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# Petrology of a suite of sedimentary, igneous and metamorphic rocks from the Caithness district, Scotland

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# Petrology of a suite of sedimentary, igneous and metamorphic rocks from the Caithness district, Scotland

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# Foreword

This report is the published product of a study by the British Geological Survey (BGS) as part of their regional geological mapping programme. It contains petrological descriptions of a suite of sedimentary, igneous and metamorphic rocks exposed in the Reay District, Caithness, Scotland. The work forms part of a multidisciplinary Caithness Devonian and Quaternary Project. This petrographical study has been carried out to aid in the detailed characterisation of the individual mapped units.

The a main aim of this project is to investigate the Devonian and Quaternary geology of the far North East of Scotland, represents an important component of the onshore geology of the UK that has a crucial role in understanding the evolution of the West Orkney and Northern North Sea basins. In addition, formulation of local planning policies on landfill, hard rock extraction and groundwater protection, in this sparsely populated but environmentally sensitive region, has demonstrated a requirement for modern geospatial data throughout the project area. This involves the resurvey of the solid and drift geology of the onshore eastern margin of the Orcadian basin (1: 50 000 Sheets 83E, 94W, 110, 115 E 116W & 116E) concentrating on the nature and distribution of the Quaternary and Devonian strata.

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# Summary

This report provides petrological descriptions of a suite of sedimentary, igneous and metamorphic rocks collected during the resurvey the Reay District, Caithness (Scotland). This work forms part of the multidisciplinary Caithness Devonian and Quaternary project which is an integral part of the BGS's Integrated Geological Survey's (North) programme.

# 1 Thin Section Descriptions

The following section contains a brief description of 29 thin sections of a variety of sedimentary, igneous and metamorphic rocks collected by Clive Auton, James Floyd, Nicholas Golledge and Michael McCormack during the resurvey of part of Sheet 115 (Reay). This work forms a continuation of the petrological analytical studies on the Neoproterozoic and Devonian rocks of the Caithness area summarised by Phillips (2002).

**Collectors Number:** MM7. **Registered Number:** N3681. **Location**: [NC 91530 63904] disused sandstone quarry, Melvich, Gleann Creadach, Sutherland. **Lithology:** coarse-grained, quartzose litharenite or microconglomerate. **Formation:** Ousdale Arkose Formation, Luchair Sandstone Member.

**Description:** This thin section is of a coarse- to very coarse-grained, poorly sorted, immature, closely packed, clast supported, pebbly, quartzose litharenite or microconglomerate. Clastic grains are typically angular, subangular to occasionally subrounded in shape with a low sphericity. However, the shape of these clasts ahs been variably modified due to grain boundary etching and pressure solution. The shape of the grains has also been modified due to the variable development of syntaxial quartz and/or feldspar overgrowths; the latter apparently accompanying pressure solution. Pressure solution resulted in the main mode of cementation within this sample.

Clastic grains range from fine sand up to small pebbles in size. There is a distinct bimodal grain size distribution with the fine- to medium-sand forming the matrix to this pebbly sandstone or microconglomerate. The larger, very coarse sand to pebble sized clasts are mainly composed of metamorphic and igneous rock fragments. Recognisable lithologies include psammite, altered granite or granitic gneiss and biotite granite to granodiorite. Feldspar within these lithic clasts has been variably altered to sericitic white mica and/or clay minerals. Biotite is altered to a orange-brown coloured, very fine-grained iddingsite assemblage. Alteration of these metasedimentary and igneous rocks probably occurred prior to the incorporation of this coarse grained detritus into this microconglomerate. These larger clasts locally represent broken fragments of much larger pebbles and are, therefore, possibly polycyclic in nature. Finer grained clasts within the sandy matrix of the microconglomeratic rock are mainly composed of monocrystalline quartz. Other minor to accessory detrital components include plagioclase, microcline, polycrystalline quartz, opaque minerals, muscovite, altered biotite, zircon and monazite.

Traces of as early (pre-dating pressure solution) chloritic or clay cement forming variably developed rims upon detrital grains has been noted. This early rim cement ahs locally been overgrown or replaced by later Fe-oxide and/or iddingsite.

**Collectors Number:** MM8. **Registered Number:** N3682. **Location**: [NC 91530 63904] disused sandstone quarry, Melvich, Gleann Creadach, Sutherland. **Lithology:** very fine-grained quartz arenite. **Formation:** Ousdale Arkose Formation, Luchair Sandstone Member.

**Description:** This thin section is of a very fine-grained, low porosity, mature, quartzose, very closely packed, clast supported, matrix-poor, moderately to well sorted quartz arenite. Clastic grains are relatively uniform in grain size and range from angular to subrounded in shape with a low to moderate sphericity. Occasional medium sand-grade clasts have also been recorded. The shape of these clasts has, however, been modified due variable pressure solution and development of syntaxial quartz overgrowths. Pressure solution resulted in the main mode of cementation within this sandstone.

The clast assemblage is dominated by monocrystalline quartz. Accessory detrital components present within this sandstone include microcline, plagioclase, zircon, white mica/muscovite, polycrystalline quartz, tourmaline and monazite. The very close packing and pressure solution of both quartz and, to a lesser extent, feldspar have resulted in the very low porosity of this rock.

**Collectors Number:** MM9. **Registered Number:** N3683. **Location**: [NC 96000 65220] Sandside Burn, Reay, Caithness. **Lithology:** laminated/cross laminated, slightly calcareous, fine-grained quartz arenite. **Formation:** Ben Dorrery Conglomerate Member.

**Description:** This thin section is of a fine- to very fine-grained, moderately sorted, low porosity, moderately sorted, laminated and weakly cross laminated, matrix-poor, clast supported, very closely packed, slightly calcareous quartz arenite (Plate 1a and b). The sedimentary lamination is defined by the variation in grain size and, to a lesser extent, a slight variation in sandstone composition.

Clastic grains are angular to subrounded in shape with a low to moderate sphericity. The shape of these grain as, however, been modified due to pressure solution and localised development of quartz overgrowths. Pressure solution forms the main mode of cementation within this sandstone. An early chloritic rim cement (pre-dating quartz overgrowths and pressure solution) is locally present forming variably developed coatings on detrital grains and occasionally infilling intergranular pore spaces. Traces of a later (post-dating pressure solution) carbonate cement(s) is also present replacing the chloritic material and unstable detrital components (e.g. feldspar). The Detrital clast assemblage is dominated by monocrystalline quartz. Minor to accessory detrital components include plagioclase, chloritised biotite, muscovite, chlorite, apatite, K-feldspar and zircon. Several stages of carbonate mineral growth/replacement have been recognised within this sandstone. The earliest resulted in the development of small, anhedral to rounded crystals of unstained, non-ferroan calcite. These are overgrown and variably replaced by very fine-grained blue to mauve coloured stained ferroan calcite. Traces of pale blue coloured ferroan dolomite have also been noted. However, the relationship of the dolomite to the other carbonate minerals is uncertain. Traces of opaque mineralisation have also been recorded which appears to have post-dated all phases of carbonate growth/replacement.

**Collectors Number:** PY709. **Registered Number:** N3684. **Location**: [ND 0105 5784] Broubster Forest, Caithness (CA 1463). **Lithology:** foliated granitic igneous or gneissose rock. **Formation:** Strathalladale Granite.

**Description:** This thin section is of a medium- to coarse-grained, inequigranular, anhedral granular, foliated granitic igneous rock or granitic gneiss (Plate 1c and d). A moderately well-developed foliation is defined by lenticular aggregates of optically aligned biotite flakes and, to a lesser extent, the variable shape alignment of quartz and plagioclase.

The bulk of the rock is composed of plagioclase and quartz with minor amounts of biotite and K-feldspar (Plate 1c and d). This mineral assemblage indicates that this possibly meta-igneous rock is broadly granodioritic in composition. Accessory phases present include opaque minerals, hornblende, apatite, zircon, titanite and muscovite. Minor alteration and hydration resulted in the patchy sericitisation or plagioclase and the chloritisation of biotite. Biotite is yellow-brown to dark brown in colour and forms anhedral to weakly subhedral flakes which possess a moderately developed pleochroism. Biotite locally contains very fine-grained inclusions of apatite, opaque minerals and zircon. Apatite is a relative common minor phase within this granitic rock.

Plagioclase forms twinned and untwinned crystals which exhibit a slight dusty appearance under plane polarised light. Plagioclase may contain rounded inclusion of quartz and, as previously stated, exhibit a preferred shape alignment parallel to the apparently gneissose foliation. In a slightly coarser grained part of the thin section, plagioclase forms weakly subhedral crystals which range up to *c*. 2.5 mm in length. These larger crystals rarely contain inclusions of fine-grained biotite. This coarser grained part of the sample contains a relict igneous texture with variably strained quartz and minor K-feldspar occurring intergranular to the subhedral plagioclase crystals. In the finer grained part of the thin section has undergone a greater degree of recrystallisation resulting in the over-printing of this pre-existing igneous texture.

Quartz is strained with a variably developed undulose extinction, sub-grain textures and deformation bands. K-feldspar, where present, forms larger 2.5 to 3.5 mm long, anhedral, intergranular poikilitic crystals which contain inclusions of finer grained plagioclase, biotite and quartz. K-feldspar forms twinned (microcline twins) and untwinned crystals which are weakly perthitic and possess a distinctive shadowy extinction. Traces of myrmekitic intergrowth have been noted developed along inter plagioclase-K-feldspar grain boundaries. These myrmekitic patches are in optical continuity with the host plagioclase and appear to be replacing the adjacent K-feldspar.

**Collectors Number:** PY710. **Registered Number:** N3685. **Location**: [ND 0095 5750] Broubster Forest, Caithness (CA 1464). **Lithology:** pyroxene-bearing olivine-phlogopite-hornblendite. **Formation:** type locality of scyelite.

**Description:** This thin section is of a very coarse-grained, inequigranular, anhedral granular, serpentinised pyroxene-bearing olivine-phlogopite-hornblendite (Plate 2). This rocks is composed on an inequigranular assemblage of olivine, hornblende, phlogopite and minor clinopyroxene. Accessory minerals present include apatite and opaque minerals.

The bulk of the rock is composed of anhedral, poikilitic hornblende and phlogopitic biotite (Plate 2). Both of these hydrous ferromagnesian minerals contain rounded to elongate pseudomorphs after olivine. Hornblende is very pale green in colour with a weakly developed pleochroism and forms large crystals up to 5.0 to 6.0 mm in length. Locally hornblende is fractured and exhibits a undulose to shadowy extinction due to varying degrees of intracrystalline deformation. Hornblende is also locally intergrown with biotite. Phlogopitic biotite is very pale brown to colourless (Plate 2) with a weakly developed pleochroism. It occasionally forms very large crystals up to *c*. 12.0 mm in length. Olivine has been total replaced by mesh-textured, very fine-grained serpentine and chlorite (Plate 2c and d). The outlines of rounded to irregular relict olivine crystals can locally be recognised within these pseudomorphs due to their mimetic

replacement by the alteration products. These pseudomorphs also contain opaque oxides released during the breakdown of olivine. Dusty looking clinopyroxene crystals up to 0.7 mm in size occur included within both amphibole and phlogopite. Large, up to 1.5 mm, anhedral apatite crystals were noted associated with, and partially enclosed within the margins of the amphibole crystals.

**Collectors Number:** PY711. **Registered Number:** N3686. **Location**: [ND 0076 5771] Broubster Forest, Caithness (CA 1465). **Lithology:** feldspar phyric diorite containing a xenolith of psammite. **Formation:** amphibolite within Strathalladale Granite.

**Description:** This thin section is of a medium- to coarse-grained, anhedral to subhedral granular, inequigranular, K-feldspar and plagioclase macroporphyritic diorite (Plate 3a and b) which contains a partially digested xenolith of psammite. The diorite is mainly composed of an inequigranular assemblage of plagioclase and quartz with minor amounts of biotite and K-feldspar (Plate 3a and b). Accessory minerals present include opaque minerals, apatite, zircon and allanite.

