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New exposed section in the Ardersier Silts Formation; November 20th-21st, 2017

Engineering Geology and Infrastructure Programme

Open Report OR/19/016

BRITISH GEOLOGICAL SURVEY

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New exposed section in the Ardersier Silts Formation; November 20th-21st, 2017

R Palamakumbura, C Auton

Keywords

Ardersier Silts; SSI, Glacial.

National Grid Reference

Centre point 277921,859239

Map

Sheet 84W, 1:50 000 scale, Fortrose

Front cover

Field photograph of a clay vein intruding into a sand unit in the newly exposed Ardersier Silts Section.

Bibliographical reference

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Foreword

This report is the published product of a field study by the British Geological Survey (BGS) of excavations created for a new water pipeline at Tornagrain, for Scottish Water, undertaken by Morrison Construction, near the village of Ardersier, in the Scottish Highlands. The study was undertaken by Romesh Palamakumbura and Clive Auton, BGS Edinburgh, in November 2017.

Acknowledgements

In addition to the BGS staff acknowledged in the Foreword, Diarmad Campbell, Chief Geologist Scotland provided funding and logistic support that contributed to the production of this report.

Several individuals in Morrison Construction, notably Ryan Keith, Project Manager for the Tornagrain pipeline and his colleague Andy Leggatt enabled timely access to the excavations, provided detailed plans of the pipeline route and initial digital photography of the exposed sequence. This enabled efficient targeting of the field study. This assistance and cooperation was vital to undertaking the study as both the scheduling and location of excavations were subject to numerous changes during the planning of the work, which took place over the preceding 12 months.

The enthusiastic support for this field work, by Vanessa Kirkbride, from Scottish Natural Heritage (SNH), was instrumental in enabling the excavations to take place within a Scottish Site of Special Scientific Interest (SSSI). The designation of the Ardersier site as a SSSI is based primarily on its importance as a locality that provides evidence of a glacial readvance, during the late Quaternary deglaciation of the Moray Firth. In her role within SNH, Vanessa is responsible for assessing the validity of Quaternary SSSI's and, where possible, increasing the scientific data and interpretations of that data available from them.

Contents

Summary

This report provides an overview of field observations from a two day visit to an exposed trench section through the Ardersier Silts Formation that crop out in the moraine that forms the Lateglacial cliffline, near the village of Ardersier in the Highlands Region of north-east Scotland. This section is within the SSSI site for the contorted silts of Ardersier, which are exposed in a nearby cliff face. The trench section exposed nearly 10 m of interbedded silts, sands and gravels and occasional clay veins.

The trench section, which was continuous, was divided into upper, middle and lower portions for ease of description. The upper part of the section comprises a gravel and fine to medium-grained light brown to grey-coloured sand with lamination and occasional planar cross-bedding. This unconformably overlies a fine to medium-grained sand with planar cross bedding.

The middle part of the section comprises a fine-grained sand with well-developed multiple beds of sand showing parallel lamination, planar-crossbedding and minor reverse faulting. In addition, relatively small (1–5 cm thick) sub-horizontal to sub-vertical clay veins cut through the entire sequence.

The lower part of the section comprises a fine to medium-grained sand with massive clay veins and brecciation of the sand within the veins. The blocks of sand vary from centimetres to metres in size. The clay veins also vary in width from 2 cm to nearly 40 cm.

Throughout the section are well-preserved fluid oxidising pathways. These both follow bedding and are displaced across bedding, by small-scale faulting and by fluid migration fronts. They form complex anastomosing networks of staining and occasional concentrations of silt and clay. Generally, the oxidising fluids appear to have migrated along the clay veins and diffused into the surrounding sand.

Structural measurements from the largest and most prominent clay veins indicate that they are all of broadly similar dip and orientation. This may indicate that they all formed as a result of the same phase of fluid movement and glaciotectonic displacement that took place during the formation of the moraine. The upper portion of the newly exposed section, exhibits many of the features previously described from the sands exposed beneath the Baddock Till at the Hillhead Section, whereas the middle and lower parts resemble the sediments and structures that exposed within the Ardersier Silts Formation, beneath the Baddock Till, in the Jamieson's Pit section.

The well-exposed sedimentary structures within the sediments of the Ardersier Silts Formation are interpreted as a coastal shallow marine setting. The well-preserved hydrofracture network within the section demonstrates the diverse range of glacial deformation that occurred during deglaciation. It is likely that the hydrofracture network developed as consequence of ice-push and possibly glacial over-riding during the deglaciation of the Moray Firth ice-stream.

1 Introduction

The superficial sediments in the Ardersier area provide a unique insight into the glacitectonic processes during Late Glacial Maximum (LGM) deglaciation (Merritt, Auton, & Firth, 1995). The contorted silts, sands and clays of the Ardersier Silts Formation (Gordon & Merritt, 1993) in this area have been designated a site of special scientific interest (SSSI) since 1984. A new sewage pipeline by Scottish Water provided a unique opportunity to study previously unexposed sediments of the Ardersier Silts Formation in this area.

The study area is north of the small village of Ardersier (Figure 1), which is approximately 12 km to the east of Inverness. The route of the pipeline is shown in Figure 2. The pipeline runs north to south from the sewage works at the shore, towards Ardersier Village. The examined trench section corresponds with, the portion of the pipeline that takes a short uphill incursion up to the top of the degraded Lateglacial cliff at *c.* 15 m above OD (Ordnance Datum), to provide a head, for flow between the sewage works and the village.

Figure 1. Google Earth © image of the study area, near the village of Ardersier in the Highlands.

The site is located on the Nairn Sandstone Formation of the Forres Sandstone Group of the Orcadian Old Red Sandstone Supergroup. The Nairn Sandstone Formation comprises a yellow-brown and grey sandstones with sporadic mudstone seams, interpreted as representing a fluvial environment during the Devonian.

The superficial sediments in the area are reflective of the Late Quaternary glacial history of the region, in particularly deglaciation after the Last Glacial Maximum (LGM). The mapped superficial sediments across the surrounding area include Holocene tidal and beach deposits, the Late Devensian Ardersier Silts Formation, raised marine deposits, Alturie Gravels Formation, Glacial till and glaciofluvial deposits. The pipeline route crosses the Holocene raised marine deposits and the Ardersier Silts Formation.

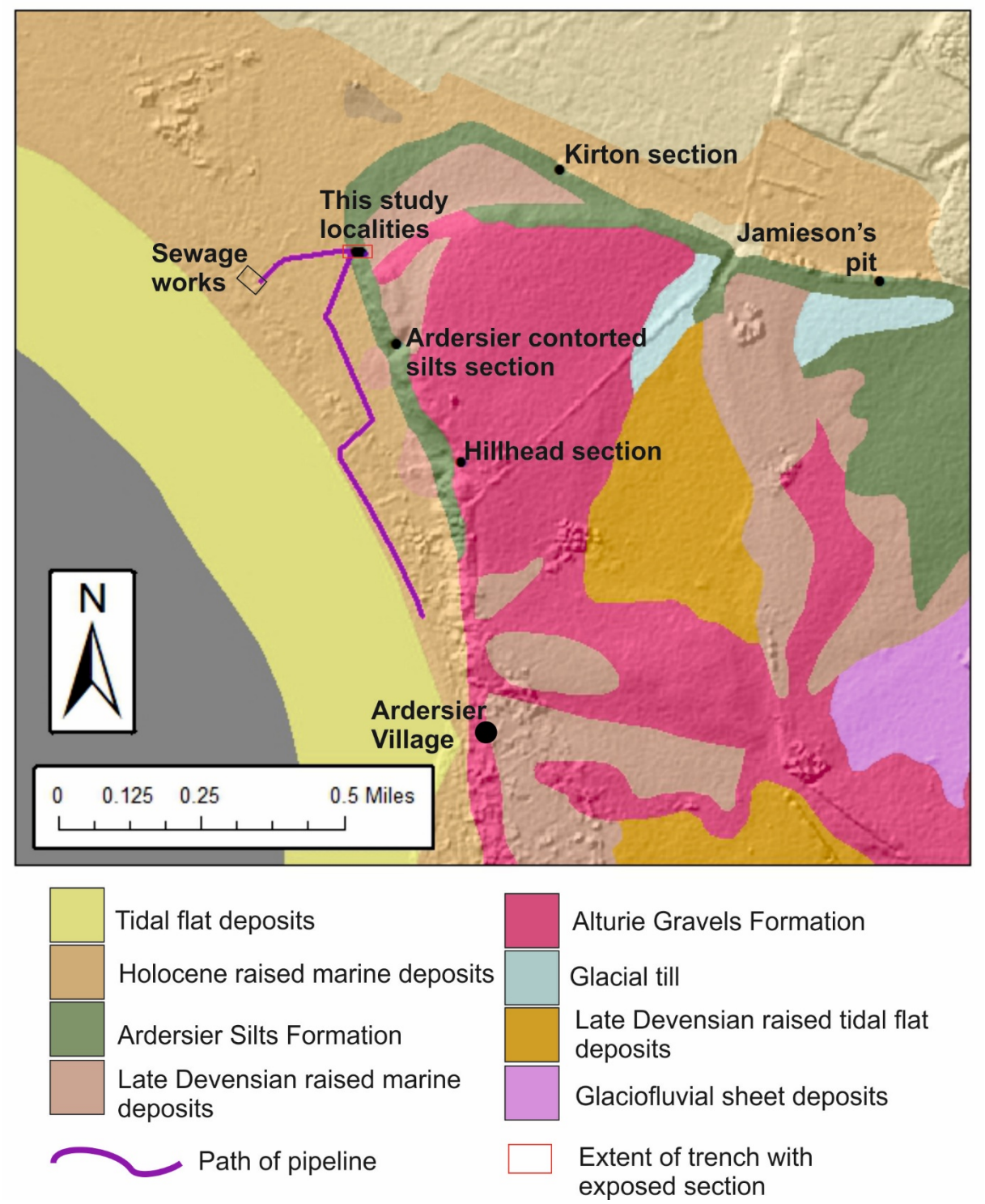

Figure 2. Superficial geological map of the study area, overlain on the Next map © surface model.

Two days of fieldwork were undertaken to study the newly exposed section prior to back filling of the trench. The aim was to document the sedimentology and secondary glacitectonic structures in the exposed trench section. The following report provides a description of the sediments and structures observed.

2 Field results

2.1 INTRODUCTION TO FIELD RESULTS

The exposed trench section started from the position of the head apparatus installed on the pipeline at the top of the degraded Lateglacial cliff where the Ardersier Silts Formation were exposed. It continued downslope into the outcrop of the Holocene raised marine deposits. The exposed trench section, which ran approximately east to west was logged from the top towards the base of the slope. The logging was confined to the outcrop of the Ardersier Formation and overlying Late Devensian raised marine deposits. The field results are presented as a series of localities, [Field Obervation Points (FOP's)] that were generally numbered sequentially from the top of the trench to the bottom. The only exception to this was Localities 13–15 which were number inversely down the section (see Figure 3, lower section log).

Field Observation Points 1-6 were assigned to previously described localities in the Arderiser Silts Formation in the Ardersier area, which are summarised to provide a brief stratigraphical context for the results from this newly exposed section (see Section 2.2 below)

The new section is described in three parts, an upper (localities 7-8), middle (localities 9-11) and lower part (localities 12-16). Each of these parts are distinguished based of different primary and secondary sedimentary and tectonic features.

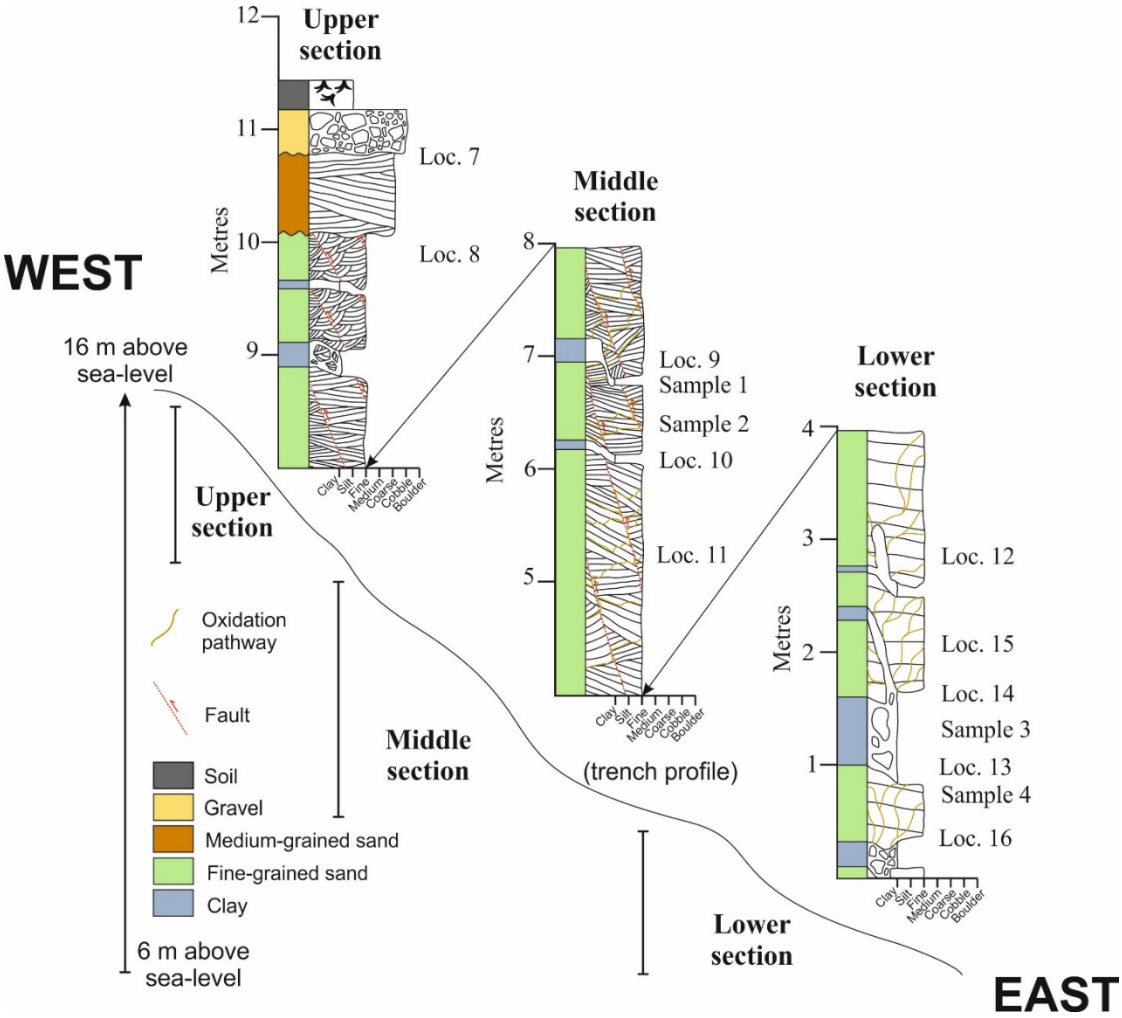

Figure 3. Sediment logs of the upper, middle and lower parts of the exposed trench based on new field observations.

