rock drumlins
Principal Engineering Significance	Sheared bedrock
Principal References	Rea (2013a), Glasser & Bennett (2004), Evans, I.S. (1996)

Image of relict form

Form / Topography

Landsystem

Process of formation

Image of modern form

Associated features

Principal engineering significance

Principal references

Engineering geology case studies

University of Portsmouth

Supporting Data

- **Comprehensive reference list**
  - Contemporary glacial & periglacial research
  - Engineering geology case studies

- **QRA Field Guide Listings**
  - Sites to observe sediments & landforms in the UK