Plagioclase forms anhedral to weakly subhedral crystals with variably developed albite twins. The weakly zoned plagioclase exhibits minor alteration to sericite and may show preferential alteration of their cores or a particular compositional zone within these crystals. Phenocrysts range up to c. 7.0 mm in length and are composed of both plagioclase and K-feldspar. These phenocrysts are rounded to slightly irregular in shape indicative of partial resorption. Biotite forms anhedral flakes and plate-like crystals which occur intergranular to, and, therefore, post-dates the crystallisation of plagioclase. Biotite contains very fine-grained inclusions of opaque minerals, apatite, zircon and rare altered allanite. Biotite typically occurs as clusters of several anhedral to irregular crystals.

The remaining interstitial areas are filled by late crystallising quartz and very minor K-feldspar. Quartz is strained and possesses a variably developed undulose extinction and sub-grain textures. Occasional poikilitic intergranular quartz crystals, which range in size up to 3.0 mm, are also present. Small pockets of carbonate have been noted filling interstitial vugs which occur between plagioclase crystals.

The xenolith is composed of a foliated micaceous psammite which possesses a moderate to well developed foliation defined by aligned biotite flakes.

**Collectors Number:** PY712. **Registered Number:** N3687. **Location**: [ND 0400 6304] Achalone, Caithness (CA 1467). **Lithology:** laminated/cross laminated very fine-grained sandstone with silty partings. **Formation:** Calder Mudstone Member, Lybster Flagstone Formation.

**Description:** This thin section is of a very fine-grained, moderately to well sorted, low porosity, relatively mature, closely packed, matrix-poor, clast supported, sandstone to possibly coarse siltstone (Plate 3c and d). The sedimentary lamination and weak cross lamination are defined by thin, dusty looking silty partings (Plate 3c) which contain a higher modal proportion of detrital mica. The micas within the siltstone laminae and adjacent sandstone layers exhibit a preferred shape alignment parallel to the lamination. Detrital grains within the sandstone are angular to

subangular in shape with a low to moderate sphericity. These clasts are mainly composed of monocrystalline quartz with minor feldspar; the latter is variably replaced by carbonate. Other minor to accessory detrital components include muscovite, biotite, plagioclase, amphibole, rutile and chlorite.

Cementation of this sandstone occurred due to pressure solution of quartz and, to a lesser extent, feldspar. Pressure solution also resulted in the modification of the original shape of detrital grains leading to the comminuted appearance of this sandstone. Unstable detrital components within the sandstone are variably replaced by carbonate (Plate 3c and d). Four stages of carbonate replacement have been identified in this thin section: (1) early growth of pale pink stained non-ferroan calcite forming small anhedral to rounded crystals; (2) subsequent growth of unstained, non-ferroan dolomite which forms anhedral to weakly subhedral rhomb-shaped crystals which locally overgrow or included earlier non-ferroan calcite; (3) growth of rims of pale blue stained ferroan dolomite upon non-ferroan dolomite rhombs; and (4) later growth of mauve to blue stained ferroan calcite which forms rounded to irregular patches of very fine-grained sieve-textured crystals. Ferroan calcite appears to be replacing earlier formed non-ferroan calcite and may locally contain small relict grains of non-ferroan calcite. Larger aggregates and single crystals of ferroan calcite appear to be mimetically replacing pre-existing, large 0.3 to 1.2 mm sized, non-ferroan calcite crystals. Ferroan calcite was also noted locally overgrowing dolomite indicating that it post-dates dolomitisation of this sandstone. Ferroan calcite was also noted filling fractures and probably accompanied minor brittle deformation of this rock.

**Collectors Number:** PY713. **Registered Number:** N3688. **Location**: [ND 0463 6097] Leans of Achaeter, Caithness (CA 1468). **Lithology:** medium-grained, slightly feldspathic quartz-arenite. **Formation:** Dorrery Sandstone Member, Lybster Flagstone Formation.

**Description:** This thin section is of a moderately to poorly sorted, low porosity, very closely packed, relatively mature, weakly laminated, slightly feldspathic, indurated quartz arenite. Detrital grains are angular to subangular in shape with a low to moderate sphericity. The shape of these clasts has however been strongly modified due to pressure solution, grain boundary etching and variable growth of trace amounts of a quartz overgrowth cement. Pressure solution resulted in the main mode of cementation within this sandstone. The detrital assemblage is dominated by monocrystalline quartz with subordinate to minor amounts of plagioclase. Other minor to accessory detrital components present include muscovite/white mica, biotite, apatite, zircon, K-feldspar and perthite. Detrital micas have undergone localised kinking during compaction. Traces of a turbid grey-brown clayey cement or matrix have been noted.

Unstable detrital components have been variably replaced by carbonate and later opaque minerals. The carbonate is unstained non-ferroan dolomite and forms small anhedral to weakly subhedral rhomb-shaped crystals as well as granular aggregates of very fine-grained to cryptocrystalline material. The carbonate is variably replaced or pseudomorphed by a turbid brown coloured to opaque assemblage. Opaque was also noted forming distinct rims upon pseudomorphs after dolomite. The turbid assemblage replacing dolomite may have developed during de-dolomitisation. The slight variation in the modal proportion of alteration products, including opaque minerals, after dolomite defines a crude banding or lamination. Occasional to rare fine-grained partings have been noted associated with these opaque/dolomite bands suggesting that carbonate replacement was partially lithologically controlled with the banding preserving a weakly developed sedimentary lamination.

**Collectors Number:** PY714. **Registered Number:** N3689. **Location**: [ND 0468 6350] Knock glass, Forss Water, Caithness (CA 1471). **Lithology:** slightly calcareous, very fine-grained sandstone. **Formation:** Calder Mudstone Member, Lybster Flagstone Formation.

**Description:** This thin section is of a very fine-grained, massive, well sorted, clast supported, low porosity, very closely to closely packed, matrix-poor, slightly calcareous sandstone (Plate 4a and b). A small number of elongate to irregular mudstone clasts have been noted near the base of the thin section. Plastic deformation and attenuation of these fragments suggests that the mud was only partially lithified/consolidated at the time of erosion and incorporation into this sandstone. These mudstone fragments are interpreted as rip-up clasts. Finer, sand-grade clasts are angular to subrounded in shape. However, in general, the shape of these detrital grains has been modified during to pressure solution; the latter resulting in the main mode of cementation within this rock. The clast assemblage is dominated by monocrystalline quartz. Other minor to accessory detrital components include muscovite, plagioclase, biotite, K-feldspar, opaque minerals and chlorite.

Unstable detrital components and trace amounts of an originally clayey matrix have been variably replaced by carbonate (Plate 4a and b). Several stages of carbonate replacement/growth have been recognised, all of which post date pressure solution and cementation of this sandstone. Stage 1 resulted in the growth of small, anhedral to rounded crystals of pink stained non-ferroan calcite; Stage 2, led to the growth of small, anhedral to subhedral rhomb-shape non-ferroan dolomite crystals; Stage 3, is denoted by the very localised growth of pale blue stained ferroan dolomite rims upon earlier non-ferroan dolomite rhombs; and Stage 4 resulted in the growth of late, very fine-grained to cryptocrystalline, granular-looking blue to mauve stained ferroan calcite which replaces or overgrows the earlier developed non-ferroan calcite crystals. Carbonate growth is post-dated by the very localised development of thin opaque rims upon dolomite crystals. Ferroan calcite is less common in this thin section that previous samples, in which this type of calcite formed the dominant carbonate within these rocks. Non-ferroan calcite was also noted forming larger, c. 1.0 mm in diameter, anhedral crystals which locally possess sieve textured rims containing very fine-grained included relict quartz detrital grains.

Needle-like crystals of an opaque minerals have been noted (Plate 4a), with mineralisation post-dating carbonate replacement.

**Collectors Number:** PY721. **Registered Number:** N3690. **Location**: [ND 0487 6559] Quarry northwest of Baillie, Caithness (CA 1478). **Lithology:** laminated mudstone with thin siltstone laminae. **Formation:** Achscrabster Flagstone Member, Spital Flagstone Formation.

**Description:** This thin section is of a laminated mudstone which contains thin, fine-grained siltstone laminae (Plate 4c). The bulk of the rock is composed of turbid grey-brown mudstone which is variably replaced by very fine-grained carbonate. The localised presence of a blue staining of this locally cryptocrystalline carbonate assemblage suggests that it includes ferroan calcite or ferroan dolomite. Silt-grade detrital grains within the mudstone are composed of muscovite/white mica, quartz and opaque minerals.

The siltstone laminae are cleaner (low modal clay component) and more quartzose in composition. Detrital grains are mainly composed of monocrystalline quartz with minor to accessory plagioclase, muscovite/white mica, biotite and opaque minerals. The silty laminae range from 0.1 to 1.0 mm in thickness and are deformed by low-angle to moderately dipping normal faults (Plate 4c) and recumbent folds. The origin of these fold structures is uncertain. They are clearly truncated at bedding surfaces and may be related to slumping rather than being tectonic. Traces of opaque replacement/mineralisation of the mudstone have been recorded.

**Collectors Number:** PY725. **Registered Number:** N3691. **Location**: [ND 0331 6561] Stemster Burn, Caithness (CA 1480). **Lithology:** calcareous, very fine-grained siltstone or mudstone with soft sediment deformation structures. **Formation:** Scrabster Flagstone Member, Mey Flagstone Formation.

**Description:** This thin section is composed of a very fine-grained calcareous siltstone with disrupted mudstone laminae. The original sedimentary lamination is highly deformed and disrupted due to soft sediment deformation which accompanied fluidisation and remobilisation of the siltstone. The slightly more clay-rich laminae where relatively more coherent/cohesive and are deformed by complex disharmonic and rootless folds. A 8.0 to 10.0 mm thick band of silty mudstone in the centre of the thin section is domed upwards due to the thickening of the underlying fluidised siltstone layer. The centre of the dome-like fold is breached by an irregular hydrofracture which is filled by fluidised silt from the underlying siltstone layer. Fluidised sediment was injected through this fracture into the overlying sediments to form an irregular, diffuse layer or patch of siltstone containing fragments of clayey siltstone; these are locally deformed by rootless folds. The patch of fluidised siltstone clearly cuts across the lamination within the mudstone.

The siltstone laminae contain angular, low sphericity clasts which are mainly composed of monocrystalline quartz and minor feldspar. Other minor to accessory detrital components present include muscovite/white mica, opaque minerals, plagioclase and zircon. The unstable detrital components and clay are variably replaced by very fine-grained to cryptocrystalline, granular non-ferroan dolomite and pale blue stained ferroan dolomite. The replacement by carbonate gives the rock a very indurated/recrystallised appearance. The clay-rich mudstone laminae are mimetically replaced by dolomite.

**Collectors Number:** NCG001. **Registered Number:** N3692. **Location**: [ND 0456 7035] drain leading to Burn of Brims, Caithness. **Lithology:** laminated calcareous siltstone. **Formation:** Brims Limestone Member, Mey Flagstone Formation.

**Description:** This thin section is of a fine-grained, laminated siltstone which possesses a distinct band across the centre of the thin section which has undergone carbonate replacement. The carbonate is mainly composed of unstained non-ferroan dolomite and minor amounts of pale blue stained, very fine-grained, granular-looking ferroan dolomite or ferroan calcite. This predominantly dolomitic carbonate phase is closely associated with a turbid brown assemblage which may represent altered dolomite; the latter possibly recording a phase of de-dolomitisation during the diagenesis of this calcareous siltstone. The replacement of the clay by non-ferroan dolomite resulted in the fine granular to indurated appearance of this rock.