2.2 SURROUNDING SITES OF INTEREST

Field observation points 1, 2, 4 and 6 are of sites of particular interest to this work and discussed below. In contrast, field observation points 3 and 5 are not relevant here and are therefore not included. The locations of these field observation points is shown on Figure 2.

2.2.1 Field Observation Point 1

Collected on: 15/11/2017 15:11:01 **At Coordinates: X:** 279390 **- Y:** 856160

Location Description: Jamieson's pit

Summary Label: Jamieson's pit

This locality corresponds with the original section described by Jamieson (1874) and subsequently known as 'Jamieson's Pit' where marine molluscs, ostracods and foraminifera where recorded associated with beds of silt and clay. The shells are of cold water aspect, but not necessarily High Arctic or particularly characteristic of ice-proximal conditions. The section is capped by a diamicton (the Baddock Till).

2.2.2 Field Observation Point 2

Collected on: 15/11/2017 16:33:11 **At Coordinates: X:** 278490 **- Y:** 856470

Location Description: Kirkton section

Summary Label: Kirkton section

The 'Kirkton Section' locality corresponds with the section excavated in 1990, into the bluff below a Late Devensian raised shoreline at 21.6 m above OD. The 1990 section exposed flat-lying, moderately to thickly bedded, rhythmically laminated sands, silts and clays, that showed little or no evidence of glacitectonic disturbance or hydrofracturing.

2.2.3 Field Observation Point 4

Collected on: 15/11/2017 16:37:42 **At Coordinates: X:** 278210 **- Y:** 855650

Location Description: Hillhead

Summary Label: Hillhead section

The 'Hillhead section' locality corresponds with the natural exposure at the top of the main Postglacial cliff line. It exposes sand with ripple and cross-bedding structures that are cut by low-angle silt-lined shears. The Baddock Till overlies the Hillhead Sand Member.

2.2.4 Field Observation Point 6

Collected on: 15/11/2017 16:50:12 **At Coordinates: X:** 278030 **- Y:** 855980

Location Description: Contorted silts section

Summary Label: Contorted silts

The 'Contorted Silts Section' locality corresponds with the natural exposure close to the top of the Main Postglacial cliffline that exposes thinly interbedded fine-grained sands and clayey silts that exhibit abundant soft sediment deformation (ball and pillow) structures. The beds are deformed by large scale (1–5 m wavelength) folds, flat lying thrusts and with small scale high-angle normal faults.

2.3 THE UPPER SECTION PART OF THE 2017 SECTION

The upper part of section is described in localities 7 and 8. Significantly, these localities include the upper boundary of the Ardersier Silts Formation with the overlying Devensian raised marine sediments.

2.3.1 Field Observation Point 7

Collected on: 21/11/2017 10:08:17 **At Coordinates: X:** 277929.508 - **Y:** 856239.477

Location Description: Top part of trench exposing Late Devensian raised beach and contact with possible Hillhead Sands Member

Summary Label: Raised beach deposit

The first locality is from the upper most part of the trench section and contains three distinct sedimentary units (Figure 4). The entire section is capped by a 20 cm thick dark brown soil. The upper most unit exposed is a 30 cm-thick gravel deposit, composed of well-rounded to sub rounded cobble-sized clasts varying in size from 1 to 12 cm. The deposit is clast supported with a coarse-grained sand matrix. The unit has poorly developed upward fining and horizontal stratification. The gravel is interpreted as a Late Devensian raised beach deposit. The unit unconformably overlies the central unit.

The central unit is a light brown, fine to medium-grained sand with planar lamination and some cross lamination picked out by with occasional dark brown-coloured layers (Figure 5). The unit is in total 60 cm thick, and does not seem to vary in thickness across the exposed section. A basal pebble lag is observed discontinuously along the basal unconformity. The lag comprises well rounded cobbles of 3–6 cm in size and with no evident internal sedimentary organisation. It is inferred that this unit is likely to be the Hill Head Sand Member.

The lowest unit (Figure 6) is a pale grey to yellow-coloured, medium to fine-grained unlithified sand with ripple cross-bedding. Steep angled lamination with some signs of shearing. The unit generally dips steeply northward. This dip is the result of local small scale faulting. Fine and medium-grained sand layers are also observed.

The unconformity separating the lower and middle units is an undulating surface, varying in height by approximately 3–5 cm (Figure 6c). A faint dark to light brown layering is observed along the unconformity, which is result of iron staining of the grains of the middle unit along this surface. The layering is parallel to the surface of the unconformity and cross-cuts the parallel lamination of the middle unit.

2.3.1.1 PHOTOS

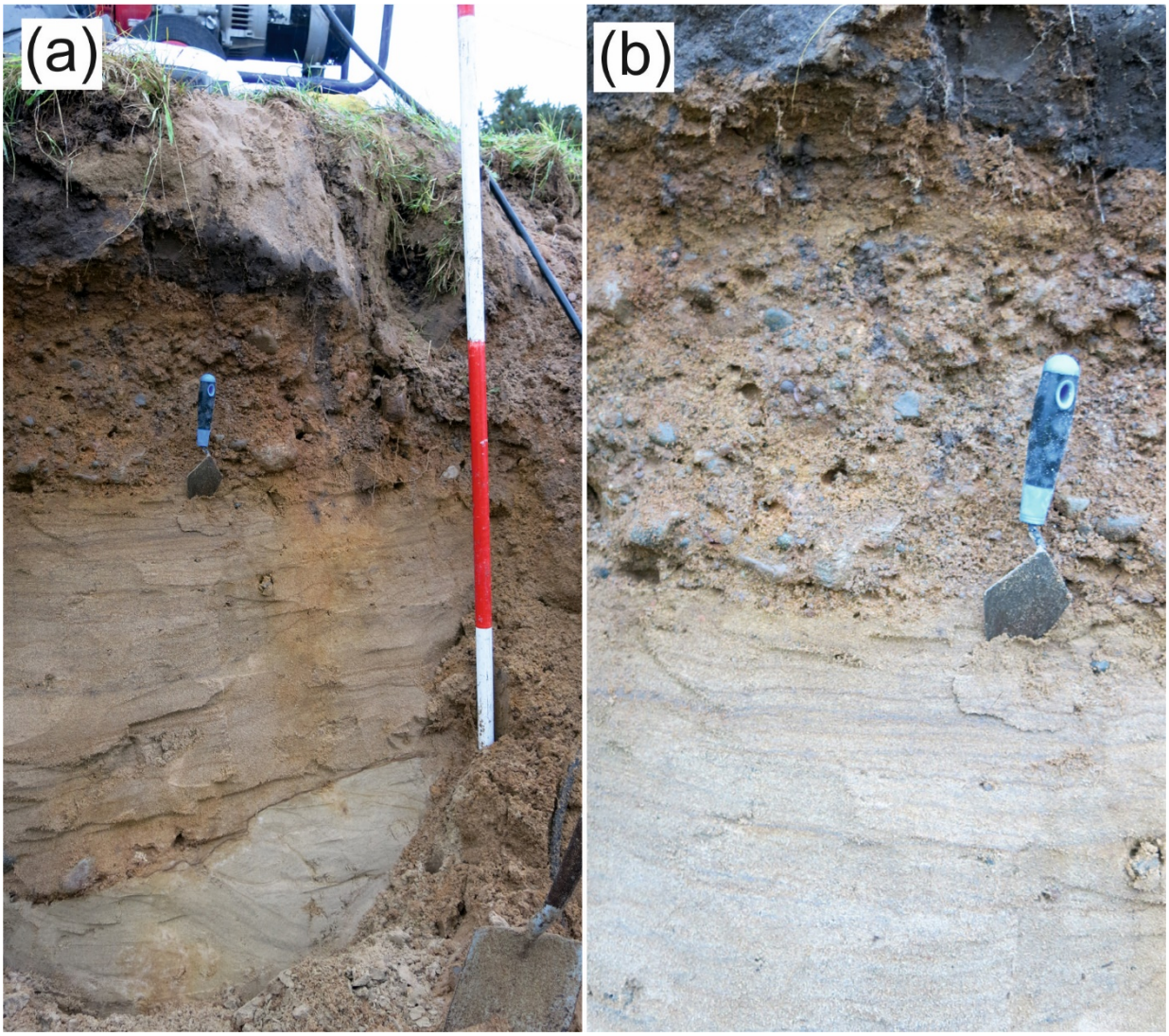

Figure 4. (a) Overview of upper part of section, covering possible Hillhead Member Sands (pale grey) and overlying raised beach deposits and (b) Contact between upper (Late Devensian) raised beach gravel and underlying (central) laminated and cross-laminated sands.

Figure 5. Unconformity between possible Hillhead Member (Ardersier Silts Formation) and overlying raised beach sands. Fine to medium-grained cross-bedding can be seen in the Hillhead Member.

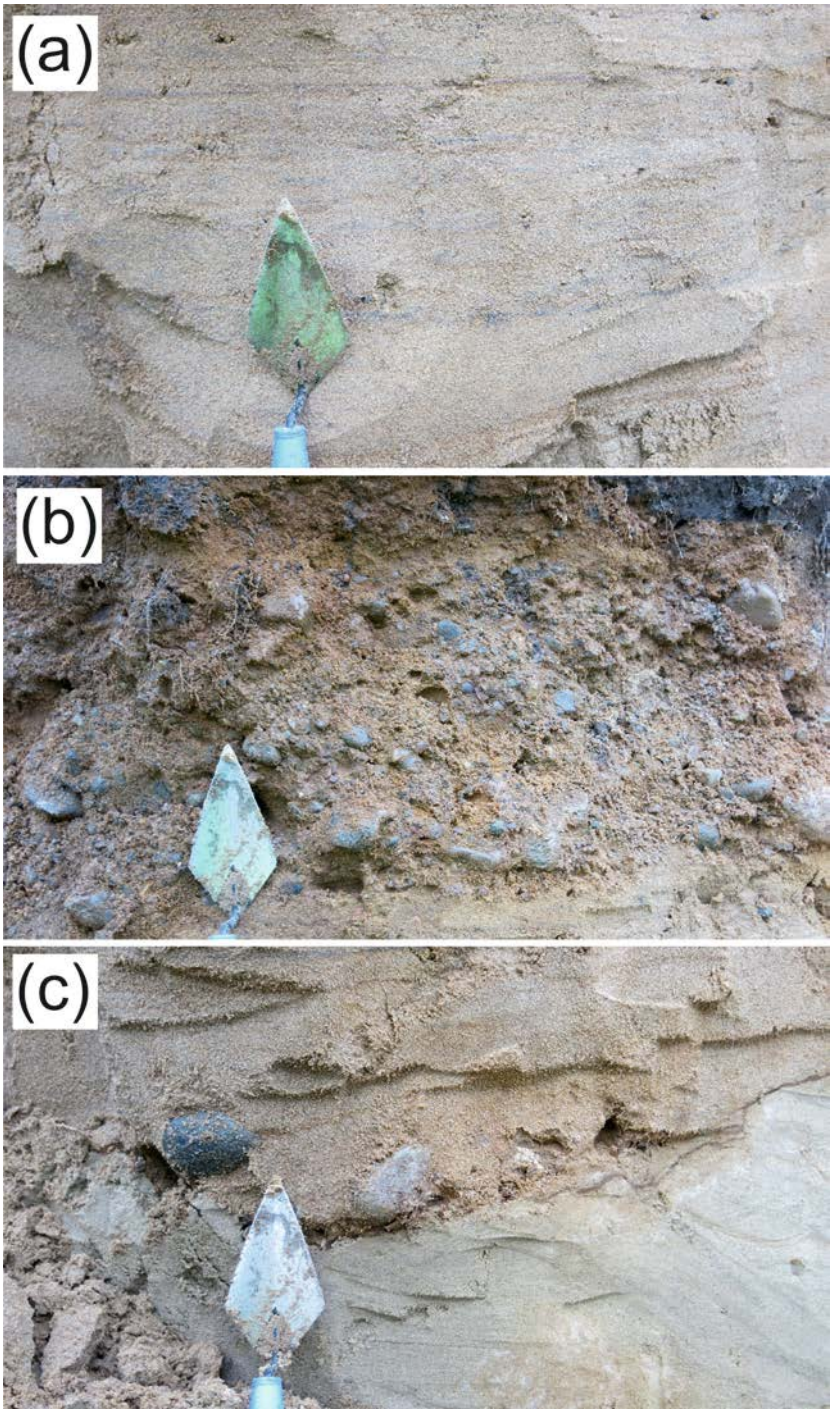

Figure 6. (a) Lamination in the (central) Late Devensian raised beach sands unit; (b) Raised Beach gravel capping the entire unit; and (c) Cobble lag along unconformity between Hillhead Member and the overlying raised beach sands.

2.3.2 Field Observation Point 8

Collected on: 21/11/2017 10:55:00 **At Coordinates: X:** 277928.673 **- Y:** 856239.577

Location Description: Start of clay and gravel injected layers in sand

Summary Label: Upper injected clay

Locality 8 is the next locality along the trench and located approximately 30 cm below the unconformity surface observed at Locality 7. This locality comprises a clay vein and brecciated

clasts composed of the surrounding sand that are observed within clay (Figure 7). The sand breccia clasts are angular and variable in shape and size from square to oblong in shape and from 5–30 cm in size. No obvious orientation or sorting was noted of the clasts. Generally, the breccia is matrix-supported. Some original sedimentary structures are visible in the breccia clasts, including lamination and cross-bedding. The surrounding clay is a pale pink in colour and forms an approximately 0.5 m thick by 1.5 m wide unit. The clay unit is massive with no obvious sedimentary structures.

The sand unit is fine to medium-grained and generally pale white in colour with occasional light brown layers. The sedimentary structures within the sand are generally sub-horizontal.