Angular detrital grains present within this siltstone are mainly composed of monocrystalline quartz. Minor to accessory detrital components present include muscovite/white mica; the latter is variably shape-aligned parallel to the sedimentary lamination. This lamination is defined by a slight variation in colour and intensity of dolomitisation, possibly reflecting subtle variations in the composition of the original sediment.

**Collectors Number:** AX2942. **Registered Number:** N3991. **Location**: [ND 0631 6229] Assery Mains, Westfield, Caithness (JF 312). **Lithology:** laminated fine-grained sandstone with silty or micaceous partings. **Formation:** Calder Mudstone Member, Lybster Flagstone Formation.

**Description:** This thin section is of a fine- to very fine-grained, laminated to cross laminated, low porosity, quartzose, matrix-poor, slightly calcareous sandstone. The lamination is preserved by the presence of thin (≤ 0.4 mm thick) silty laminae which contain a slightly higher modal proportion of detrital white mica/muscovite flakes.

The shape of the detrital grains has been strongly modified due to pressure solution; the latter resulting in the main mode of cementation within this sandstone. Rarely preserved grains unaffected by pressure solution are angular to subrounded in shape with a low to moderate sphericity. The clast assemblage is dominated by monocrystalline quartz. Other minor to accessory detrital components present include plagioclase, muscovite, biotite, opaque minerals, chlorite, apatite, monazite and zircon. Compaction resulted in the localised kinking of detrital micas.

Traces of a yellow-brown coloured, dusty looking clay or chloritic rim cement or matrix have been noted within this sandstone. This matrix and unstable detrital components have been variably replaced by carbonate. Four separate generations of carbonate have been recognised: (1) early, pale pink stained non-ferroan calcite forming single, isolated, anhedral crystals as well as granular aggregates of very fine grains; (2) small, anhedral to subhedral rhomb-shaped crystals of non-ferroan dolomite; (3) blue to mauve stained ferroan calcite overgrowing or replacing earlier non-ferroan calcite and occasionally non-ferroan dolomite; and (4) traces of pale blue stained ferroan dolomite which forms rims upon earlier developed dolomite rhombs. The relative age relationship between the ferroan dolomite and ferroan calcite is uncertain; locally it appears that the ferroan calcite may post-date the formation of dolomite. The ferroan calcite typically forms patches of very fine-grained to cryptocrystalline crystals. However, occasional larger (≤ 0.8 mm in size) patches or single crystals of ferroan calcite were recorded, possibly replacing earlier crystals of non-ferroan calcite. All the phases of carbonate replacement post-date pressure solution.

The upper part of the thin section contains wispy to irregular clasts or patches of mudstone. It is possible that these patches may represent highly distorted mudstone rip-up clasts. However, an alternative interpretation is that these features may represent mud lined or filled water escape features which developed due to the concentration of fines during dewatering of this sandstone.

**Collectors Number:** AX2944. **Registered Number:** N3992. **Location**: [ND 0546 6251] Forsie Quarry, 600 m southwest of Forsie, Caithness (JF 314). **Lithology:** laminated, calcareous silty mudstone with siltstone partings. **Formation:** Calder Mudstone Member, Lybster Flagstone Formation.

**Description:** This thin section is of a calcareous, finely laminated silty mudstone with this clay-poor coarse siltstone to very fine-grained sandstone partings (Plate 5a). The mudstone is turbid brown in colour and contains scattered very fine-grained monocrystalline quartz grains and muscovite mica flakes. Small-scale normal grading of the mudstone and siltstone laminae is denoted by a change in colour and grain size. The mudstone laminae range from 0.3 to 6.0 mm thick and are variably replaced by later carbonate. Where it is well developed the carbonate completely replaces the a particular laminae. Elsewhere, the carbonate forms rounded to irregular patches within the mudstone and siltstone laminae (Plate 5a). Two stages of carbonate replacement have been recognised within this sample: Stage 1 resulted in the development of very fine-grained to cryptocrystalline, granular to rhomb-shaped crystals of unstained non-ferroan dolomite; Stage 2 led to the later growth of elongate aggregates (parallel to bedding) of mauve to blue stained ferroan calcite. The ferroan calcite is apparently preferentially developed within the siltstone laminae. Carbonate replacement was post-dated by the localised replacement of the mudstone by opaque minerals.

Detrital grains within the siltstone laminae are mainly composed of monocrystalline quartz. Other minor to accessory detrital components include muscovite/white mica, biotite, plagioclase and chlorite.

**Collectors Number:** AX2945. **Registered Number:** N3993. **Location**: [ND 0590 6338] water pipe trench, Forsie, Caithness (JF 315). **Lithology:** inter-laminated mudstone, siltstone and very fine-grained sandstone. **Formation:** Calder Mudstone Member, Lybster Flagstone Formation.

**Description:** This thin section is composed of inter-laminated mudstone, siltstone and very fine-grained sandstone which exhibit varying degrees (minor) of replacement by carbonate. Soft sediment deformation resulted in the localised folding and boudinage of the siltstone laminae. The erosive base of a prominent, *c*. 5.0 mm thick, very fine-grained sand layer truncates the soft sediment deformation structures developed in the underlying mudstone and siltstone suggesting that deformation occurred due to either slumping or disturbance due to storm activity. Lenticular to rounded fragments of sandstone and siltstone present within the thicker mudstone laminae may represent boudinaged silty or sandy layers. These lenses are wrapped by the very fine-scale lamination present within the mudstone.

The sandstones and siltstone laminae are mainly composed of moderately sorted, angular to subangular clasts of monocrystalline quartz. Other minor to accessory detrital components present include muscovite/white mica, biotite and plagioclase. The detrital micas are variably aligned parallel to the sedimentary lamination. The clay and unstable detrital components within the mudstones and siltstones are variably replaced by carbonate. Four stages of carbonate replacement have been recognised in this sample: (1) early development of pink stained non-ferroan calcite; (2) later development of small rhomb-shaped crystals of non-ferroan dolomite; (3) very localised development of ferroan dolomite rims upon dolomite rhombs; and (4) late development of mauve to blue stained ferroan calcite which appears to be replacing the earlier developed non-ferroan calcite. Cementation within the siltstone and sandstone laminae, however, appears to have mainly occurred as a result of pressure solution; this event pre-dated the development of carbonate. The mudstone laminae have been variably replaced by very fine-grained to cryptocrystalline, unstained ?dolomite.

Carbonate replacement was post-dated by minor opaque mineralisation within the sandstone and siltstone laminae. The opaque minerals form elongate, needle-like crystals as well as small patches of very fine-grained granular to massive crystals. Opaque replacement/mineralisation within the mudstone laminae is more restricted.

**Collectors Number:** AX2946. **Registered Number:** N3994. **Location**: [ND 0813 6265] Achscrabster Quarry, Westfield, Caithness (JF 316). **Lithology:** finely laminated siltstone with mudstone partings. **Formation:** Achscrabster Member, Spital Flagstone Formation.

**Description:** This thin section is of a very finely laminated siltstone with thin mudstone partings (Plate 5b). Lenticular pockets of coarser grained siltstone and very fine-grained sandstone are present at the bases of some of the thicker siltstone laminae, representing small-scale lag deposits. The siltstone laminae may locally exhibit normal, grain size grading and may possess thin silty to clayey tops. Dark brown, turbid, possibly organic-bearing claystone partings have been noted at the top of some of these graded laminae. A slight thickening and thinning of some of the siltstone laminae has also been recorded within this sample. In general, the individual laminae range from 0.1 to 2.0 mm thick and may possess sharp erosional bases.

Clastic grains are mainly composed of monocrystalline quartz. Other minor to accessory detrital components present include muscovite/white mica, altered biotite, plagioclase and chlorite. The detrital phyllosilicates are variably shape aligned parallel to bedding. Traces of secondary, replacive dolomite and ferroan calcite have been noted within the siltstone laminae.

**Collectors Number:** PY745. **Registered Number:** N3995. **Location**: [ND 04075 67520] Forss Water, Old Bridge, Caithness (CA 1502). **Lithology:** fine-grained, slightly calcareous sandstone (quartz arenite). **Formation:** Holborn Sandstone Member, Mey Flagstone Formation.

**Description:** This thin section is of a fine-grained, slightly feldspathic, relatively mature, quartzose, moderately to poorly sorted, moderately to closely packed, clast supported, massive, slightly calcareous sandstone (Plate 5c and d). Detrital grains are angular to subangular in shape with a low to occasionally moderate sphericity. Rare well rounded clasts have also been noted. The detrital assemblage is dominated by monocrystalline with minor plagioclase. Other minor to accessory detrital components include polycrystalline quartz, muscovite, apatite, rutile, biotite, K-feldspar, opaque minerals, chlorite, zircon, garnet and microcline. Compaction resulted in the localised kinking of the detrital micas.

The shape of the detrital grains has been variably modified (grain boundary etching) due to pressure solution, with the latter resulting in the main mode of cementation within this sample. by Trace amounts of a clay or chloritic matrix, as well as unstable detrital components, are variably replaced by later carbonate. Trace amounts of non-ferroan calcite and non-ferroan dolomite are locally overgrown or replaced by later blue to mauve stained ferroan calcite. Ferroan calcite is the dominant carbonate mineral and forms very fine, granular aggregates as well as coarser grained (≤ 0.5 mm in size) sparry, anhedral crystals. Fine detrital quartz grains are locally included/overgrown by these sparry ferroan calcite crystals resulting in the development of a very localised cement supported texture.

**Collectors Number:** PY752. **Registered Number:** N3996. **Location**: [ND 02364 69350] quarry west of Hill of Lybster, Caithness (CA 1507). **Lithology:** laminated very fine-grained sandstone and siltstone with mudstone partings. **Formation:** Sandside Bay Sandstone Member, Sandside Sandstone Formation.

**Description:** This thin section is of a laminated, very fine-grained sandstone to coarse siltstone with thin mudstone partings. The sandstone and siltstone laminae are matrix-poor, clast supported, closely to very closely packed and normally graded from sand at the base, through silt to a thin mudstone parting at the top of some of these graded units. Detrital grains are angular to subangular in shape with a low sphericity. The shape of these clastic grains has, however, been modified due to pressure solution. The latter has resulted in the main mode of cementation within the rock and resulted in the overall indurated appearance of the sample. The detrital assemblage is dominated by monocrystalline quartz. Minor to accessory detrital components include muscovite, biotite, plagioclase, chlorite, opaque minerals, apatite and zircon.

Traces of a chloritic or clay matrix have been noted. This matrix and the more unstable detrital components have been variably replaced by secondary carbonate. Four generations of carbonate have been recognised within this sample: (1) early pink stained non-ferroan calcite which forms small anhedral to rounded crystals; (2) anhedral to subhedral rhomb-shaped crystals of non-ferroan dolomite; (3) pale blue stained ferroan dolomite forming very locally developed rims upon earlier non-ferroan dolomite rhombs; and (4) dark blue to mauve stained ferroan calcite. The relationship of the ferroan calcite to ferroan dolomite is uncertain, however, growth of this ferroan carbonate clearly post-dates the earlier non-ferroan carbonate minerals. The carbonate appear to be slightly coarser grained and preferentially developed within the sandstone and coarse siltstone laminae.

**Collectors Number:** PY753. **Registered Number:** N3997. **Location**: [ND 01861 69774] adjacent to Hing Geo, Caithness (CA 1508). **Lithology:** mudstone containing ptygmatically folded siltstone and very fine-grained sandstone veinlets. **Formation:** Dounreay Siltstone Member, Sandside Sandstone Formation.

**Description:** This thin section is of a massive to very finely laminated mudstone which contains highly deformed, ptygmatically folded siltstone to very fine-grained sandstone veinlets or layers (Plate 6a and b). The sandstone and siltstone layers vary from < 0.1 mm up to *c*. 2.0 mm thick and are locally highly attenuated on the limbs of the folds. These sandstone layers can be locally observed cross cutting a very fine-scale lamination in the host mudstone, indicating that the sand and silt was injected along hydrofractures within the mudstone. The highly complex, ptygmatic nature of the folds (see Plate 6a and b) suggests that deformation occurred either during or immediately after hydrofracturing and injection of the fluidised sand and/or silt. Hydrofracturing of the mudstone suggests that it was relatively cohesive at the time of deformation and may have already undergone at least the initial stages of dewatering. The axial planes of the folds are sub-parallel to the lamination present within the host mudstone.

Detrital grains within the sandstone and siltstone are angular to subangular in shape with a low sphericity. They are mainly composed of monocrystalline quartz with minor to accessory plagioclase, muscovite/white mica, biotite, chlorite, amphibole, opaque minerals and apatite also present within the clast assemblage. Traces of non-ferroan calcite, dolomite and ferroan dolomite replacing the unstable detrital components within the sandstone layers have been noted. The

mudstone is variably replaced by a turbid brown coloured unstained carbonate (?non-ferroan dolomite) and traces of blue stained ferroan carbonate.

**Collectors Number:** PY755. **Registered Number:** N3998. **Location**: [ND 0330 6919] east side of Forss Water Valley, Caithness (CA 1510). **Lithology:** coarse siltstone with wispy mudstone filled dewatering features. **Formation:** Sandside Bay Sandstone Member, Sandside Sandstone Formation.

**Description:** This thin section is of a coarse siltstone which contains irregular to occasionally wispy looking mudstone lenses and patches. These patches of mudstone are highly irregular in shape and do not represent a single disrupted clay layer. Consequently, they are interpreted as having developed due to the concentration of fines during water-escape.

The siltstone possesses a closely packed, clast supported texture and contains small, intergranular patches of dusty grey clay-grade matrix. Detrital grains are angular to subangular in shape with a low to occasionally moderate sphericity. The clasts are mainly composed of monocrystalline quartz with minor to accessory muscovite, biotite, plagioclase, opaque minerals and chlorite. Trace amounts of dolomite and ferroan calcite have been recorded with the dolomite forming small anhedral to rhomb-shaped crystals. The dolomite rhombs are locally rimmed by opaque minerals. Trace amounts of late opaque mineralisation was also noted with the opaque forming small aggregates of needle-like crystals.

**Collectors Number:** PY756. **Registered Number:** N3999. **Location**: [ND 0294 6958] west side of mouth of Forss Water Valley, Caithness (CA 1516). **Lithology:** very fine-grained sandstone. **Formation:** Sandside Bay Sandstone Member, Sandside Sandstone Formation.

**Description:** This thin section is of a very fine-grained, massive, very closely packed, clast supported, low porosity, quartzose sandstone. The shape of the detrital grains has been modified due to pressure solution and grain boundary etching, with pressure solution resulting in the main mode of cementation within this sandstone. Traces of a quartz rim cement have also been noted. Relict detrital grains are angular to subangular in shape with a low sphericity. They are mainly composed of monocrystalline quartz with minor to accessory plagioclase, muscovite, biotite, chlorite, apatite and opaque minerals.

Three generations of carbonate have been recorded replacing unstable detrital components and matrix of this sandstone. Early replacement post-dated pressure solution and resulted in the growth of small anhedral crystals of pale pink stained non-ferroan calcite. This was followed by the growth of small rhombs of non-ferroan dolomite. Both of these non-ferroan carbonate minerals are locally overgrown or replaced by blue to mauve stained ferroan calcite. Ferroan calcite forms small patches of cryptocrystalline to very fine-grained crystals. Small pockets of intense carbonate replacement are locally developed and may be dominated by single, relatively large (≤ 1.0 mm in size), anhedral to irregular ferroan calcite crystals. These may contain small relicts of non-ferroan calcite.

Traces of opaque mineralisation post-dated carbonate replacement and resulted in the development of rod to needle-like crystals. Irregular, diffuse patches of slightly dusty looking

silty sand are present within this sandstone, recoding a slight variation in the modal proportion of the matrix.

**Collectors Number:** PY760. **Registered Number:** N4000. **Location**: [ND 0500 6937] Burn of Brims, Caithness (CA 1520). **Lithology:** finely laminated, calcareous silty mudstone with irregular patches/veinlets of coarse siltstone. **Formation:** Holborn Sandstone Member, Mey Flagstone Formation.

**Description:** This thin section is of a finely laminated silty mudstone which contains irregular patches or veinlets of coarse siltstone or very fine-grained sandstone. These sandy patches appear to represent partially fluidised/remobilised and ptygmatically folded laminae and/or hydrofracture fills. The sedimentary lamination is defined by the slight variation of included silt-grade detritus.

The bulk of the rock is composed of silty mudstone which contains angular, low sphericity clasts of predominantly monocrystalline quartz. Other minor to accessory detrital phases present include plagioclase, muscovite/white mica, opaque minerals, microcline and biotite. The clay-grade component is variably replaced by cryptocrystalline to very fine-grained, unstained carbonate (?non-ferroan dolomite). Small pockets or patches of blue stained ferroan calcite have also been noted replacing this mudstone. Traces of non-ferroan calcite are associated with the coarse siltstone and sandstone.

**Collectors Number:** PY761. **Registered Number:** N4001. **Location**: [ND 0479 6984] drain north of Burn of Brims, Caithness (CA 1521). **Lithology:** calcareous laminated siltstone with coarse siltstone to very fine-grained sandstone filled hydrofractures. **Formation:** Holborn Sandstone Member, Mey Flagstone Formation.

**Description:** This thin section is of a calcareous, finely laminated mudstone with thin siltstone partings. The rock is cut by a network of coarse siltstone to very fine-grained sandstone filled hydrofractures (Plate 6c). Hydrofracturing also resulted in localised brecciation of the adjacent mudstone host rock. Mudstone fragments within the fluidised sandstone and siltstone are angular in shape and exhibit very little obvious rounding or plastic deformation. This suggests that the mudstone was relatively cohesive at the time of deformation and may have undergone at least the initial stages of dewatering prior to hydrofracturing. The siltstone and sandstone hydrofractures link into a 5.0 to 6.0 mm thick siltstone layer which occurs ate the top of the thin section.

The siltstone and very fine-grained sandstone which in fills the hydrofractures is matrix-poor and possesses a very closely packed, clast supported texture. Trace amounts of clay-grade matrix present within the siltstone and sandstone are variably replaced by non-ferroan calcite, non-ferroan dolomite and mauve to blue stained ferroan calcite. Detrital grains within these silty to sandy sedimentary rocks are mainly composed of angular to subangular, low sphericity monocrystalline quartz fragments. Other minor to accessory detrital components present include plagioclase, muscovite, biotite, opaque minerals and rutile. Compaction resulted in the localised kinking of detrital micas.

The mudstone is variably replaced by very fine-grained to cryptocrystalline, pale blue stained ferroan calcite and/or non-ferroan dolomite. Dolomite forms distinctive small, anhedral to

subhedral rhomb-shaped crystals. Carbonate replacement has also effected the more unstable detrital components and clay-grade matrix within the fluidised siltstone and sandstone. The replacement of these components within the fluidised siltstone and sandstone indicates that carbonate development post-dated hydrofracturing and dewatering of these sediments.

**Collectors Number:** PY762. **Registered Number:** N4002. **Location**: [ND 0358 5970] Broubster, Caithness (CA 1522). **Lithology:** laminated and cross laminated coarse siltstone and very fine-grained sandstone. **Formation:** Dorrery Sandstone Member, Lybster Flagstone Formation.

**Description:** This thin section is of a finely laminated and cross laminated, coarse to fine siltstone and very fine-grained sandstone. The lamination is defined by the variation in grain size and modal proportion of a turbid brown coloured clay matrix component. This matrix shows localised staining by brown Fe-oxide and/or minor replacement by opaque minerals. Detrital grains are angular in shape with a low sphericity. These clasts are mainly composed of monocrystalline quartz. Minor to accessory detrital components present include muscovite, plagioclase, biotite, opaque minerals, chlorite, apatite and K-feldspar. Detrital micas exhibit a preferred shape alignment parallel to the sedimentary lamination, with the micas being concentrated into the finer siltstone laminae. Compaction resulted in the localised kinking of detrital micas. The cross lamination is defined by well developed asymptotic laminae which may exhibit fine-scale normal grading of the fore-sets. No obvious carbonate replacement has been recorded within this sample.

**Collectors Number:** PY763. **Registered Number:** N4003. **Location**: [ND 0396 5946] Broubster Quarry, Caithness (CA 1523). **Lithology:** weakly laminated, medium-grained quartz arenite. **Formation:** Dorrery Sandstone Member, Lybster Flagstone Formation.

**Description:** This thin section is of a fine- to medium-grained, poorly to very poorly sorted, moderately to closely packed, clast supported, low porosity, slightly feldspathic quartz arenite (Plate 7a and b). This sandstone also contains patches of finer grained silty material, forming a poorly developed matrix. Detrital grains are angular to subangular in shape with a low sphericity. However, rare subrounded grains are also present. These grains locally appear to be broken fragments of larger clasts and are, therefore, considered to be polycyclic in origin. The clast assemblage is dominated by monocrystalline quartz with subordinate plagioclase. Other minor to accessory detrital components present include K-feldspar, microcline, muscovite, polycrystalline quartz, tourmaline, apatite, chlorite, opaque minerals, zircon, monazite and granitic rock fragments. Pressure solution of both quartz and plagioclase resulted in the main mode of cementation within this sandstone. However, traces of an apparently earlier clay or chloritic rim cement have been noted locally forming a coating on detrital grains. No obvious carbonate replacement has been recorded in this sample.

**Collectors Number:** PY765. **Registered Number:** N4004. **Location**: [ND 04948 57195] northwest flank of Beinn Freicendain, Caithness (CA 1524). **Lithology:** very weakly laminated sandy siltstone. **Formation:** Dorrery Sandstone Member, Lybster Flagstone Formation.

**Description:** This thin section is of a poorly sorted, weakly laminated, weakly graded, coarse siltstone (Plate 7c and d) with scattered fine- to medium-grained sand-grade clasts. These sand-grade clasts are mainly composed of monocrystalline quartz. The primary sedimentary

lamination is defined by a slight variation in grain size and modal proportions of a minor clay matrix component. The latter may be partially derived from degraded unstable detrital components. These unstable detrital components and the matrix exhibit variable replacement by carbonate. The latter is mainly composed of blue to mauve stained ferroan calcite which locally forms ≤ 0.6 mm in size, anhedral to irregular crystals. These larger crystals may contain traces of non-ferroan calcite and/or non-ferroan dolomite. Locally the anhedral to rhomb-shaped crystals non-ferroan dolomite crystals are enclosed within a fine rim of pale blue stained ferroan dolomite.

Sand-grade clasts are angular, subangular to occasionally subrounded in shape with a low to rarely moderate sphericity. In contrast, the finer grained silt-grade clasts are dominated by angular, low sphericity fragments. The clasts are mainly composed of monocrystalline quartz. Minor to accessory detrital components present include plagioclase, muscovite, biotite, opaque minerals, zircon, chlorite and apatite.

**Collectors Number:** PY767. **Registered Number:** N4005. **Location**: [ND 0398 5802] east bank of Forss Water, Caithness (CA 1526). **Lithology:** weakly laminated micaceous siltstone. **Formation:** Multeadh Sandstone Member, Ulbster Sandstone Formation.