2.3.2.1 PHOTOS

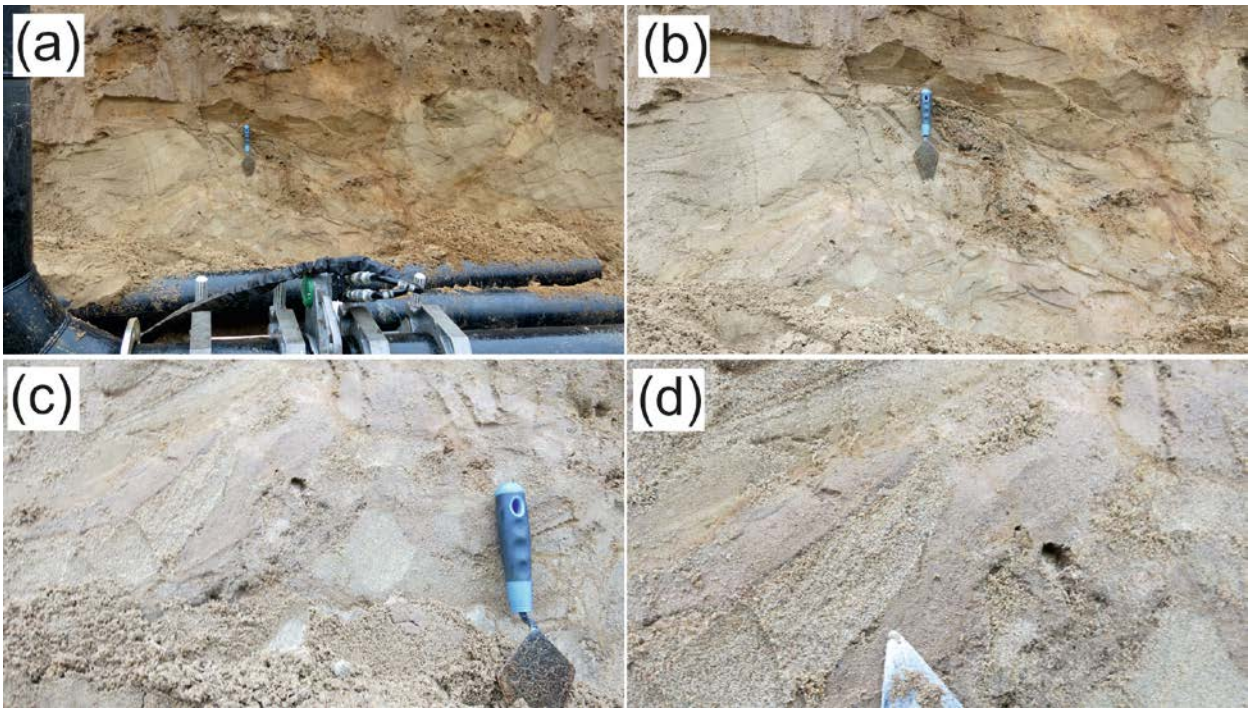

Figure 7. (a) Overview of top of Ardersier Silts section, showing clay and gravel injections and brecciated sand blocks; (b) Small-scale brecciation in the top part of the Ardersier Silts (Hillhead Member); and (c-d) Small scale brecciation in the top part of the Ardersier Silts (Hillhead Member).

2.4 MIDDLE SECTION PART OF SECTION

2.4.1 Field Observation Point 9

Collected on: 21/11/2017 11:15:51 **At Coordinates: X:** 277926.601 **- Y:** 856239.945

Location Description: Thin (1-3 cm) clay injections in tilted sand unit, in the upper part of section.

Summary Label: Upper clay injection

This locality is situated further eastwards along the trench and down section at 2.2 m depth, representing a slightly lower part of the pale white-colour unlithified sand seen at Locality 8. There are least three units identified in the sand, distinguished by different sedimentary structures and cross-cutting relationships (Figure 8). Firstly, the upper sand truncates the cross-bedded middle unit. Generally, the sand grains are sub-angular, well-sorted and comprised of quartz, feldspar and occasional heavy minerals. Small reverse faults of mostly 2–5 cm displacement, with occasional 20 cm displacements, are observed to cross-cut the entire exposed section. Secondly, a 1 m thick

unit of light brown to grey, fine to medium-grained sand with planar cross-bedding. Finally, the upper most part of the sand is a pale white to grey in colour, fine-grained and comprises planar lamination and some small planar cross-bedding (Figure 9). The lower unit of pale white, fine-grained sand with planar lamination.

Two sub-horizontal to sub-vertical clay veins are observed in the upper part of the middle section (Figure 3 and Figure 8). The larger of the two clay veins is sub-horizontal in the upper most part of the sand, and then steeply dips down to truncate the entire exposed sand section (Figure 10). The clay vein is *c.* 20 cm in thickness when sub-horizontal, but reduces in thickness to 5 cm thick where it becomes sub-vertical. The sub-horizontal part of the clay cuts acutely across the parallel lamination preserved in the sand, and then follows the path of a reverse fault, which has approximately 20 cm of displacement. The clay is a pinkish red in colour with discontinuous reddish brown staining. The orientation of the reddish brown staining is variable, but it is generally parallel to the orientation of the clay vein and predominantly observed along the edges of the vein. A number of brown-coloured fluid staining pathways are noted. These start in the clay vein and continue into the sand unit, before fading out after 30–50 cm. The staining pathways have highly variable orientations, but tend to both follow and also cross-cut sedimentary structures (Figure 11).

The second clay vein is 1–2 cm thick and approximately 20 cm long, dipping at *c.* 45^{o} (Figure 12). The clay is a reddish grey colour and is apparently structureless at the macro-scale. Samples were taken from the two clay veins at this locality, with the aim of describing any possible microstructures associated with them, in order to understand the processes controlling their emplacement.

2.4.1.1 PHOTOS

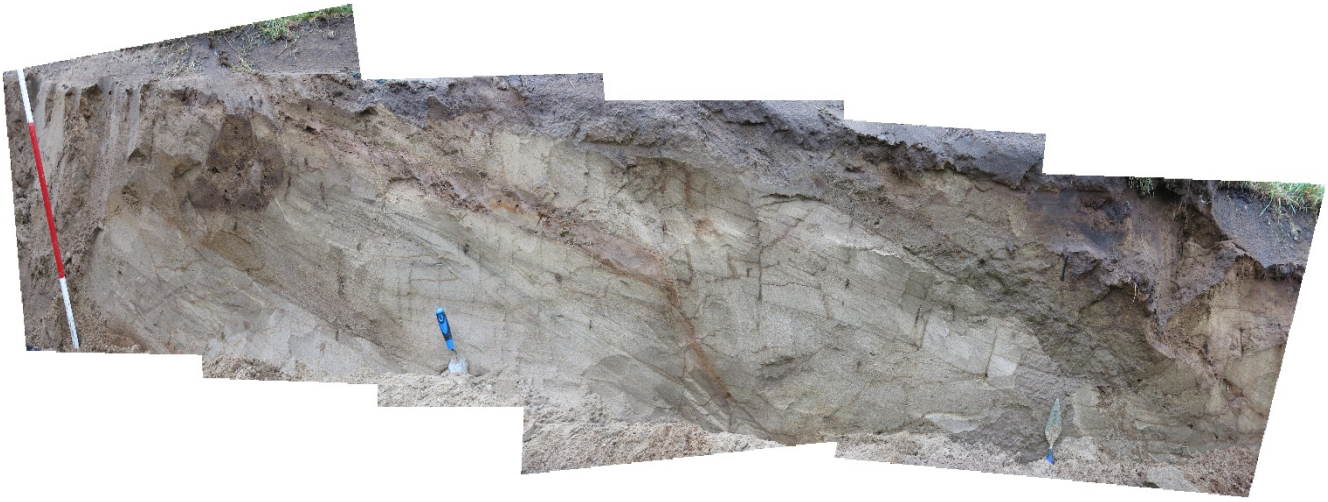

Figure 8. Overview of section with SW dipping clay layers (injections?) in laminated and occasionally layered sand.

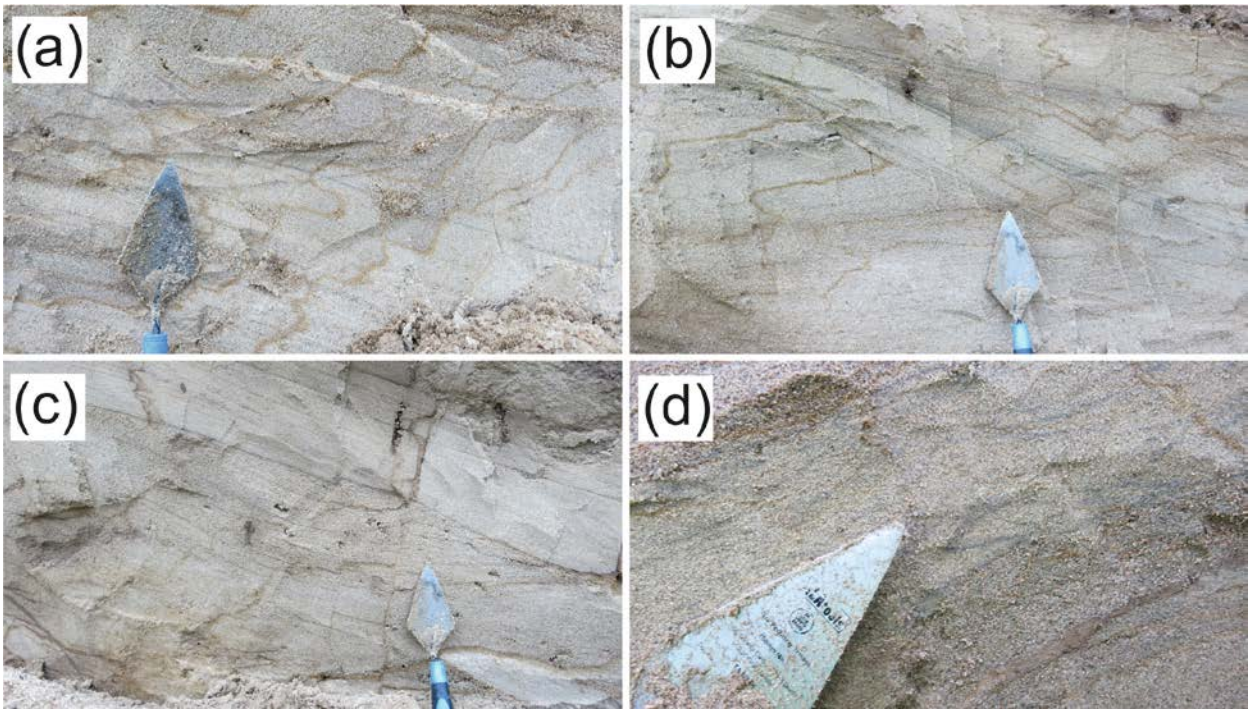

Figure 9. (a) Oxidation along lamination and stepping up between lamination; (b) Planar to tabular cross-bedding with alteration along bedding. Alteration commonly truncated at base of cosets; some high-angle features cut cross lamination; (c) Fine and coarse-grained sand layers in the cross-bedded units; and (d) Fine and coarse-grained sand layers in the cross-bedded units (possible traces of silt drapes on ripples in finer sand unit).

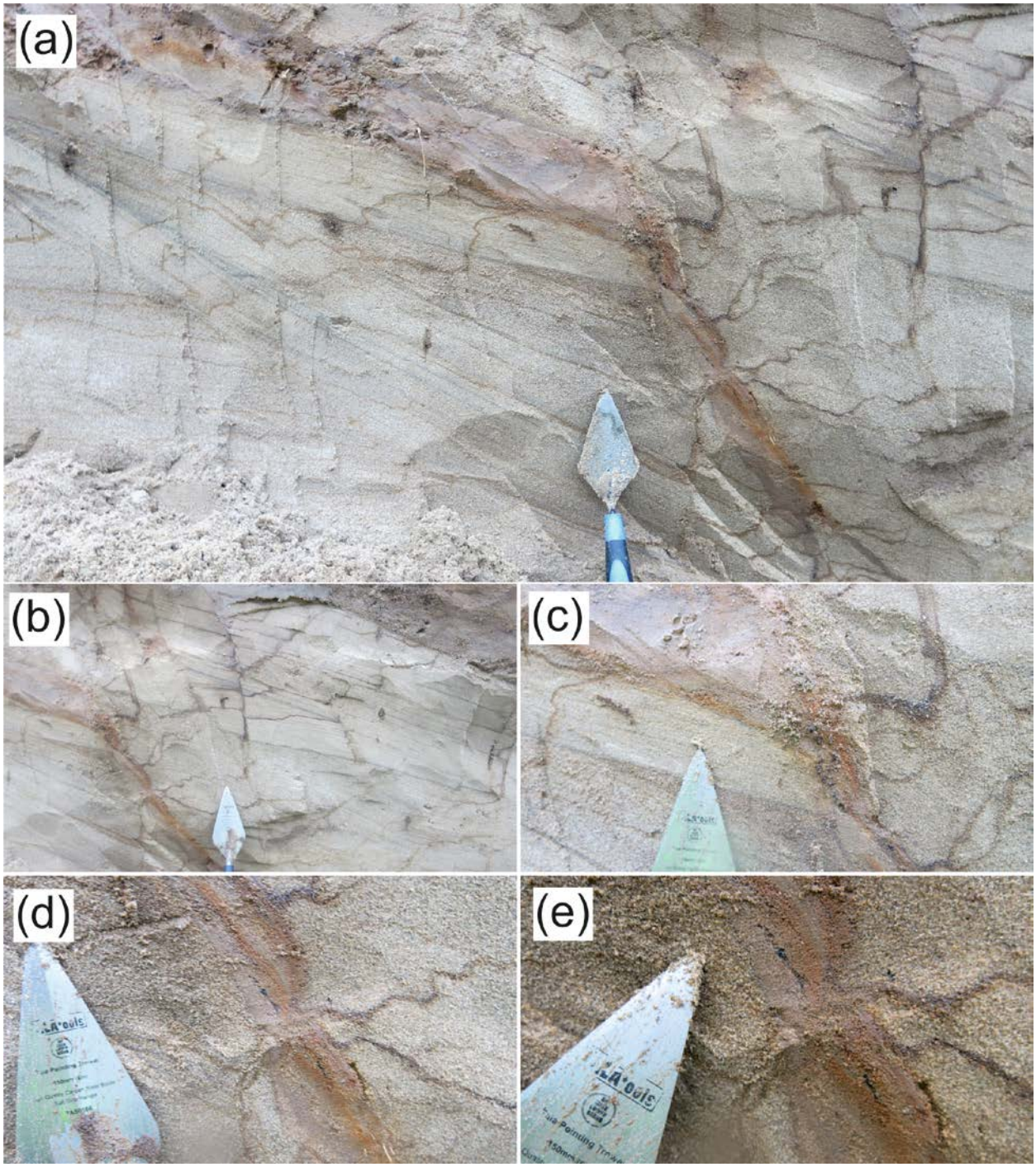

Figure 10. Clay layer changing orientation and thickness from bedding parallel (thick, shallow dipping) to thin, steeply dipping. In addition, oxidation veins appear to come off the clay layer.

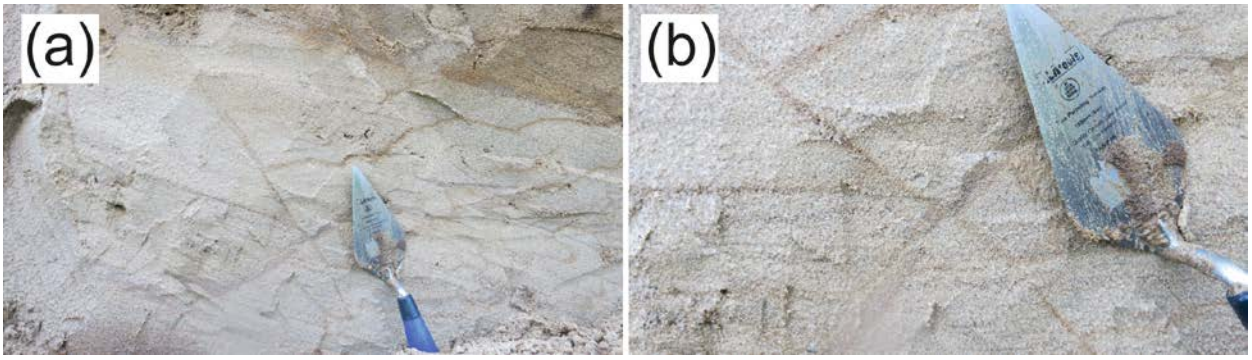

Figure 11. Thin clay/silt layer cross-cutting lamination structures in sand with oxidation bands coming off the clay.

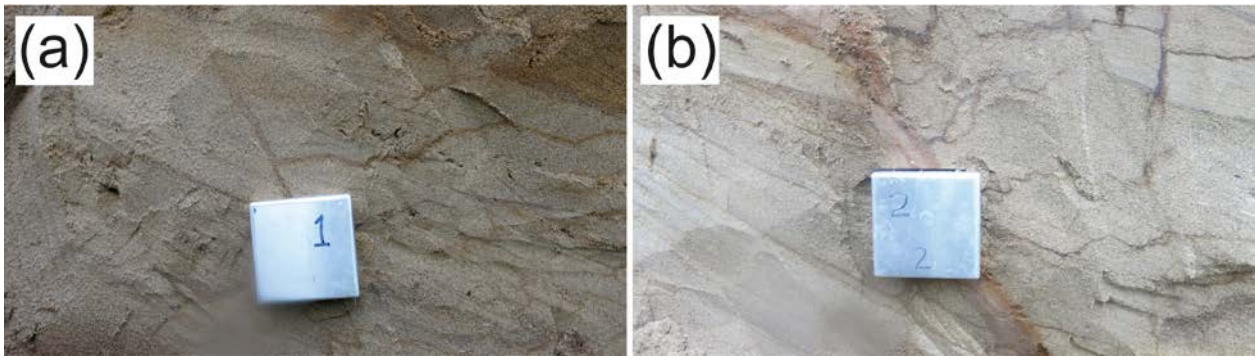

Figure 12. Photo of samples 1 and 2 box in the section.

2.4.1.2 SAMPLES

Original Sample Number	Sample Type	Sample Comment
CAA_1	Superficial Deposit Sample	45° clay injection which is 25 cm long and 1 cm wide. The clay truncates medium to coarse sand. Sample is at 2.2 m depth.
CAA_2	Superficial Deposit Sample	45° sub vertical clay injection with brown veining coming off in multiple roughly oblique directions. Sample is from 2.7 m depth.

2.4.1.3 STRUCTURAL OBSERVATIONS

Feature	Azimuth	Dip	2nd Attrib	3rd Attrib	Grouping	Comment
Strata_Inclined_2	270	50				dip of clay seam of sample 2

2.4.2 Field Observation Point 10

Collected on: 21/11/2017 13:17:26 **At Coordinates: X:** 277922.19 **- Y:** 856239.945

Location Description: Brecciated blocks of sand surrounding a clay layer

Summary Label: Clay layer breccia

Field observation point 10 is at a breccia horizon within the sand, which is at 4.6 m depth in the section. The breccia predominantly comprises 5–10 cm sub-angular blocks of sand, some rounded blocks are also present (Figure 13). Variation in the orientation of sedimentary structures within the blocks suggest that they are locally rotated. The breccia is associated with a sub-horizontal approximately 2 cm-thick clay vein. It comprises a reddish brown clay with light brown edges and occasional centimetre-sized pockets of silt. As was the case with the previous clay veins in the section, there are a number of fluid oxidation pathways, which propagate from the veins. The fluid

veins follow a stepped path away from the clay seams. They follow bedding structures for several centimetres and then step to the next structure.

2.4.2.1 PHOTOS

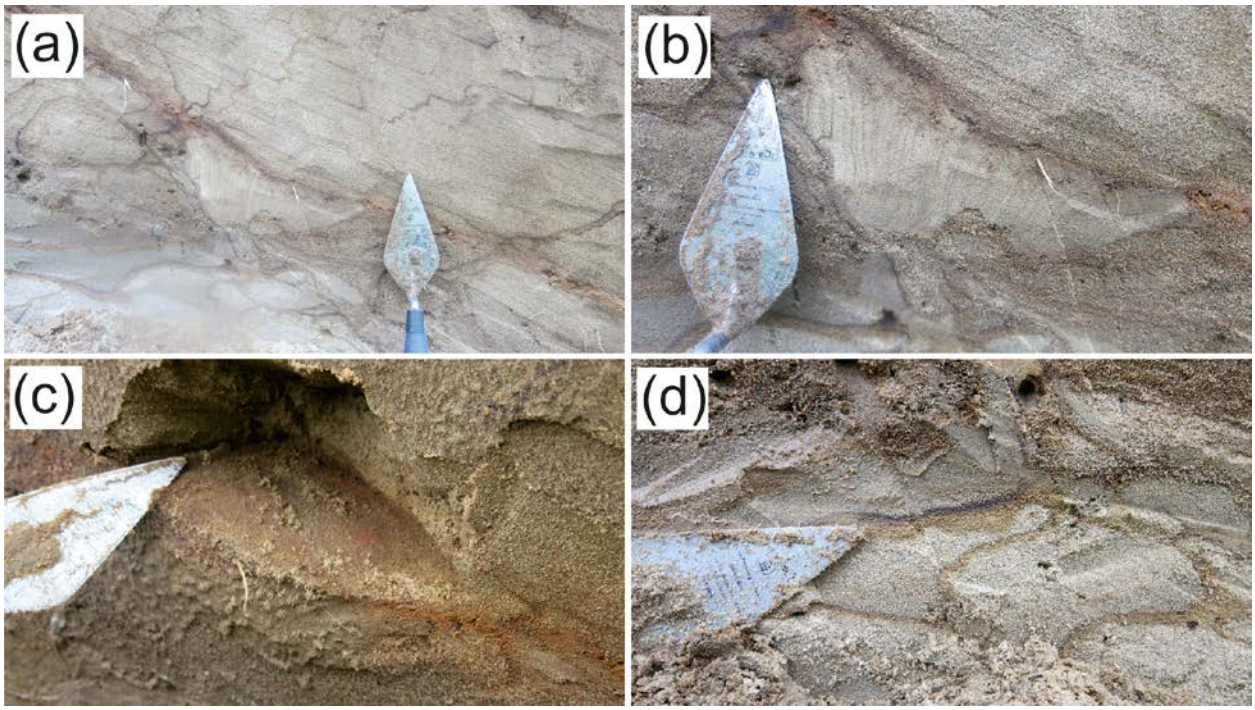

Figure 13. Brecciation of sand unit along clay layer (vein/intrusion?). Lamination structures are visible and rotated. The dug out clay/iron pan used for dip measurements is shown in (c).

2.4.3 Field Observation Point 11

Collected on: 21/11/2017 13:45:36 **At Coordinates: X:** 277920.337 - **Y:** 856240.192

Location Description: Heavy veining along lamination and potential faulting.

Summary Label: Veining and faulting

The next field observation point 11 is located immediately below the clay vein and breccia of observation point 10 in the logged section. The observation point represents an approximately 2 m-thick part of the section comprising fine to medium-grained, pale grey to maroon-coloured sand (Figure 14). Similar sedimentary structures to those seen at observation point 10 are present. These include planar lamination and low angle planar cross-bedding. In addition, a number of reverse faults are also observed, with centimetres of offset visible and with variable steep dips of between 45º–70º. This part of the section is also rich in oxidising fluid pathways, marked by brown staining. These follow both the sedimentary structures and the faults (Figure 15 and Figure 16). The fluid pathways are light to dark brown in colour and vary in thickness from 2–4 cm. At the contact between a reverse fault and the planar lamination the oxidising veins often form an oxidised unit that is 5-10 cm thick.

2.4.3.1 PHOTOS

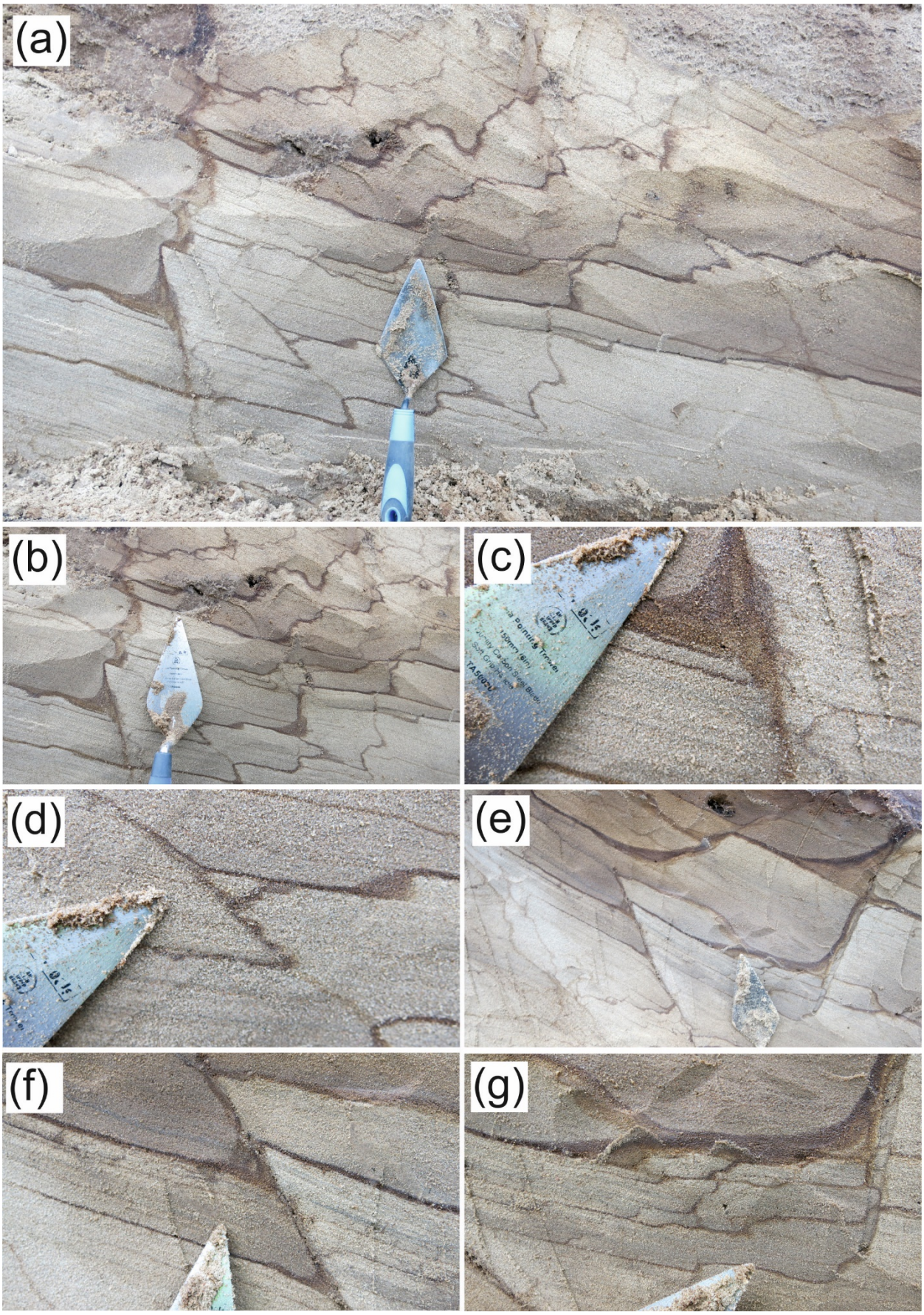

Figure 14. Oxidation pathways along planar bedding, stepping up between bedding pathways and interacting with inferred faults.