**Description:** This thin section is of a weakly laminated, clay-poor, very closely packed, clast supported, micaceous siltstone. Detrital micas within this siltstone exhibit a well developed preferred shape alignment parallel to bedding. Compaction resulted in the localised kinking of the detrital phyllosilicates which are variably distorted against neighbouring more rigid quartzose grains. The pressure solution of quartz resulted in the main mode of cementation within this sample and the modification of the shape of included detrital grains. The clast assemblage is dominated by monocrystalline quartz with subordinate amounts of muscovite. Other minor to accessory detrital components present include biotite, plagioclase, chlorite and opaque minerals. The detrital micas are variably replaced or pseudomorphed by opaque minerals. Very fine-grained aggregates of opaque have also been noted replacing the matrix to this siltstone. Detrital feldspar is variably altered to sericite. No obvious carbonate replacement has been recorded in this thin section.

**Collectors Number:** NCG001. **Registered Number:** N4006. **Location**: [ND 05206 69164] Burn of Brims Farm, Caithness. **Lithology:** finely laminated siltstone. **Formation:** Holborn Sandstone Member, Mey Flagstone Formation.

**Description:** This thin section is of a finely laminated siltstone in which the sedimentary lamination is defined by the variation in grain size and modal proportion of a honey brown coloured clay matrix. The clay locally forms thin silty mudstone partings. Traces of anhedral to rhomb-shaped crystals of non-ferroan dolomite have been recorded. These dolomite rhombs are rimmed by pale blue stained ferroan dolomite. Trace amounts of mauve stained ferroan calcite are also present, however, the relationship of this carbonate to dolomite is uncertain. Carbonate replacement is typically associated with the cleaner coarse siltstone laminae.

Detrital grains are angular in shape with a low sphericity. The shape of these clasts has, however, been variably modified during pressure solution which resulted in cementation of this rock. The clast assemblage is dominated by monocrystalline quartz. Minor to accessory detrital components present include plagioclase, opaque minerals, muscovite, biotite, chlorite, zircon and

amphibole. Detrital phyllosilicates exhibit a locally well developed preferred shape alignment parallel to bedding. Compaction resulted in the localised kinking of these detrital micas.

**Collectors Number:** NCG002. **Registered Number:** N4007. **Location**: [ND 05069 69296] Burn of Brims Farm, Caithness. **Lithology:** weakly laminated mudstone. **Formation:** Holborn Sandstone Member, Mey Flagstone Formation.

**Description:** This thin section is of a weakly laminated, yellow-brown coloured mudstone in which the sedimentary lamination is defined by a slight variation in colour and variable occurrence of minor, very fine silt-grade detrital grains. A weakly developed bedding-parallel plasmic fabric is locally present within the mudstone and is defined by the optical alignment of the clay plasma. Trace amounts of detrital quartz, muscovite and opaque minerals have been recorded. No obvious carbonate replacement has been recognised in this thin section.

**Collectors Number:** NCG003. **Registered Number:** N4008. **Location**: [ND 06893 67665] Hopefield Farm, Caithness. **Lithology:** inter-laminated, calcareous siltstone and mudstone with load and soft-sediment deformation structures. **Formation:** Scrabster Flagstone Member, Mey Flagstone Formation.

**Description:** This thin section is of a inter-laminated, calcareous siltstone and mudstone which has undergone varying degrees of loading and soft sediment deformation. Deformation also included hydrofracturing, with the latter being filled by coarse siltstone. A hydrofracture in the basal part of the thin section terminates immediately below a dark clay-rich layer. The fluidised siltstone which fills this fracture spread laterally/parallel to bedding below this mudstone layer. The silty material filling these hydrofractures is lithologically similar to the siltstone laminae. The sedimentary lamination is defined by the variation in grain size, with individual laminae showing normal grading from siltstone at the base to mudstone at the top. Load structures and sand balls are developed at the case of some of the coarser grained siltstone laminae. One of the siltstone layers is contorted with locally developed convolute folds and rare recumbent fold structures. This layer also varies in thickness, as a result of localised attenuation. Recumbent folds developed within the siltstone and mudstone laminae are confined to within a single layer and may have developed in response to slumping and/or disturbance due to storm activity.

The mudstone laminae are locally cut by funnel-shaped water-escape conduits. One of the mudstone layers also contains or is associated with highly irregular patches of mauve to blue stained, replacive ferroan calcite. This ferroan carbonate was also noted filling thin, irregular, laterally impersistant veinlets within the mudstone. Traces of ferroan and rare non-ferroan calcite have been notes elsewhere within this sample. Detrital grains within the siltstone layers are angular to irregular in shape, with these shape of these clast being variably modified due to grain boundary etching associated with carbonate replacement. The clast assemblage is dominated by monocrystalline quartz with subordinate amounts of muscovite, biotite, plagioclase and opaque minerals. Carbonate is very fine-grained to cryptocrystalline and is apparently composed of unstained, non-ferroan dolomite.

Very dark coloured mudstone laminae may originally have been richer in organic material.

**Collectors Number:** NCG004. **Registered Number:** N4009. **Location**: [ND 07589 67592] Hopefield Farm, Caithness. **Lithology:** laminated siltstone and silty mudstone. **Formation:** Scrabster Flagstone Member, Mey Flagstone Formation.

**Description:** This thin section is of a laminated and weakly graded siltstone and silty mudstone. This sample is lithologically similar to sample N4008. The lamination is defined by a slight variation in the grain size and modal proportion of a yellow-brown coloured clay-grade matrix. Traces of ferroan and non-ferroan dolomite as well as rare ferroan calcite have been noted within this sample. Carbonate replacement is very limited, with dolomite locally forming anhedral to weakly subhedral rhomb-shaped crystals. Detrital grains are angular in shape with a low sphericity. They are mainly composed of monocrystalline quartz with minor to accessory muscovite, biotite and plagioclase. The siltstone laminae are locally graded with slightly coarser grained bases.

# Glossary

*Amphibolite* – A metamorphosed basic igneous rock with a mineral assemblage comprised largely of amphibole and plagioclase, usually with quartz and epidote.

*Atoll structure* – A structure developed in metamorphic rocks consisting of a core of one mineral entirely surrounded by a rim of another mineral. For example garnet forming a core entirely surrounded by plagioclase.

*Augen gneiss* – A gneissose metamorphic rock with abundant *augen* (eyes) represented by porphyroblasts (typically K-feldspar) enveloped by the foliation.

*Alkali* – A prefix applied to igneous rocks which contain either: (a) modal feldspathoids and/or alkali amphibole or pyroxenes; or (b) normative feldspathoids or acmite.

*Alkali basalt* – Term originally used for basalts containing accessory feldspathoids. These rocks typically contain a Ti-augite and olivine as their main ferromagnesian phases. Now defined geochemically using the Total Alkali-Silica diagram as a variety of basalt.

*Alkali gabbro* – A variety of gabbro which is alkaline in character due to the presence of analcime or nepheline and ferromagnesian phases such as barkevikite, kaersutite and/or Ti-augite.

*Andesite* – An intermediate volcanic rock, usually porphyritic, consisting of plagioclase (frequently zoned from labradorite to oligoclase), pyroxene, hornblende and/or biotite. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

*Basalt* – A volcanic rock consisting essentially of calcic plagioclase and pyroxene. Olivine and minor feldspathoids may also be present. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

*Basaltic andesite* – A volcanic rock with plagioclase compositions expected for andesites but containing ferromagnesian minerals more commonly found in basalts. Now defined geochemically using the Total Alkali-Silica diagram.

*Benmoreite* – A variety of basaltic igneous rock defined geochemically as the sodic variety of trachyandesite using the Total Alkali-Silica diagram.

*Bow-tie structure* – Aggregates of elongate prismatic and acicular crystals in a metamorphic rock which are arranged to give the appearance of a bow-tie. Commonly exhibited by amphiboles in *garbenschiefer* that have grown in the foliation plane under low stress.

*Calc-silicate rock* – A metamorphic rock with a chemistry dominated by calcium and silica (e.g. a metamorphosed calcareous mudstone, marl), consisting of the hydrous or anhydrous calc-silicate minerals such as tremolite, diopside and grossular garnet. Carbonate minerals may also be present.

*Cleavage* – A fabric developed within a metamorphic rocks defined by a sub-parallel set of closely spaced approximately planar surfaces produced during rock deformation. Defined by the preferred alignment of platy or elongate mineral grains (usually phyllosilicate minerals such as muscovite, biotite, chlorite).

*Corona or reaction rim* – A texture developed in metamorphic rocks composed of a monomineralic or polymineralic rim totally surrounding a core of another mineral phase. It typically represents an arrested reaction between the core phase and other components within the rock.

*Camptonite* – A variety of lamprophyre composed of phenocrysts of combination of olivine, kaersutite, Ti-augite and Ti-biotite in a matrix of the same minerals (except olivine) with plagioclase and sometimes subordinate alkali feldspar and feldspathoids.

*Cement supported* – Describes a fragmentary deposit where the detrital grains are, to varying degrees, isolated/supported within the cement.

*Cement* – The material bonding the fragments of clastic sedimentary rocks together and which was precipitated between the grains after deposition.

*Clast supported* – Describes a fragmentary deposit where all the detrital grains are in contact.

*Crinanite* – A variety of olivine-analcime dolerite or gabbro composed of olivine, Ti-augite and labradorite with minor analcime. Although it has less analcime and more olivine than teschenite the two names have been used interchangeably.

*Cryptocrystalline* – A term used to describe crystals in an igneous rock which are too small to be identified even with the petrological microscope.

*Crystallinity* – (a) H*olocrystalline*, an igneous rock composed of 100% crystals; (b) *holohyaline*, an igneous rock composed of 100% glass; and (c) *hypocrystalline*, intermediate between the two end-members and can be described more precisely by stating the relative proportions of crystals and glass.

*Dacite* – A volcanic rock composed of quartz and sodic plagioclase with minor amounts of biotite and/or hornblende and/or pyroxene. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid diagram or geochemically using the Total Alkali-Silica diagram.

*Decussate structure* – A term used to describe interlocking, randomly orientated, elongate, prismatic or subhedral crystals in a metamorphic rock which are generally of a single mineral phase.

*Detritus* – A general term for fragmentary material, such as gravel, sand, clay, worn from rock by disintegration. Detrital grains in clastic sedimentary rocks may be composed of single mineral grains (e.g. monocrystalline quartz, plagioclase), polycrystalline mineral grains (e.g. polycrystalline quartz) or lithic fragments including sedimentary, igneous and metamorphic rock fragments.

*Dolerite* – An igneous rock of intermediate grain size between a basalt and gabbro (i.e. synonym for *microgabbro*), and composed of essentially plagioclase, pyroxene and opaque minerals. Often contains an ophitic texture. If olivine is present may be called an olivine-dolerite; if quartz, a quartz-dolerite.

*Equigranular* – All the crystals in an igneous rock are approximately the same size.

*Essexite* – A variety of nepheline monzogabbro or nepheline monzodiorite containing Ti-augite, kaersutite and/or biotite with labradorite, lesser alkali feldspar and nepheline.

*Felsite* – A rock term initially used for the microcrystalline groundmass of porphyritic igneous rocks. Now commonly used for microcrystalline rocks of granitic composition (i.e. dacite to rhyolite).

*Gneiss* – A coarsely banded high-grade metamorphic rock consisting of alternating, mineralogically distinct layers.

*Granoblastic texture* – An aggregate consisting of equidimensional, typically rounded to anhedral crystals in a metamorphic rock which are of approximately equal size.

*Granulite* – A high-grade metamorphic rock typically with a granoblastic texture and with an assemblage containing pyroxene and anorthite-rich plagioclase.

*Greenschist* – A low-grade metamorphosed basaltic rock consisting of the assemblage actinolite, chlorite, epidote, albite, quartz and accessory titanite (sphene).

*Grain size* – Refers to the size of fragmentary material present in unconsolidated sediments and sedimentary rocks: (a) clay < 0.0039 mm in size; (b) silt, 0.0039 to 0.0625 mm in size; (c) fine sand, 0.0625 to 0.25 mm in size; (d) medium sand, 0.25 to 0.5 mm in size; (e) coarse sand, 0.5 to 1.0 mm in size; (f) very coarse sand, 1.0 to 2.0 mm in size; (g) granules 2.0 to 4.0 mm in size; (h) pebbles 4.0 to 64 mm in size.