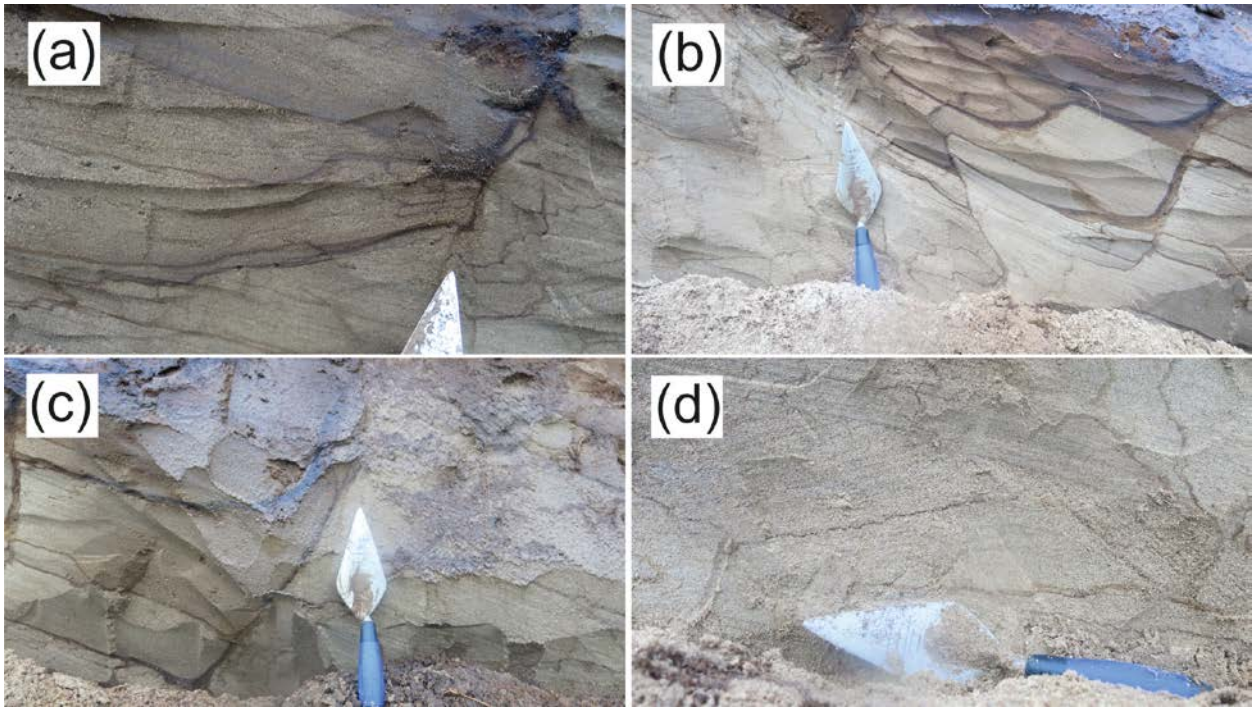

Figure 15. Oxidation along bedding in cross-bedded sands.

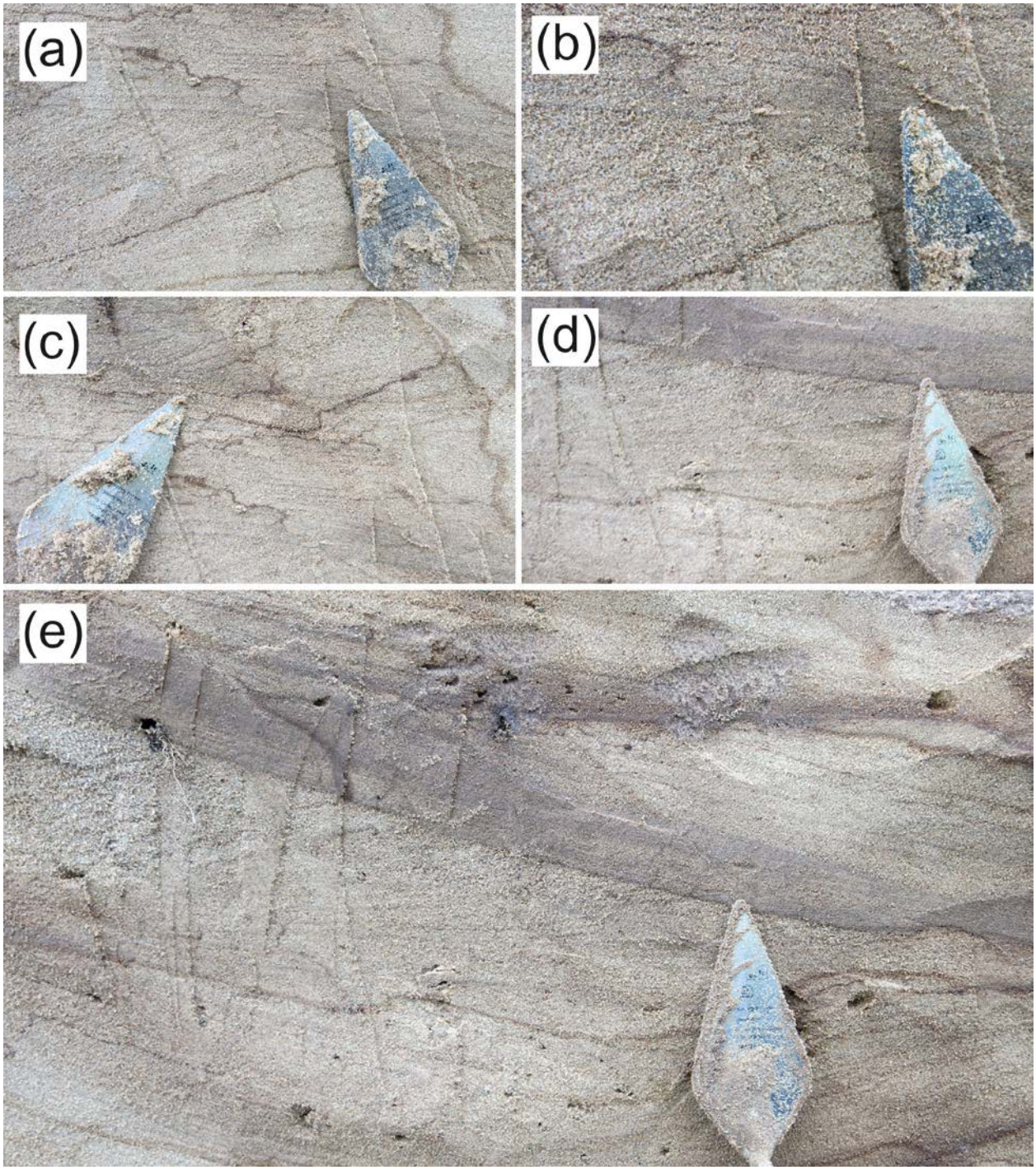

Figure 16. Laminated sand with oxidation pathways cross-cutting bedding.

Figure 17. Oxidation along fault with diffusion along bedding.

2.5 LOWER SECTION PART OF SECTION

2.5.1 Field Observation Point 12

Collected on: 21/11/2017 14:02:47 **At Coordinates: X:** 277918.43 - **Y:** 856240.182

Location Description: Thick vertical clay vein within sand

Summary Label: Thick clay vein

Field observation point 12 marks the start of the lower section (see Figure 3), which is at approximately 6 m-depth in the overall exposure. The main part of this observation point is the 20–40 cm thick sub-vertical clay vein that cuts across the entire trench (Figure 18). The vein is thinnest (20 cm) at the base of the exposure and thickens upwards to 40 cm. At the start of the thickest part of the vein there is a small veinlet (*c.* 3 cm thick) on its lower (left) side. The main clay vein is pale grey to light brown in colour, with a faint sub-vertical discontinuous layering (parallel to the vein orientation). Parts of the edges of the main vein have a dark brown diffuse oxidation boundary grading into the surrounding sand. This is particularly notable on the upper (right hand) of the vein. Within the clay vein there are discontinuous layers and lenses of fine-grained sand and silt. Occasional roots are observed penetrating the clay vein from the sloping ground surface above.

The clay vein cuts through medium-grained, grey-coloured sand, with faint planar bedding and oxidising fluid pathways along the bedding planes. The sand is sub-angular to angular and well-sorted. There are also a number of smaller (1–5 cm wide), grey-coloured clay veins in the sand. These clay veins also have thin-discontinuous layers of silt and fine-grained sand within the clay, parallel to the orientation of each vein. Fluid oxidation pathways are a light-brown colour and run straight through the sand without following any of the faint sedimentary structures.

2.5.1.1 PHOTOS

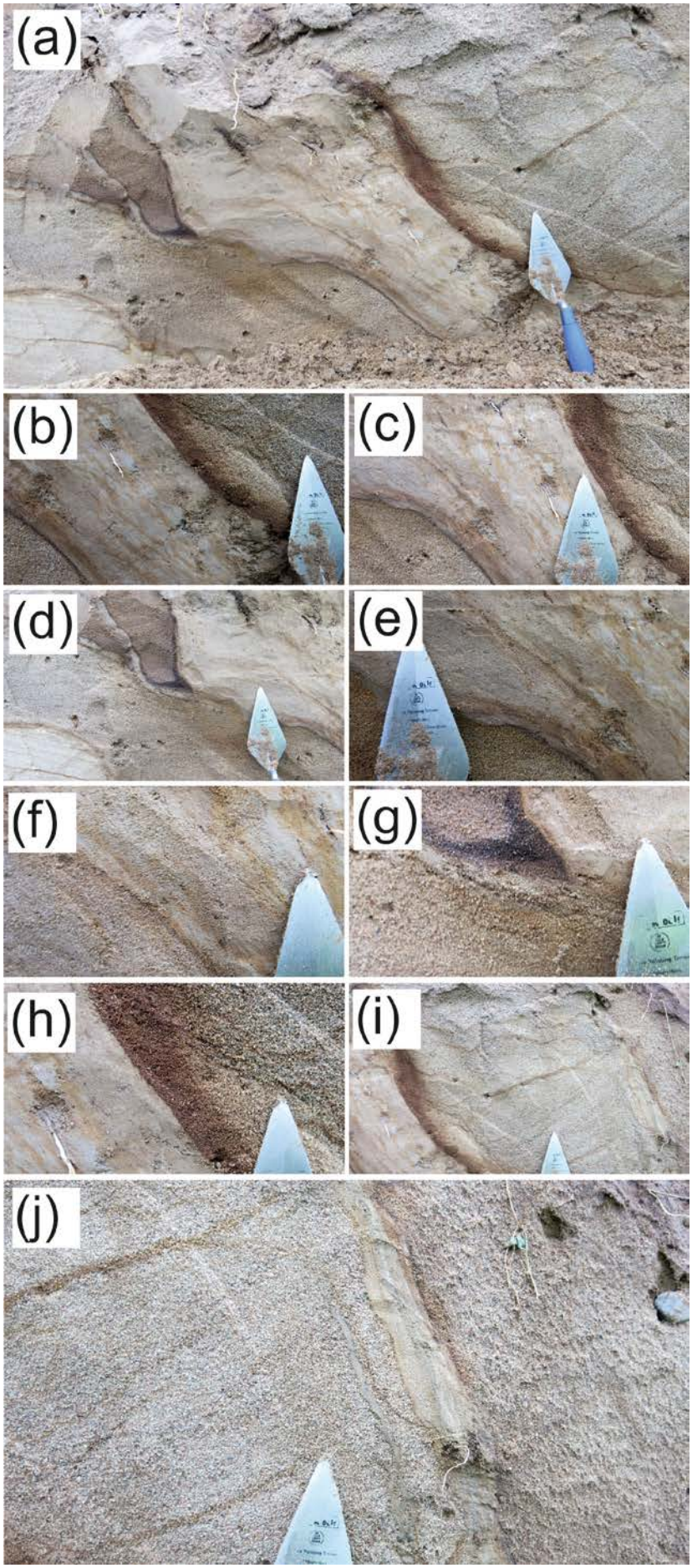

Figure 18. (a) Overview photograph of thick clay injection into sands; (b) Oxidation layering and diffusive oxidation boundary off the thick clay injection; (c) Close up of oxidation layering and diffusive oxidation boundary off the thick clay injection; (d) Small clay veins coming off the main unit, with diffusive oxidising upper boundary; (e) Oxidation layering in clay; (f) Diffusive oxidation boundary along clay vein and main clay injection unit; (g) Sandy lenses within the central part of the large clay injection; (h) Diffusive oxidation along the boundary of the clay into the sand; (i) Diffusive oxidation along the boundary of the clay into the sand; and (j) Vertical clay/silt vein with graded lamination cutting across laminated sand.

2.5.1.2 STRUCTURAL OBSERVATIONS

Feature	Azimuth	Dip	2nd Attrib	3rd Attrib	Grouping	Comment
Strata_Inclined_2	246	58				dipping clay vein
Strata_Inclined_2	248	73				dipping clay vein

2.5.2 Field Observation Point 13

Collected on: 22/11/2017 09:29:23 **At Coordinates: X:** 277919.091 - **Y:** 856240.909

Location Description: Sand and clay deformation with ripple structures

Summary Label: sand and clay deformed

Field observation point 13 is lower in the trench and nearer to the base of the sequence. It is interpreted as a large multi-phase hydrofracture system of approximately 1.5 m thick with an infill of clay, silt and fine to coarse-grained sand (Figure 19).

Some sedimentary structures are preserved in the sand layers, including planar lamination and ripples (Figure 20). However, the coarser-grained sand layers have no preserved internal sedimentary structures. The sand can be interpreted as beds that are broken up into 20–100 cm-sized blocks, but appear to be essentially *in situ*, but they are surrounded by clay. The blocks generally dip towards the west. Alternatively, this part of the sequence could be interpreted as large blocks of clay surrounded by brecciated or fluidised sand. This seems less likely as the sand contains depositional structures such as ripples and planar lamination that are less likely to be formed during injection of fluidised sand. Across the trench section are patches of dark to light reddish brown iron oxide coatings of sand grains (Figure 22). These are isolated patches rather than that characteristic of the discrete fluid pathways seen elsewhere.

Micromorphology Sample No. 4 (Figure 21) was taken from a part of the section comprising sub-vertical interbedded clay and silt layers, to investigate microstructures related to emplacement of the hydrofracture sediment.

2.5.2.1 PHOTOS

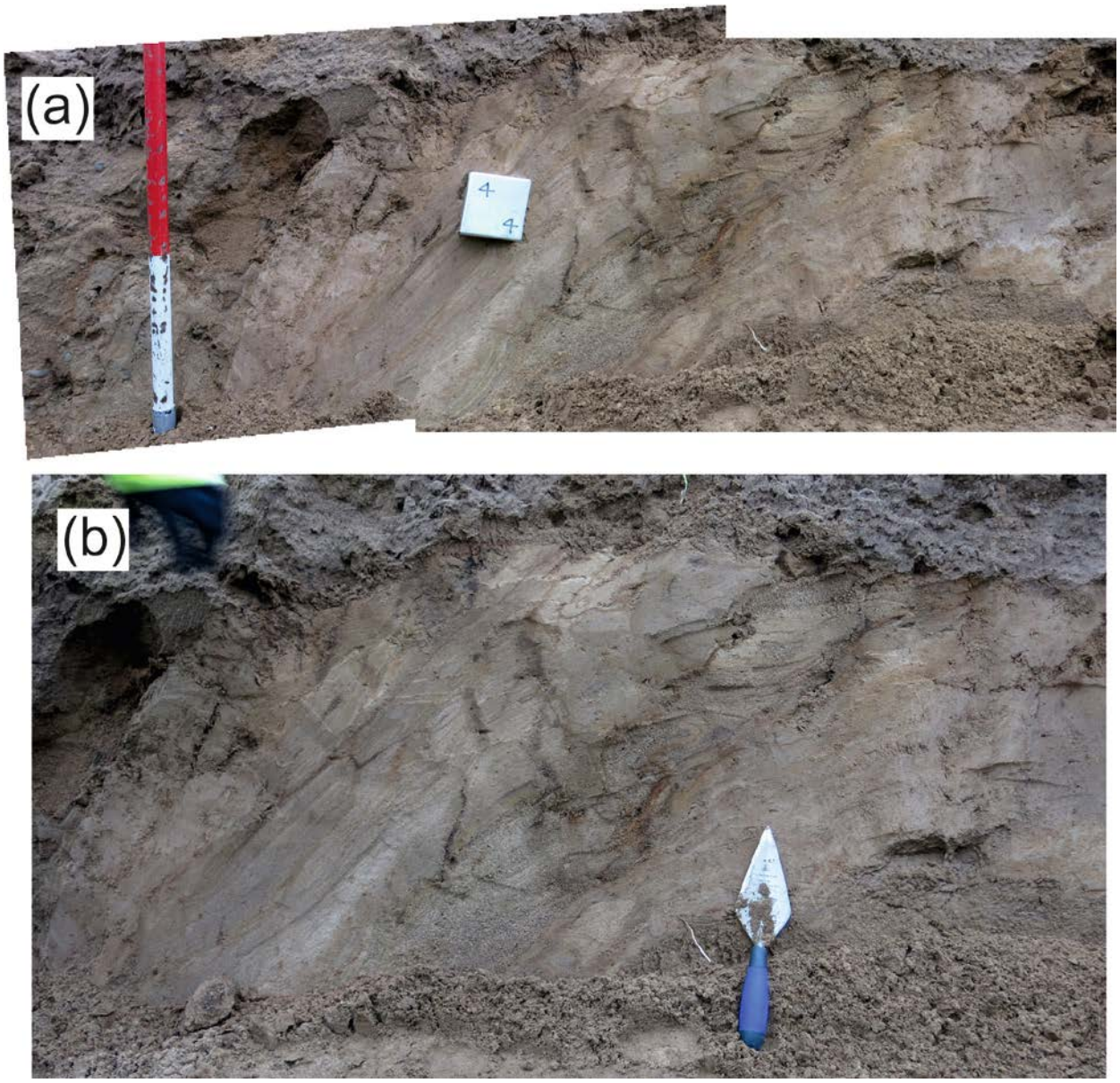

Figure 19. Overview of section of blocks of sand and silt, with some preserved sedimentary structures, in clay, in the lower part of the section.

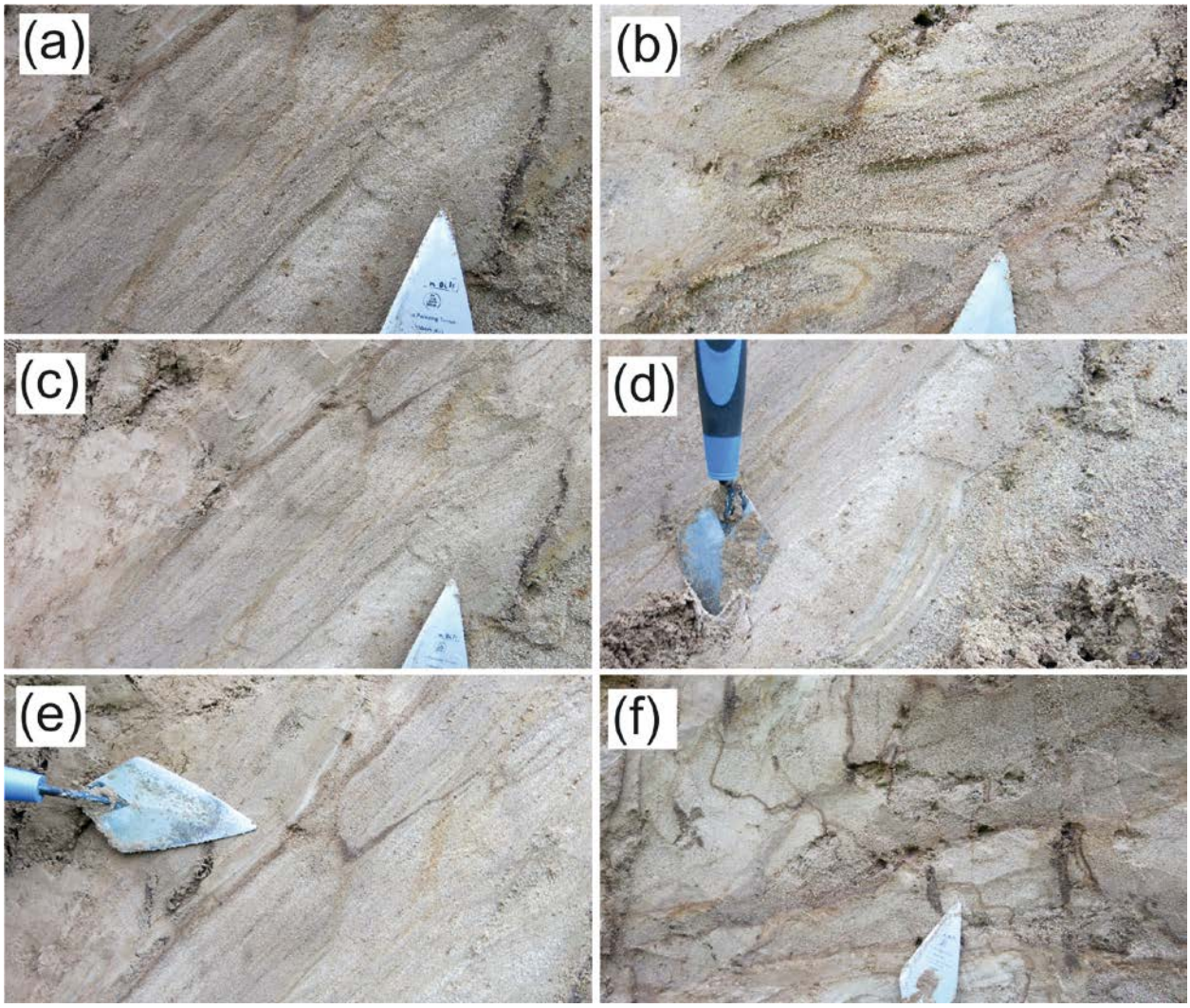

Figure 20. A blocks of sand with cross-bedding preserved dipping down to the SW.

Figure 21. Close up of the sample 4 box.

Figure 22. Diffusive oxidation in a cross-bedded sand.

2.5.2.2 SAMPLES

Original Sample Number	Sample Type	Sample Comment
CAA_4	Superficial Deposit Sample	Sample taken at the contact between the clay and graded sands within major hydrofracture infill

2.5.3 Field Observation Point 14

Collected on: 22/11/2017 09:46:31 **At Coordinates: X:** 277917.305 **- Y:** 856241.174000001

Location Description: Brecciated sand surrounded by clay

Summary Label: Brecciated sand

Field observation point 14 is located above field observation point 13 and represents an areas of brecciated sand with blocks from 2–20 cm in size (Figure 23). The blocks are surrounded by light grey to brown-coloured clay. There are a number of vertical and horizontal oxidation fluid pathways that cut across the sand blocks and follow the edges of clay patches.

Micromorphology Sample 3 (Figure 24) is taken from a horizontal clay vein that cuts through the sand with a vertical oxidation fluid pathway and some poorly-preserved small ripples.

2.5.3.1 PHOTOS

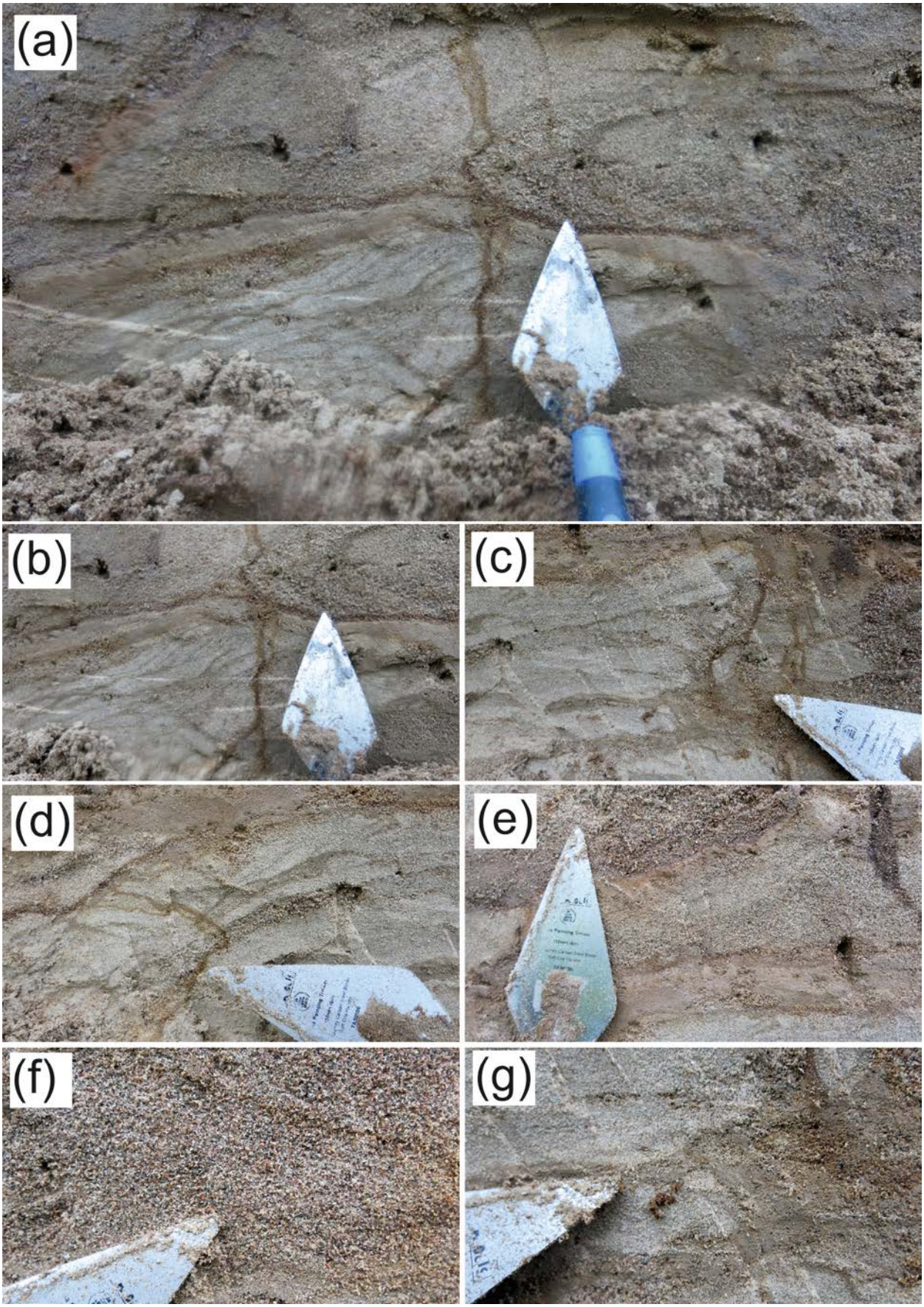

Figure 23. Vertical oxidation veins cutting through cross-bedded silt and clay; close up photograph of one of the blocks of sand, showing the well-sorted nature of the sand; and

moderately-rounded 5 cm block of fine-grained sand surrounded by clay and a contact between coarse to fine-grained sand and clay.

Figure 24. Photograph of the sample 3 tin inserted into the section.

2.5.3.2 SAMPLES

Original Sample Number	Sample Type	Sample Comment
CAA_3	Superficial Deposit Sample	Sample through blocky sand, horizontal veining and clay

2.5.4 Field Observation Point 15

Collected on: 22/11/2017 10:22:06 **At Coordinates: X:** 277917.147 **- Y:** 856240.380000001

Location Description: intensive clay veining in sand

Summary Label: intensive clay veins

Field observation point 15 is situated further east along section from field observation point 12. The section comprises grey to light brown, fine to coarse-grained sand with interconnected clay veins (Figure 25 and Figure 26). The clay veins are 1–30 cm thick and up to 1.5 m long, and dip towards the west at approximately 45^{o}. Although the veins are predominantly comprised of clay, they also contain occasional 1–5 cm thick layers of silt and fine-grained sand. The intensive clay

veining has resulted in the brecciation of the sand, with rounded to angular blocks of sand surrounded by clay.

The top edges of several clay veins form iron oxidation boundaries with the surrounding sand. Several of these boundaries are diffuse over several centimetres. The iron oxide grain coatings are a dark black-brown to light brown in colour.

Occasional scattered well-rounded, 1–4 cm-sized pebbles are observed within the sand.