*Grain size* – Refers to the size of crystals present in igneous rocks: (a) coarse-grained, crystals > 5.0 mm in size; (b) medium-grained, crystals 1.0 to 5.0 mm in size; (c) fine-grained, crystals < 1.0 mm in size.

*Hornfels* – A hard, fine- to medium-grained granoblastic metamorphic rock produced by high-grade contact metamorphism.

*Hawaiite* – A variety of basaltic igneous rock defined geochemically as the sodic variety of trachybasalt using the Total Alkali-Silica diagram.

*Inequigranular* – Term used to describe crystals present within an igneous rock which are of substantially different grain sizes. Common variety, porphyritic texture, can be subdivided into: (a) *microporphyritic*, phenocrysts ≤ 2.0 mm in size; and (b) *macroporphyritic*, phenocrysts > 2.0 mm in size.

*Kersantite* – A variety of lamprophyre consisting of phenocrysts of Mg-biotite, with or without hornblende, olivine or pyroxene in a groundmass of the same minerals plus plagioclase and occasionally alkali feldspar.

*Matrix* – Material, usually clay minerals or micas, forming a bonding substance to grains in a clastic sedimentary rock. The matrix material was deposited with the other grains or developed authogenically by diagenesis or slight metamorphism. Also used more generally for finer grained material in any rock in which large components are set.

*Matrix supported* – Describes a fragmentary deposit where the detrital grains are, to varying degrees, isolated/supported within a finer grained matrix.

*Microcrystalline* – crystals in an igneous rock which can only be identified with a petrological microscope. Crystals only just large enough to show polarisation colours (< 0.01 mm in size) are called *microlites*.

*Minette* – Term used for a variety of lamprophyre consisting of phenocrysts of phlogopite-biotite and occasionally amphibole in a groundmass of the same minerals plus orthoclase and minor plagioclase. Mg-olivine and diopsidic pyroxene may also be present.

*Olivine-basalt* – A commonly used term for a basalt containing olivine as an essential constituent.

*Packing* – Describes, as the term suggests, how closely the individual detrital grains are packed together within a fragmentary deposit. The term closely packed is used where all the grains are in contact and there is very little obvious matrix or cement; moderately packed and open packed are used with an increase in the porosity, matrix and/or cement.

*Porosity* – The volume of voids expressed as a percentage of the total volume of the sediment or sedimentary rock.

*Phyllite* – A well-cleaved metamorphosed mudstone characterised by a distinctive sheen on foliation surfaces; generally of intermediate grain size and metamorphic grade between slate and schist.

*Poikiloblast* – A term used to describe porphyroblasts present within a metamorphic rocks which contain abundant mineral inclusions.

*Porphyroblast* – A metamorphic mineral (e.g. garnet) that has grown to much larger size than the minerals of the surrounding matrix.

*Porphyroblastic* – A term used to describe a metamorphic rock containing large porphyroblasts within a finer grained matrix.

*Porphyroclast* – A large relict crystal, or crystal fragment in a fine-grained matrix of a deformed rock.

*Post-tectonic growth* – Growth of metamorphic minerals or parts of a mineral which occurred after deformation had ceased.

*Pressure shadow* – A region of low strain developed immediately adjacent to a rigid or competent object in a rock (e.g. a garnet porphyroblast).

*Pre-tectonic growth* – Metamorphic mineral growth before deformation has occurred.

*Pseudomorph* – A mineral or aggregate of minerals having taken the form/shape of another mineral phase that it/they have replaced.

*Quartz-dolerite* – A variety of *microgabbro* (dolerite) composed mainly of plagioclase and pyroxenes with interstitial quartz. The rock has tholeiitic affinities and its pyroxenes are usually sub-calcic augite accompanied by pigeonite or orthopyroxene.

*Rounded* – Describes the smoothness of the surface of a detrital grain present within a sediment or sedimentary rock. The terms *well-rounded*, *rounded*, *subrounded*, *subangular*, *angular*, *very angular* are used to describe the increasingly angular/irregular/rough nature of the surface of detrital grains.

*Seriate texture* – Refers to a continuous range in crystal size of principal minerals in an igneous rock.

*Sorting* – Well sorted describes a fragmentary deposit in which all the detrital grains are of approximately uniform size. In reality most fragmentary deposits contain a range of grain sizes and can be described as moderately sorted, poorly sorted or in extreme cases unsorted.

*Spessartite* – Term used for a variety of lamprophyre consisting of phenocrysts of hornblende with or without biotite, olivine or pyroxene in a groundmass of the same minerals plus plagioclase and minor K-feldspar.

*Sphericity* – Describes the how closely a detrital grains present within a sediment or sedimentary rock approximates to a sphere. The terms low sphericity, moderate sphericity and high sphericity are used to describe how spherical (ball-like) the detrital grains are.

*Schist* – A metamorphic rock of broadly pelitic composition (i.e. a metamorphosed mudstone) with a well-developed schistosity.

*Schistosity* – A planar structure developed in a metamorphic rock defined by the alignment of elongate minerals such as micas and amphibole.

*Teschenite* – A variety of analcime gabbro consisting of olivine, Ti-augite, labradorite and analcime.

*Tholeiitic basalt* – Commonly used term for a variety of basalt composed of labradorite, augite, hypersthene or pigeonite with olivine (often showing reaction relationship) or quartz, and often with interstitial glass.

*Trachyte* – A volcanic rock consisting essentially of alkali feldspar. Now defined modally on a Quartz-Alkali feldspar-Plagioclase-Feldspathoid ternary diagram or geochemically using the Total Alkali-Silica diagram.

*Trachyandesite* – A term originally used for volcanic rocks intermediate in composition between trachyte and andesite and containing equal amounts of alkali feldspar and plagioclase. Later used for volcanic rocks containing feldspathoids as well as alkali feldspar and plagioclase. Now defined geochemically using the Total Alkali-Silica diagram.

*Trachybasalt* – Term mainly used for basaltic volcanic rocks containing labradorite and alkali feldspar. Now defined geochemically using the Total Alkali-Silica diagram.

*Trachytic texture* – The sub-parallel alignment of microcrystalline feldspar in the groundmass of a *holocrystalline* or *hypocrystalline* igneous rocks. Sub-divided into pilotaxitic texture and *hyalopilitic* texture depending on whether the material between the feldspar is crystalline or glassy. *Trachytoid* texture, alignment of tabular, bladed or prismatic crystals which is visible to the naked eye. The terms *flow* and *fluxion* texture are sometimes used as synonyms for trachytic and trachytoid textures. However, they are best avoided due to their genetic implications.

# References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

PHILLIPS, E. R. 2002. *A review of petrological data available for the Reay District, Caithness, Scotland*. British Geological Survey. **IR/02/074**. pp 110.

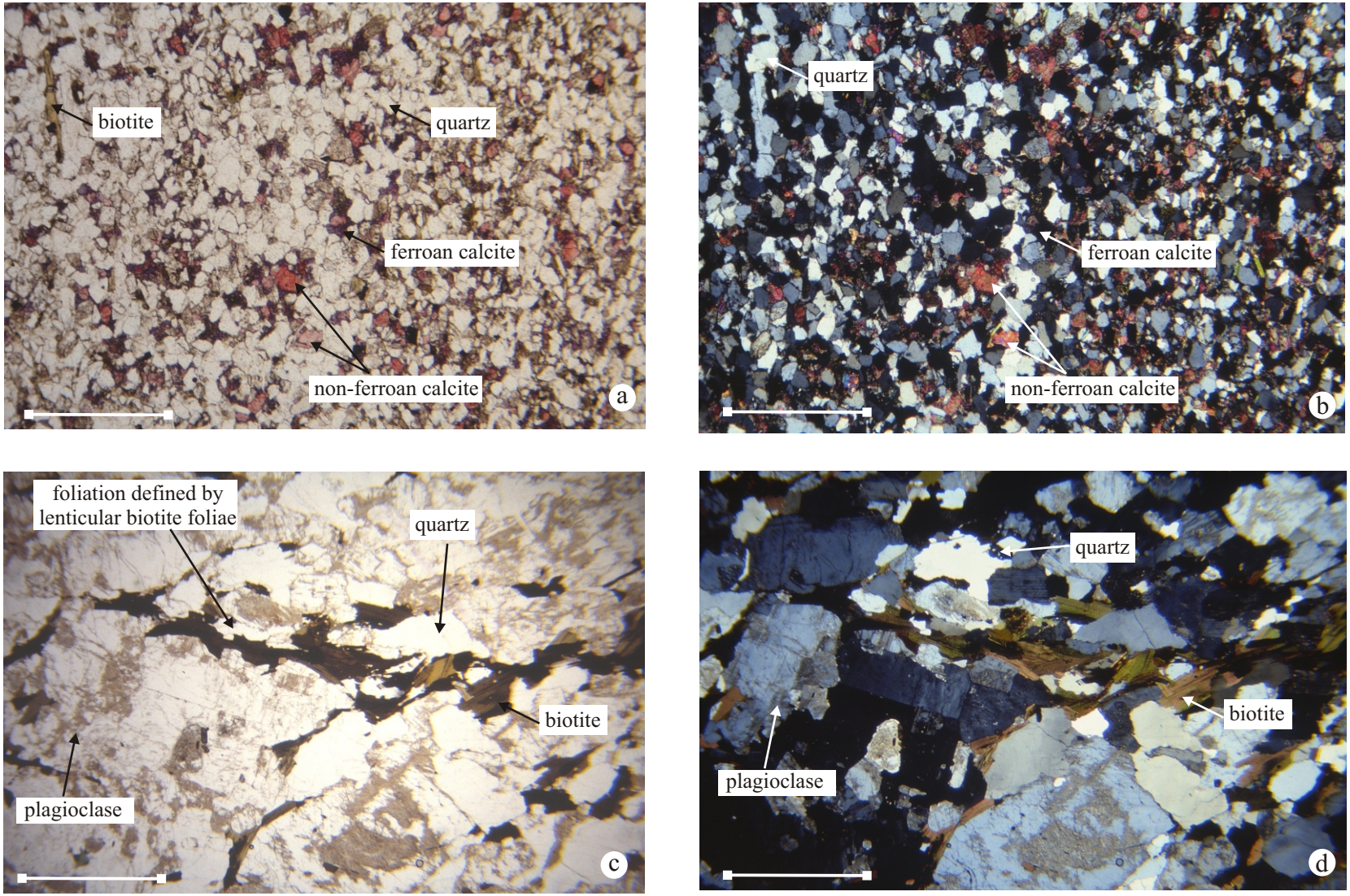



**Plate 1.** (a and b) Fine-grained sandstone containing minor amounts of pale pink stained non-ferroan calcite and dark blue to mauve ferroan calcite (Sample N3683, plane and crossed polarised light, scale bar = 1 mm). (c and d) Foliated granitic rock with fabric defined by lenticular domains or foliae of biotite (Sample N3684, plane and crossed polarised light, scale bar = 4 mm).

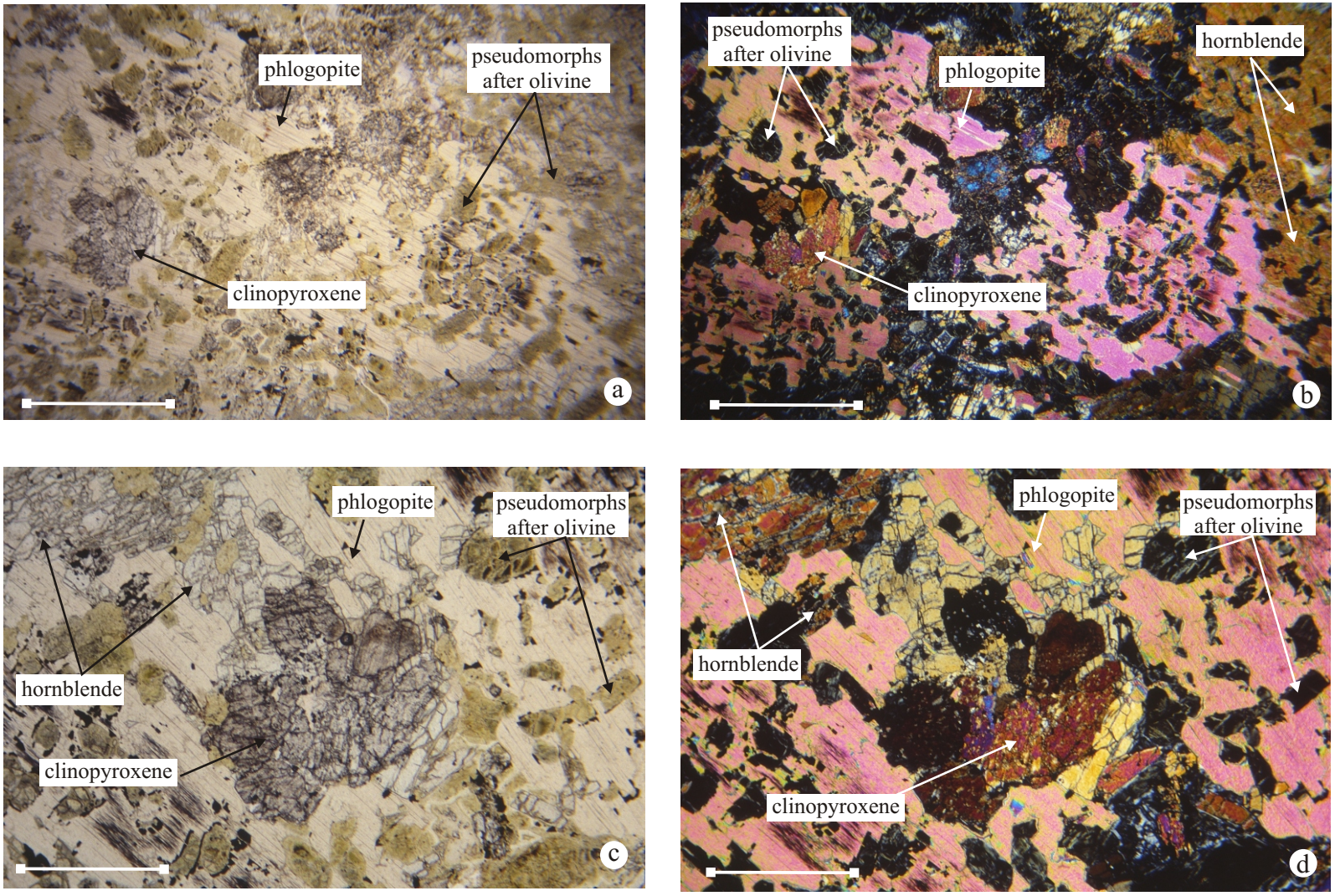
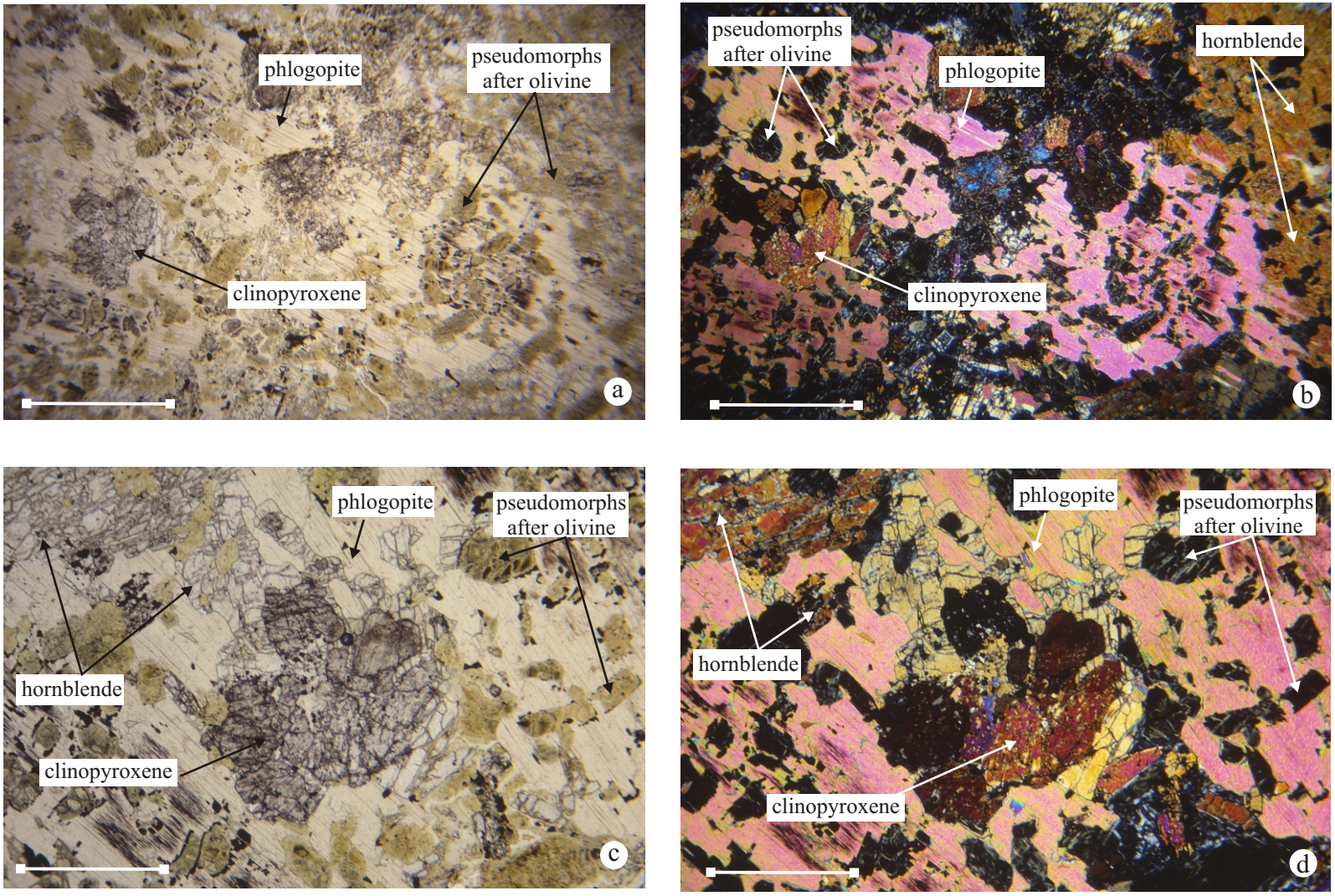



**Plate 2.** Clinopyroxene-bearing olivine-phlogopite-hornblendite in which the olivine has been completely replaced by mesh-textured serpentine (Sample N3685, plane and crossed polarised light, scale bar = 4 mm).

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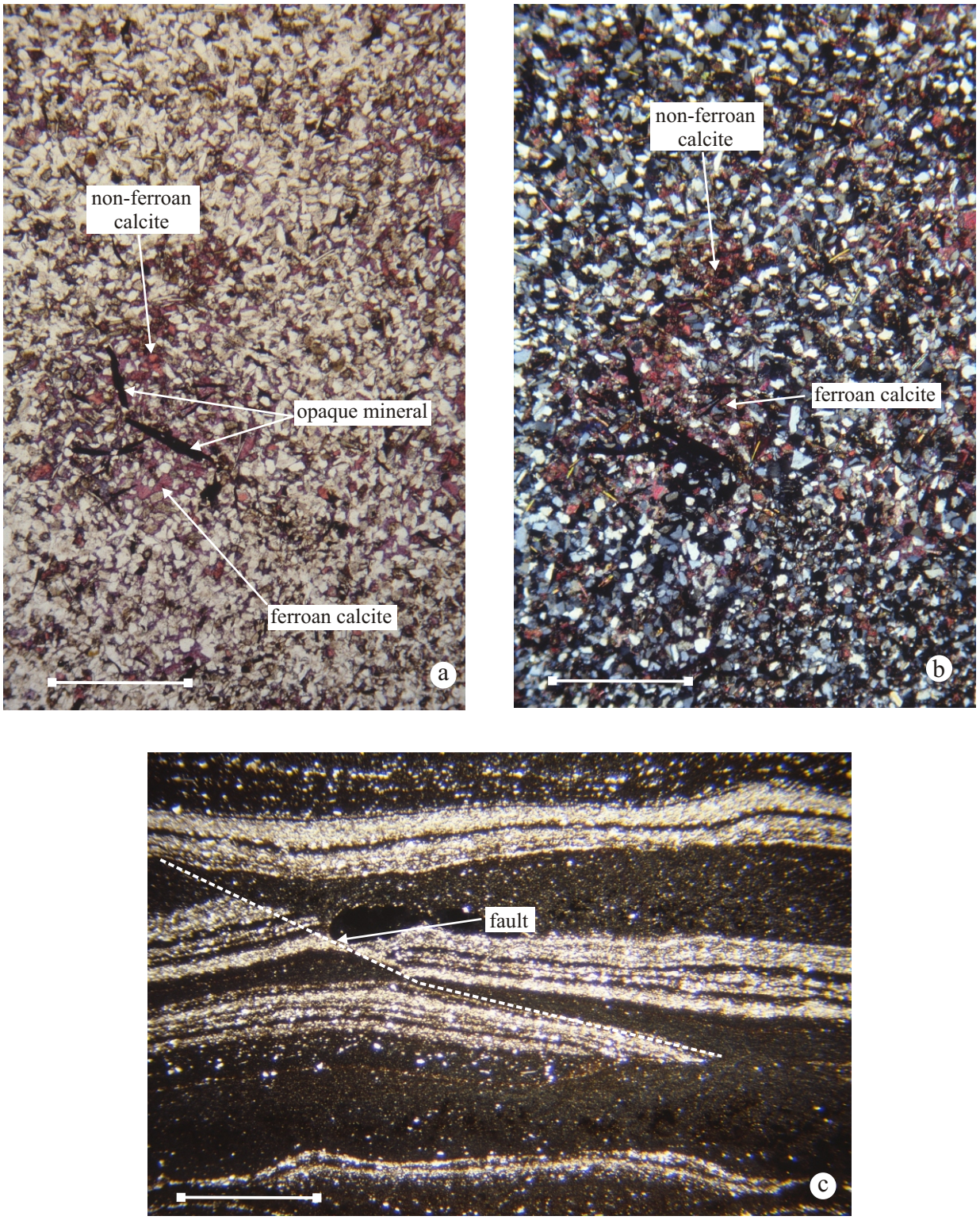


**Plate 4.** (a and b) Fine-grained sandstone containing minor amounts of dark blue to mauve ferroan calcite which locally contains relict pale pink non-ferroan calcite (Sample N3689, plane and crossed polarised light, scale bar = 1 mm). (c) Laminated siltstone and mudstone in which the lamination is deformed by a moderately dipping normal fault (Sample N3690, plane polarised light, scale bar = 4 mm).