2.5.4.1 PHOTOS

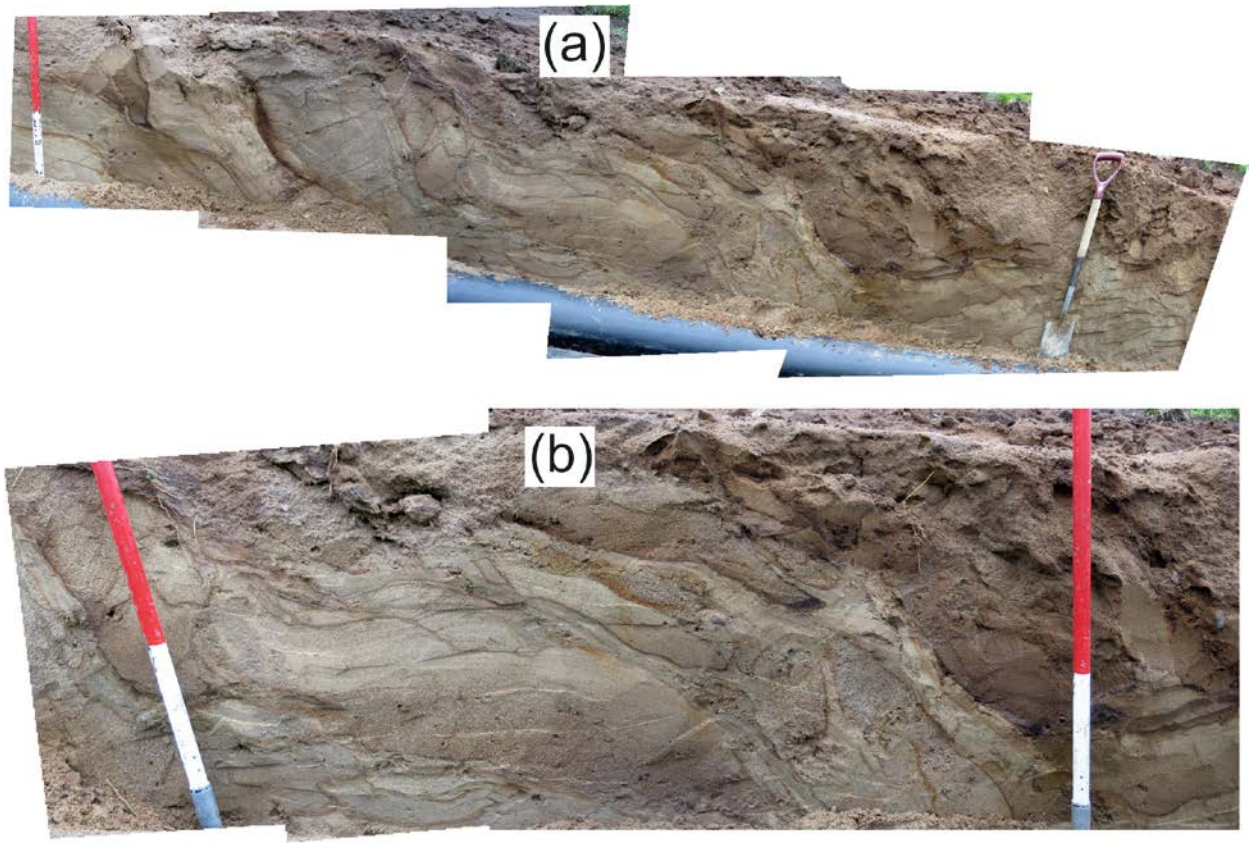

Figure 25. (a) Overview of section from a thick (30-40 cm) sub-vertical clay vein (left) to a series of thinner (10-20 cm) clay veins inter-fingering the sand (right); and (b) Overview section of the thinner (10-20 cm) sub-vertical to sub-horizontal veins inter-fingering the sand host.

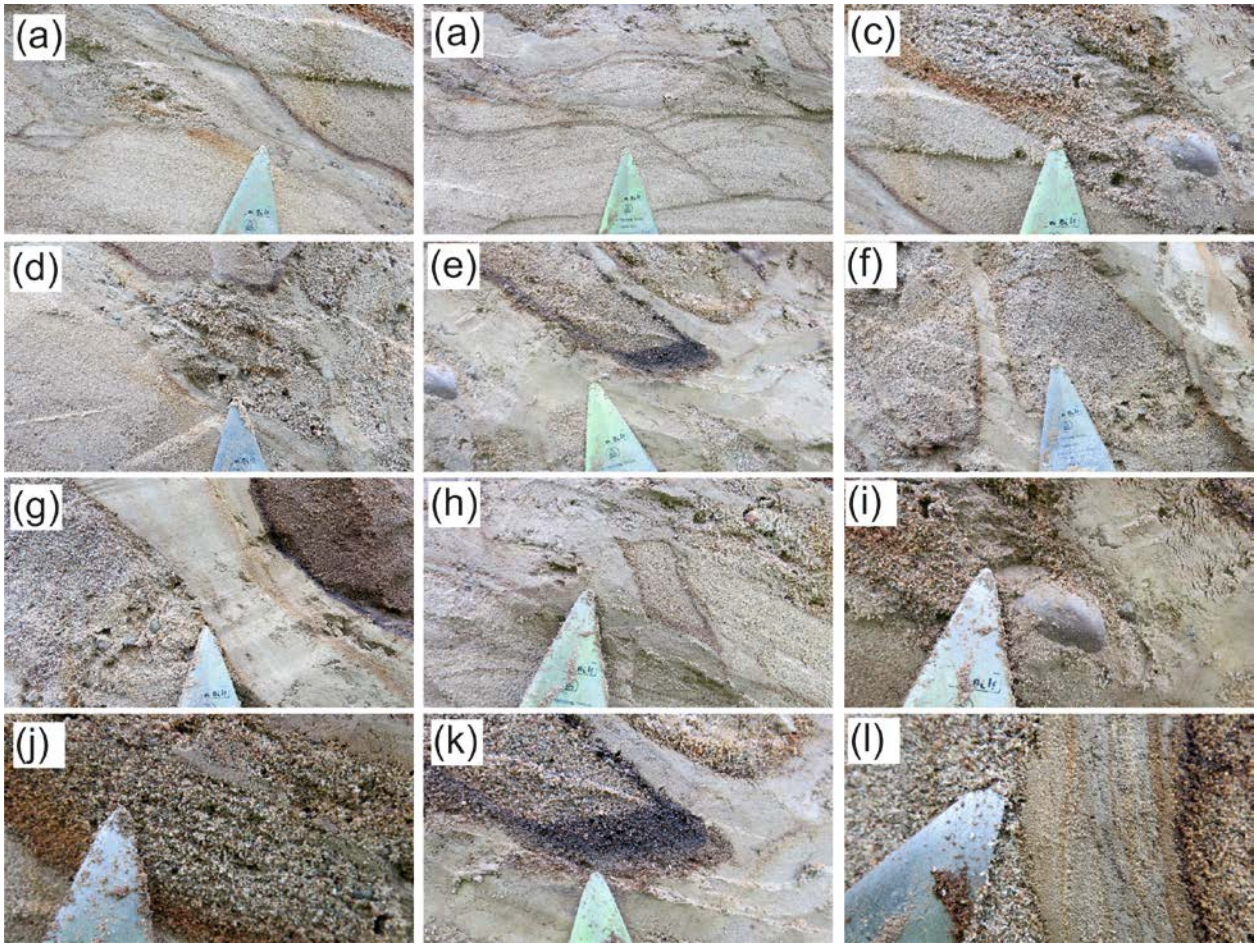

Figure 26. (a) Vein of clay with lenses and small blocks of medium-grained sand and with an (iron stained) oxidised upper boundary; (b) Thin clay veins truncating lamination and cross-bedding in the sand. Oxidised upper boundaries of the clay; (c) Layers of silt and sand with well-rounded cobble-sized clasts; (d) Thin veins of clay inter-fingering with sand producing isolated small blocks of sand; (e) Diffusive oxidation boundary along top edge of clay vein; (f) Clay veining surrounding a sand unit with a faint sub-vertical bedding preserved; (g) Contact between sand and silt/clay. Faint sub-horizontal bedding in sand preserved. Sub-vertical layering in silt/clay, defined by variations in colour; (h) Fragmented blocks of sand within a clay vein; (i) Close up photograph of oxidised sand and small fragmented clay layer; (j) Well-rounded cobble-sized clast in sand unit; (k) Close up photograph of the boundary between two veins, with dark manganese-coloured coating of sand; and (l) Faint vertical layering of fine-grained sand and silt within the clay veins.

2.5.5 Field Observation Point 16

Collected on: 22/11/2017 10:52:06 **At Coordinates: X:** 277913.972 **- Y:** 856240.221000001

Location Description: intensive clay veining causing brecciation of sand.

Summary Label: Clay and breccia

The final observation point (FOP 16) is situated at the base of the exposed section and represents a 50 cm wide major hydrofracture network with extensive clay veins in an apparently unstratified sand unit (Figure 27). The base of the exposed vein is at approximately 8 m depth from the uppermost unconformity near the top of the overall sequence. The surrounding sand is fine to medium-grained and a light yellow to grey colour.

The clay vein veining has resulted in the major brecciation of the sand forming sub-rounded blocks that appear to have been deformed within the clay veins. Some of the sand blocks have also been faulted but apparently undeformed. The blocks of sand are highly variable in size from less than 5 cm to nearly 40 cm. Small elongate lenses of fine-grained sand are observed within the clay veins, these are either stretched blocks of sand or original discontinuous layers within the clay.

The clay is dark grey in colour with light brown iron oxide patches along a handful of edges. At the edges of the hydrofracture system there are various iron oxidation fluid pathways associated with the edges of the clay, which meander through the massive structureless surrounding sand. Several of the iron oxidised edges of clay veins comprises two layers, a dark black-brown layer that is less 1 cm thick and a dark to light orange-brown layer that is 1 cm to 5 cm thick and passes diffusely into the sand or clay.

2.5.5.1 PHOTOS

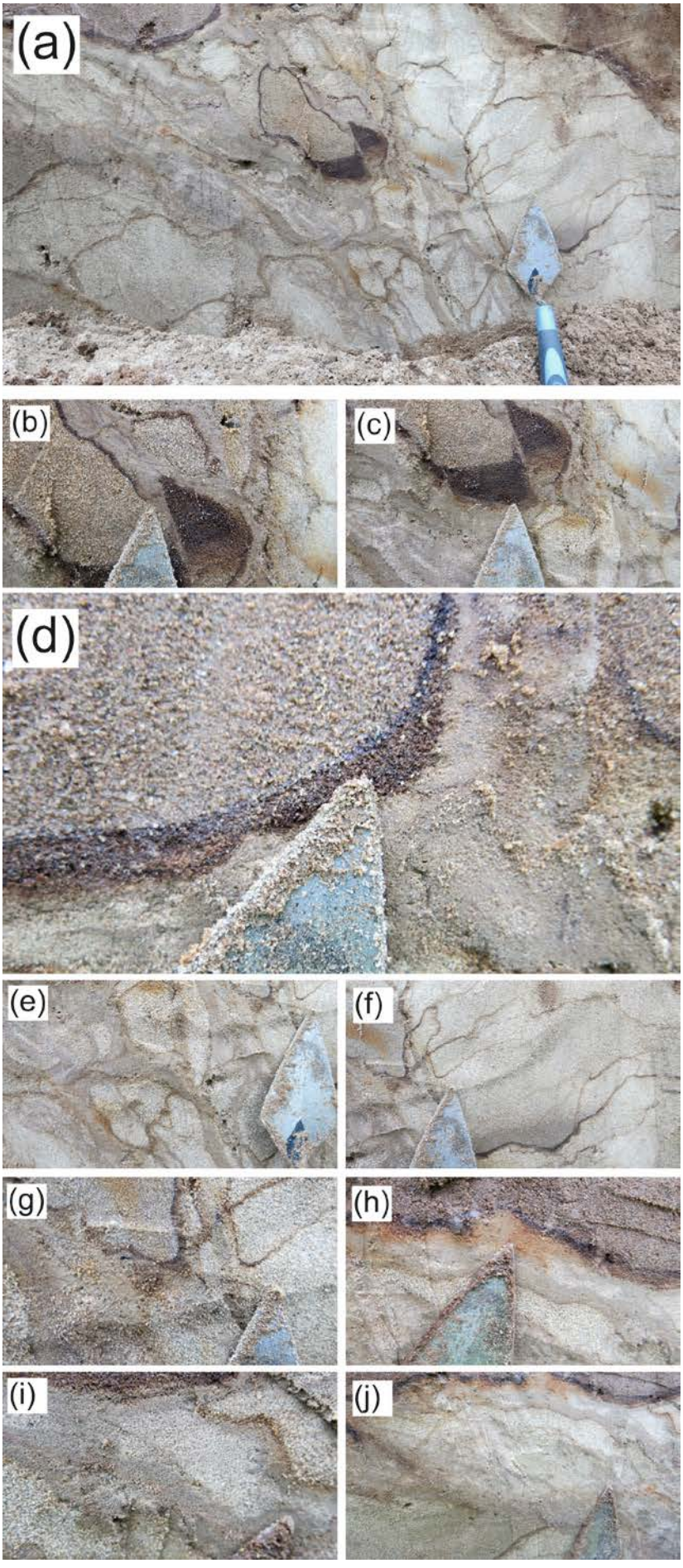

Figure 27. (a) Overview of section, showing brecciation of sand due to intensive clay veining; (b-c) Fragmented piece of manganese-stained (oxidised) sand; (d) Undulating oxidation boundary along upper clay vein margin and into sand; (e) Blocks of sand surrounded by clay; (f) Oxidation veins that appear to come from clay with highly sporadic pathway through sand; (g) Oxidation boundary on the edge of sand clast; (h) Varying colour of oxidation of clay and sand. Nodules of fine-grained sand to silt within clay veins. Rounding of blocks of sand, from the more distal part of the vein system; (i) Small irregular 'pods' of fine-grained sand to silt enclosed by clay veins; and (j) Rounding of blocks of sand, from the deeper (more distal?) part of the vein system. Close to the base of the logged sequence.

2.5.6 Field Observation Point 17

Collected on: 22/11/2017 11:05:30 **At Coordinates: X:** 277924.262 **- Y:** 856239.911

Location Description: clay vein

Summary Label: clay vein at 3.6 m depth

2.5.6.1 PHOTOS

Figure 28. Dug out clay vein surface, for dip measurement.

2.5.6.2 STRUCTURAL OBSERVATIONS

Feature	Azimuth	Dip	2nd Attrib	3rd Attrib	Grouping	Comment
Strata_Inclined_2	299	42				dip of clay vein

2.5.7 Field Observation Point 18

Collected on: 22/11/2017 11:32:58 **At Coordinates: X:** 277920.877 **- Y:** 856240.856

Location Description: dipping clay vein

Summary Label: dipping clay vein

2.5.7.1 PHOTOS

Figure 29. Dug out clay vein surface for taking dip measurement.

2.5.7.2 STRUCTURAL OBSERVATIONS

Feature	Azimuth	Dip	2nd Attrib	3rd Attrib	Grouping	Comment
Strata_Inclined_2	278	38				dipping clay vein

2.5.8 Field Observation Point 19

Collected on: 22/11/2017 11:39:08 **At Coordinates: X:** 277916.273 - **Y:** 856240.38

Location Description: clay vein in breccia

Summary Label: clay vein in breccia

2.5.8.1 PHOTOS

Figure 30. Dug out clay vein surface for taking dip measurement.

Figure 31. Dug out clay vein surface for taking dip measurement.

2.5.8.2 STRUCTURAL OBSERVATIONS

Feature	Azimuth	Dip	2nd Attrib	3rd Attrib	Grouping	Comment
Strata_Inclined_2	262	36				dipping clay vein
Strata_Inclined_2	255	62				dipping clay vein

2.6 CLAY VEIN ORIENTATIONS

Dip and azimuth measurements were taken from seven clay veins across the sequence to look for variations in orientation of the veining. When taking a dip and azimuth measurement the overlying sand was dug out and the measurement taken on the planar top surface of the vein (e.g. field observation points 17–19; Figures 28–31). Figure 32 shows the orientations of the clay veins plotted on an equal area stereonet. In general, most of the veins appear to have a similar orientation, steeply dipping towards the west. This is suggestive of clay vein emplacement that is associated with a similar stress field. This veining may be the result of one or multiple events.

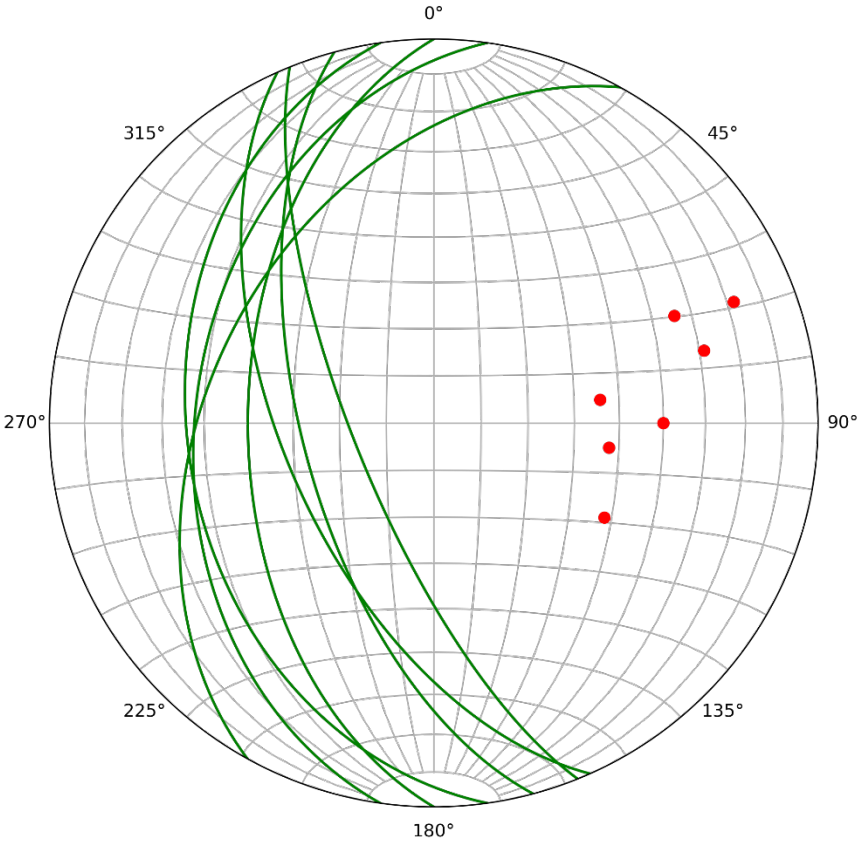

Figure 32. Stereonet plot of the great circles and poles of the several clay veins.

2.7 KESSOCK NARROWS CORE

A photograph of a core sample of sediments, showing several of the characteristic attributes of the Ardersier Silts was collected by J D Peacock from one of the offshore site investigation boreholes drilled prior to the construction of the Kessock Bridge, across the Kessock Narrows in the Inner Moray Firth. The site investigation was undertaken in 1969–70. Although the exact borehole from which the sample was collected is now unknown and its depth was not recorded, it was from material that occurred beneath a diamicton, interpreted as a glacial till (J D Peacock and JW Merritt, pers. com.).

Figure 33. Photograph of core sample of Ardersier Silts, from a Kessock Bridge offshore site investigation borehole, collected and photographed by J D Peacock c. 1969-70.

From detailed study of the photograph, the sample comprises thinly interbedded blue-grey silty clay and rhythmically laminated olive grey sandy silts, which show intricate involuted sedimentary contacts (Figure 33). Some deformation of the margins of the core are evidently a result of the drilling and extraction of the core (clearly visible in the ‘dished’ appearance in the top 5cm of the

sample). However, the involuted nature of the silt-clay interbeds in the middle and lower portions of the core, are the result of soft sediment deformation that is likely associated with the original deposition of the sediment. These features are characteristic of the Ardersier Silts in nearby onshore exposures, such as those at Balnaglack, and at the Kirkton section (Merritt, Auton and Firth, 2017). The olive grey silt units comprise upward-fining rhythmites and there appears to be the presence of possible clay intraclasts, notably within the zone between 5–10 cm from the top of the sample. Incipient ball and pillow and flame structures are associated with small-scale flat-lying rootless folds in the bottom portion of the sample. All of these features are characteristic of the Ardersier Silts exposed in the coastal hinterland between Inverness and Nairn.

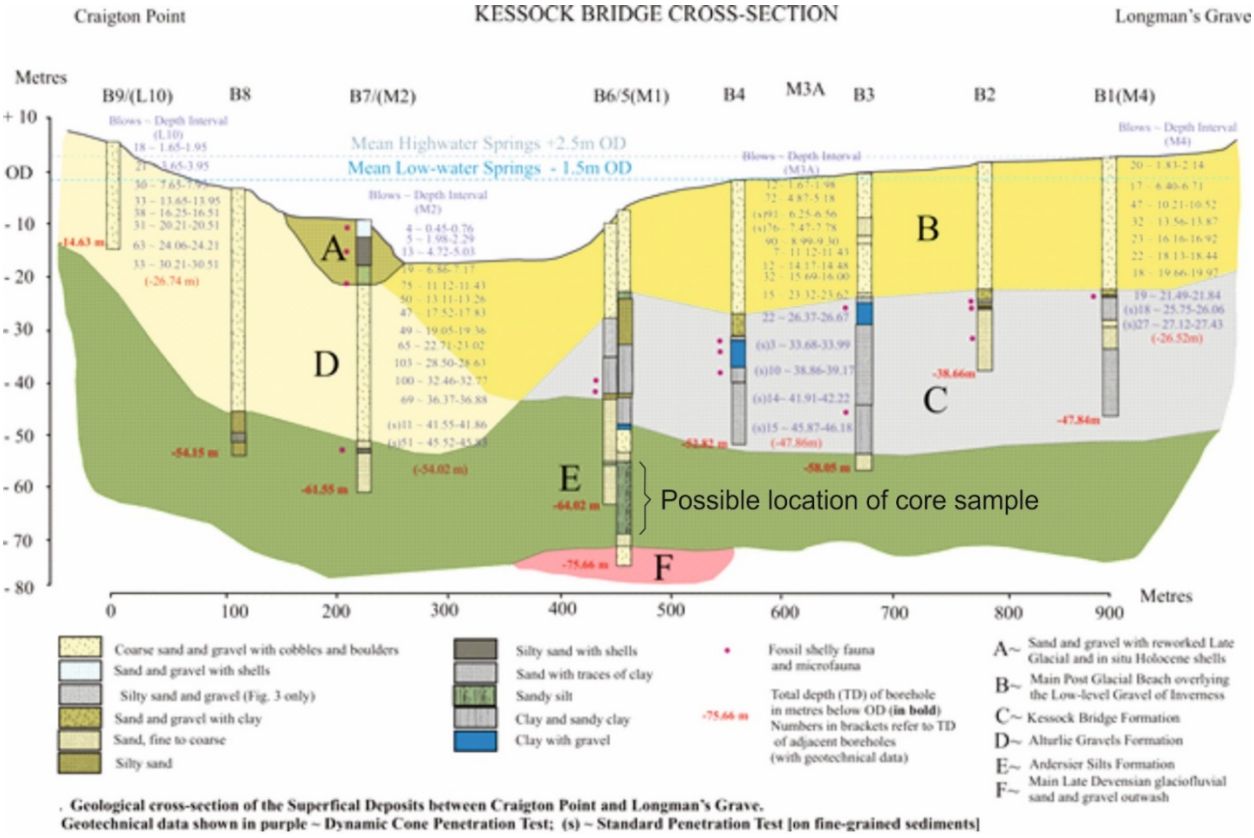

Figure 34. Cross-section of the geology seen in the Kessock Bridge boreholes, showing the possible position of the photographed core sample (modified from Auton, 2006).

Although there is no original record of which borehole core the sample was collected from, examination and interpretation of the borehole and geotechnical logs and accompanying site investigation report for the Kessock Bridge (Auton, 2006), suggests that only one borehole (B5/M1) encountered Ardersier Silts, beneath a diamicton (clay with gravel [blue] in Figure 34) that was interpreted as till. If this is the case, then the photographed core sample was probably collected at between 60–70 m below OD, at a depth of 53–63 m in the core.

The photograph of the core sample is the first image of sediment, identified as being part of the Ardersier Silts Formation, from the offshore area of the Kessock Narrows, and indeed within the subtidal zone of the Inner Moray Firth. It is in the region of 50 years since the core was collected and photographed, but it provides compelling support for the modelled and mapped extent of Late Devensian glaciomarine sediments in the Inverness area.

3 Discussion

The newly described section of Quaternary sediments, outside Ardersier Village, provides new insights into the depositional environment and temporal changes of the Moray Firth ice-stream during the Devensian deglaciation.

Three depositional units, separated by discontinuities, are distinguished in the newly described section. Firstly, an upper gravel unit of less than 30 cm erosionally overlies a sand unit of 60 cm thick. The final lowest unit makes up the majority of the section and is likely over 8 m thick. The base of this lower most unit was not exposed in the excavated trench. Throughout the lower unit are number of glacitectonic features including brecciation, clay veins and local thrust faults. Each of the depositional and structural features are summarised and discussed below.

3.1 DEPOSITIONAL SETTING

The upper most unit comprises a poorly sorted gravel with well-rounded to sub-rounded clasts, that vary in size from 1–12 cm. The deposit is clast supported with a coarse-grained sand matrix. Overlying the deposit is a dark brown-coloured soil. This unit likely represents a raised-beach setting associated with the Main Postglacial Cliffline, which is similar to that described at the top of the Kirkton section (Merritt et al., 1995).

Unconformably underlying the raised beach deposit is a dark brown-coloured sand with planar lamination and low-amplitude tabular cross-bedding. The internal sedimentary architecture of this unit is similar to that described from the Hillhead Sand Member at the Hillhead Section (Merritt et al., 1995), which was interpreted as a high-energy shallow marine setting.

The majority of the sequence is the interbedded sequence of fine-grained sands and silts with sedimentary structures that include planar and cross lamination and structureless massive sand. The planar cross-bedding is bi-directional, towards the north-west and towards the south-east. Overall, the unit is composed of a rhythmically stacked sequence of bedded silt and fine-grained sand. The succession is interpreted as a shallow-marine setting which was effected by tidal currents. This entire unit is interpreted as part of the Ardersier Silts Formation, as it is similar in many respects to the sequence from the Jamieson's Pit section (as described in Fletcher et al., 1996). The observed sedimentary structures fit with the Ardersier Silts Formation being interpreted as a glacial subaqueous deposit. The offshore core provides an insight into the distal low energy part of the system, representing a low energy anoxic setting.

Overall, the entire section represents three distinct depositional units, including: 1) the oldest part of the sequence is a distal low energy marine environment of the Ardersier Silts Formation; 2) unconformably overlying the lower-most unit is a shallow-marine deposit of the Hillhead Sand Member; and finally 3) unconformably overlying the entire section is raised-beach deposit associated with the Postglacial Cliffline.

3.2 STRUCTURAL DISCUSSION

The main body of the section, interpreted as the Ardersier Silts Formation, contains a number glaciotectonic features such as clay veining, brecciation and faulting. The deformation does not continue into the overlying Hillhead Member and beach deposits, suggesting that the deformation was prior to the deposition of these units. Three major types of deformation are observed, firstly clay veining of varying scales from 1–40 cm thick and varying from sub-vertical to sub-horizontal. The clay veins are observed at various points throughout the section. Due to limited exposure of the section within the trench the full length of each vein could not be traced. In general, the clay veins were structureless except on occasion along the boundaries where some poorly developed layering, of silt and clay, parallel to the boundary of the vein was observed.

Brecciation of the inclusions of silt and sand into angular poorly-sorted clasts within a clay vein was observed at several points in the upper (FOP 8) and lower (FOP 16) parts of the section. The scale of brecciation greatly varies from within veins of 10 cm thickness up to clay-vein features that were 40 cm thick.

Finally, small-scale thrust faults were observed within the upper and central parts of the section with offsets of approximately 5 cm (FOP 10). The faulting was most clearly observed within the central part of the section where no clay veining or brecciation were present. Major iron staining pathways were observed in this central section, which followed fault planes and sedimentary bedding structures. Smaller scale deformation structures, such as brecciated intraclasts and ball and pillow and flame structures, are also observed offshore within the lower energy clays.

The hydrofracture system-type features are typically found in glacial sediment that have been subsequently overridden by an ice stream (Lee and Phillips, 2008; Phillips and Hughes, 2014). Ice-stream related deformation of the Ardersier Silts Formation is also interpreted for the nearby-contorted sediments section (Firth, 1989; Gordon and Merritt, 1993). However, there is one major difference, which is in the style of deformation, which in the newly described section is brittle compared to ductile in the contorted Ardersier Silts section. This variation in the style of the deformation is not uncommon and is seen in other hybrid hydrofracture networks with multiple phases of deformation, such as in Norfolk, England (Lee and Phillips, 2008).

3.3 REGIONAL COMPARISON

The newly studied section predominantly comprises sediments of the Ardersier Silts Formation. The section is *c*. 8 m thick and comprises sedimentary structures that represent a coastal to shallow-marine setting, which is equivalent to the Ardersier Silts Formation sediments observed locally at the ‘consorted silts’ locality and at Jamieson’s Pit (Merritt et al., 2018). The well-preserved hydrofracture network, although different to that observed at the contorted silts section, is also likely formed as a consequence of ice-push and possible glacial over-riding by the Moray-Firth ice-stream during deglaciation.

4 Conclusions

The studied section provides new insights into the depositional setting of Ardersier Silts Formation and development of hydrofracture networks during the retreat of the Moray Firth ice-stream. The well-exposed sedimentary structures suggest a coastal shallow marine setting for the sediments of the Ardersier Silts Formation in this area. In addition, the well-preserved hydrofracture network within the section demonstrates the diverse range of glacial deformation that occurred in the Ardersier Silts Formation during deglaciation.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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