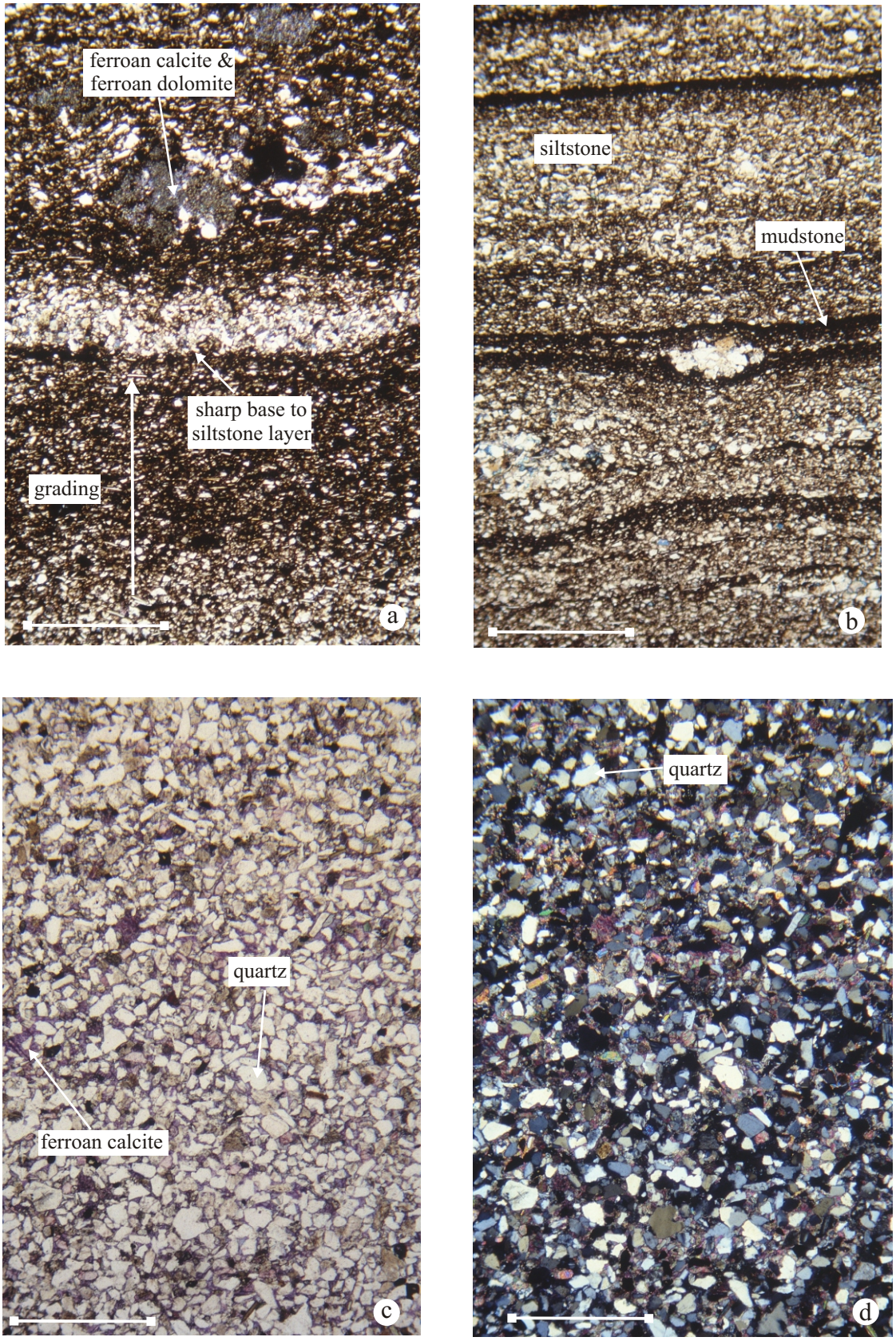


**Plate 5.** (a) Laminated mudstone with minor amounts of replacive ferroan calcite and ferroan dolomite (Sample N3992, plane polarised light, scale bar = 4 mm). (b) Laminated siltstone with mudstone partings (Sample N3994, plane polarised light, scale bar = 4 mm). (c and d) Fine-grained sandstone containing minor amounts of pale blue to mauve ferroan calcite (Sample N3995, plane and crossed polarised light, scale bar = 1 mm).

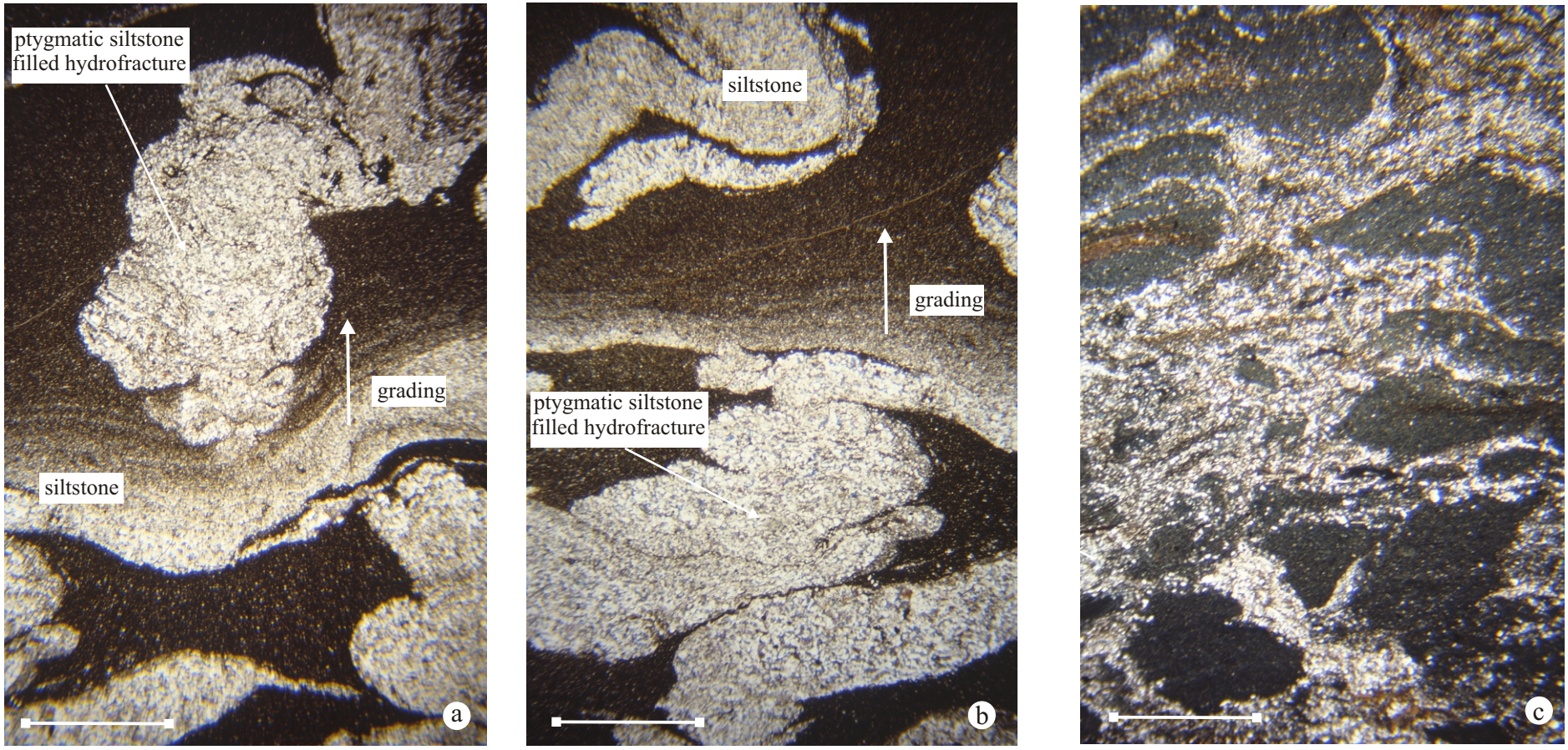


**Plate 6.** (a and b) Mudstone with graded siltstone laminae which contains ptygmatically folded siltstone filled hydrofractures (Sample N3997, plane polarised light, scale bar = 1 mm). (c) Calcareous mudstone deformed by a network of siltstone filled hydrofractures (Sample N4001, plane polarised light, scale bar = 4 mm).

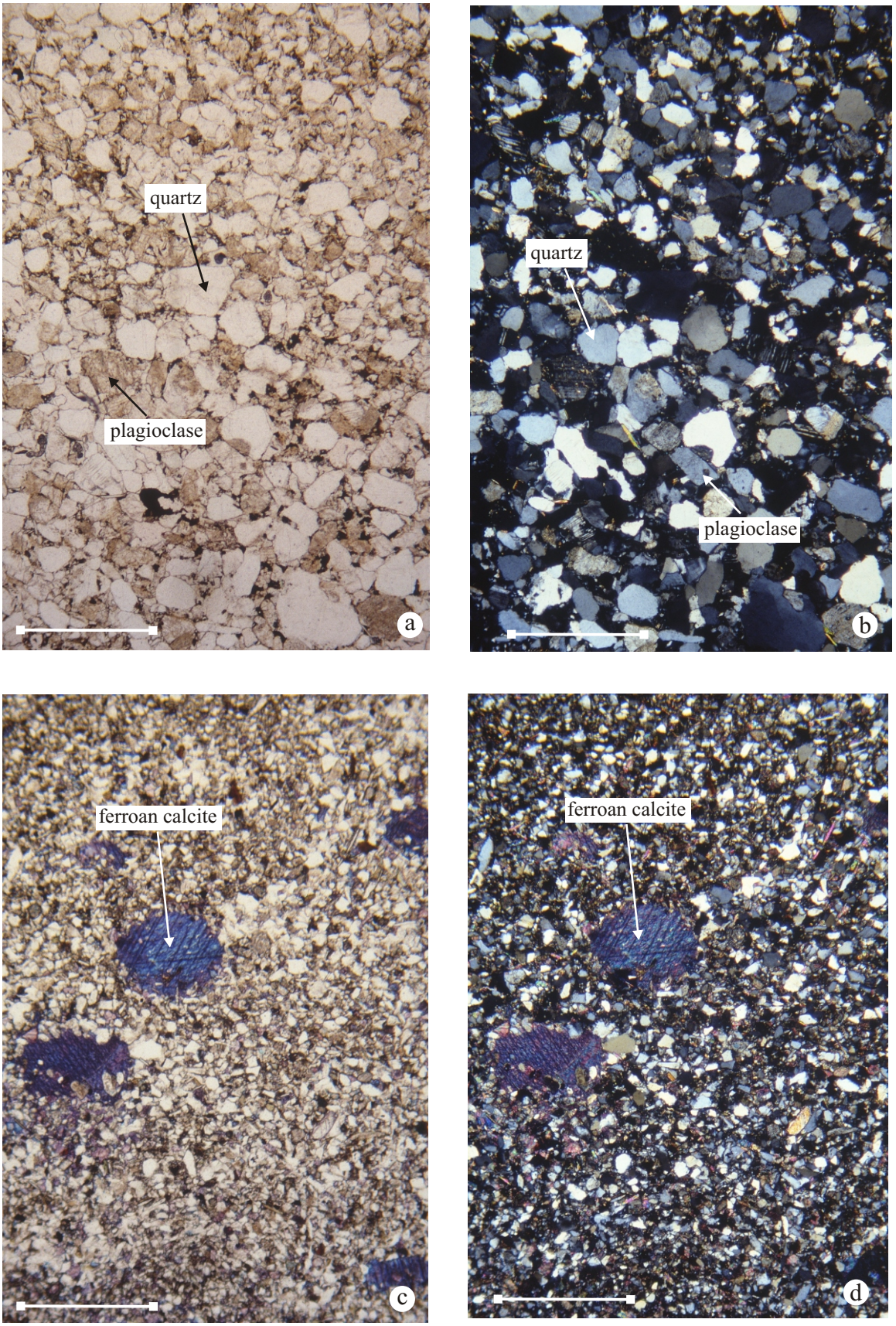


**Plate 7.** (a and b) Slightly feldspathic quartzose sandstone (Sample N4003, plane and crossed polarised light, scale bar = 1 mm). (c and d) Fine-grained sandstone containing minor amounts of dark blue to mauve ferroan calcite (Sample N4004, plane and crossed polarised light, scale bar = 1 mm).